Reducing the UK's carbon footprint

Committee on Climate Change | April 2013

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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 four progress reports in October 2009, June 2010, June 2011 and 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, bioenergy, and the role of local authorities. In September 2010, July 2011 and July 2012, 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 on the UK's carbon footprint and lifecycle emissions of low-carbon technologies. It supports our advice published in April 2013: **Reducing the UK's carbon footprint and managing competitiveness risks**.

Acknowledgements

The Committee would like to thank:

The core team that prepared the analysis for this report. This was led by Ute Collier and David Kennedy and included: Owen Bellamy, Adrian Gault, Hanane Hafraoui, Nina Meddings and Kavita Srinivasan.

Other members of the Secretariat that contributed to the report: Tara Barker, David Joffe, Swati Khare-Zodgekar, Jo McMenamin, and Joanna Ptak.

A number of organisations for their support, including: Carbon Capture and Storage Association, Carbon Trust, Department of Energy and Climate Change, Department for Environment, Food and Rural Affairs, International Energy Agency, Low Carbon Vehicle Partnership, Parliamentary Office of Science and Technology, RenewableUK, Tyndall Centre for Climate Change Research, University of Bath Sustainable Energy Research Team, University of Birmingham Centre for Nuclear Education and Research, University of Leeds, University of Manchester Sustainable Consumption Institute, University of Oslo Center for International Climate and Environmental Research (CICERO) and University of Surrey Sustainable Lifestyles Research Group.

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

Contents

The Committee

The Rt. Hon John Gummer, Lord Deben, Chairman
The Rt. Hon John Gummer, Lord Deben established and chairs Sancroft, a Corporate Responsibility consultancy working with blue-chip companies around the world on environmental, social and ethical issues. He was the longest serving Secretary of State for the Environment the UK has ever had. His experience as an international negotiator has earned him worldwide respect both in the business community and among environmentalists. He has consistently championed an identity between environmental concerns and business sense.

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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.

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Professor Samuel Fankhauser is 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.

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Paul is the director of the Institute for Fiscal Studies. He has worked on the economics of public policy throughout his career. Paul has been chief economist at the Department for Education and director of public spending in HM Treasury, where he had particular responsibility for environment (including climate change), transport and public sector pay and pensions. Between 2004 and 2007 Paul was deputy head of the Government Economic Service. He has also served on the council of the Economic and Social Research Council.

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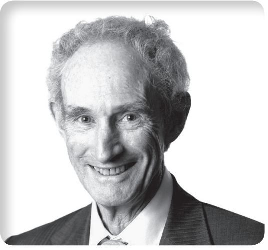
Professor Dame Julia King DBE FREng Vice-Chancellor of Aston University. She led the 'King Review' for HM Treasury in 2007-8 on decarbonising road transport. She was formerly Director of Advanced Engineering for the Rolls-Royce industrial businesses, as well as holding senior posts in the marine and aerospace businesses. Julia is one of the UK's Business Ambassadors, supporting UK companies and inward investment in low-carbon technologies. She is an NED of the Green Investment Bank, and a member of the Airports Commission.

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 Councils UK Energy Strategy Fellow and Professor of Sustainable Energy at Imperial College London. He was previously Research Director at the UK Energy Research Centre (UKERC) and 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.

Introduction and key messages

UK carbon budgets are defined on the basis of territorial emissions (i.e. those that are produced within the UK's borders), in accordance with the United Nations Framework Convention on Climate Change and the Kyoto Protocol. On this basis, UK greenhouse gas emissions have fallen substantially over the last two decades. However, UK imports of goods and services have risen significantly over the same period and a number of studies, as well as estimates produced for us (see chapter 1), have suggested that the emissions embedded in these imports have caused the UK's overall 'carbon footprint' (i.e. emissions measured on a consumption basis) to increase.

These studies also indicate that the UK has one of the largest gaps between production and consumption emissions in the world, with our net imports of emissions higher than those of most other countries. This is due to the types of goods and services we trade – we import a large quantity of manufactured goods, and we primarily export services. Our high level of net emissions raises concerns about the possible impact of climate policies on competitiveness (i.e. that the cost of measures to meet ambitious targets might encourage businesses to relocate, leading the UK to simply re-import the emissions, so-called 'carbon leakage').

Consideration of the UK's full carbon footprint is also important in relation to the low-carbon options we propose to achieve carbon budgets (e.g. renewable power and heat, nuclear power and electric vehicles). It will be important that the footprint of these options is substantially lower than those of the fossil-fuel technologies currently in use, whether the emissions occur in the UK or elsewhere. While we have previously discussed lifecycle emissions for certain technologies in our 2011 Renewable Energy and Bioenergy reviews, in this report we carry out a comprehensive assessment of lifecycle emissions for a greater range of low-carbon technologies and their conventional counterparts.

The consideration of consumption and lifecycle emissions raises questions as to whether the current approach to target setting (which does not take explicit account of consumption emissions) is appropriate and whether enough policy effort is devoted to consumption measures.

The UK House of Commons Energy and Climate Change (ECC) Committee produced a report on consumption-based accounting in 2012. It argued that if the Government wishes the UK to continue its lead on climate policy it must recognise the growth in the UK's consumption-based emissions and the impact on territorial emissions in other countries. It recommended that:

- The Department for Energy and Climate Change (DECC) should explore the options for setting emission targets on a consumption-basis at the national level.
- Additionally, DECC should incorporate consumption-based emissions data in to the policy making process.
- While recognising uncertainties inherent in consumption-based emissions, this should not be used by the Government as an excuse for inaction.

The ECC Committee suggested that the Government should commission the Committee on Climate Change to undertake work on these issues, which the Government subsequently asked us to do. We agreed with the Government that the scope of the work should cover:

- Estimates of past and current consumption emissions
- Possible pathways for UK consumption emissions towards 2050;
- Data/methodological issues
- Priority technologies/products
- Merits of a two stage approach to consumption monitoring (input-output & lifecycle emissions)
- Implications of current and future consumption emission trends on the design of policies

The results of this work are presented in this report. We begin by examining methodologies for estimating the UK's carbon footprint, presenting new estimates of recent trends in consumption emissions and setting out some possible scenarios for the UK's footprint to 2050. We then assess lifecycle emissions of conventional fossil fuel and key low-carbon technologies in power, heat and surface transport. Finally, we look at a range of options for reducing the UK's carbon footprint and examine the implications for carbon accounting.

Our key findings are:

- **Trends in the UK's carbon footprint**. The UK's carbon footprint has increased over the past two decades, as growth in imported emissions has more than offset reductions in production emissions. However, our analysis shows that offshoring of industry in response to low-carbon policies has had at most a minor impact in reducing production emissions, and the carbon footprint would have increased more had production emissions not been reduced.
- **The UK's future carbon footprint**. To achieve the climate objective[1], there is a need for a global deal to substantially cut global emissions over the next decades. A consequence of this would be that the UK's carbon footprint would fall. Our analysis suggests a reduction in the UK's carbon footprint of around 70% on current levels in 2050 is broadly consistent with global emissions pathways to achieve the climate objective.
- **Data/methodological issues**: Consumption-based emission estimates are more uncertain than production-based estimates. Different methodologies and data sets can produce different estimates. Nevertheless, there is a consistent finding across studies that the UK's carbon footprint has increased. Consumption-based estimates are useful as an investigative tool but they have to be treated with caution.

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[1] To keep central estimates of global mean temperature as close to 2°C above pre-industrial levels as possible, and to limit the likelihood of temperature change above 4°C to very low levels (e.g. 1%). This is the climate objective that underpins all our advice.

- **Lifecycle emissions of low-carbon technologies**. Our assessment suggests that the key low-carbon technologies (i.e. in power, heat and surface transport) offer significant savings over fossil-fuel technologies even when accounting for lifecycle as well as operating emissions.
- **Policies to reduce consumption emissions**: Our findings highlight the importance of achieving an ambitious and comprehensive global deal for driving down global emissions and meeting the climate objective. Border carbon adjustments are not an alternative to a global deal but should not be ruled out as a possible transitional measure if there were to be slow progress agreeing a global deal. Policies to encourage resource efficiency and sustainable consumption could help to reduce the UK's carbon footprint.
- **Carbon accounting**. It remains appropriate to account for carbon budgets on the basis of production emissions given accounting conventions and available policy levers. However, consumption emissions should be monitored to check whether these are falling in line with global action required to achieve the climate objective, or whether further action is required. Input-output analysis remains the best option for monitoring consumption emissions, as there are no regular updates of lifecycle emission estimates of products.

We set out our analysis in 3 chapters:

1. Current and future consumption emissions
2. Carbon footprint of low-carbon technologies
3. Options for addressing the UK's carbon footprint

A summary report, which brings together key findings from this report with findings from our work on managing competitiveness risks of low-carbon policies, can be found on our website:

http://www.theccc.org.uk/publications/carbon-footprint-and-competitiveness/

Chapter 1: Current and future consumption emissions

Introduction and key messages

The Climate Change Act requires us to assess progress towards carbon budgets and the target to reduce emissions by 80% in 2050 on 1990 levels. To date, our assessment has focused on territorial emissions (i.e. those occurring only within the UK's borders) which are the basis of carbon budgets. However, with the Government's recent publication of consumption-based emission statistics and a rapidly growing evidence base, it has become possible to look at the UK's broader carbon footprint, including emissions embedded in imports, and trends over time.

In this chapter, we examine methodologies for estimating the UK's carbon footprint, we present new estimates of recent trends in consumption emissions and we analyse key drivers. We then set out some possible scenarios for the UK's carbon footprint to 2050, exploring whether the UK is likely to remain a net importer of emissions.

Our key messages are:

- **UK carbon footprint**. Our analysis suggests that the UK's carbon footprint has increased (by an estimated 10% over the past two decades), as growth in imported emissions has more than offset reductions in production emissions. The increase in imported emissions is largely a result of rising incomes which has increased demand for manufactured goods; these are, due to globalisation, now mostly produced elsewhere.
- **UK production emissions and offshoring**. The fall in production emissions was not due to significant offshoring in response to low-carbon policies. Rather, production emissions fell due to reductions in emissions from power generation and non-CO_2 gases (e.g. methane from waste). There has also been a reduction in industry emissions which reflects a falling carbon intensity of production due to energy efficiency improvement and fuel switching, industrial restructuring related to broader processes of globalisation, and more recently the impact of the recession. If production emissions had not been reduced, the increase in carbon footprint would have been greater.
- **International comparisons**. The UK is estimated to rank among the top 10 countries in the world by consumption and production emissions, but has relatively low emissions compared to other large emitting countries. The UK is among the highest per capita emitters on a consumption basis, but is broadly in line with other developed countries with service-based economies.
- **Future UK carbon footprint**. Our analysis suggests that the UK is likely to continue to remain a net importer of emissions in 2050 but that a reduction in the carbon footprint of around 70% on current levels is broadly consistent with a global emissions pathway to achieve the climate objective underpinning the Climate Change Act.

- **Uncertainty**. Consumption emissions estimates are subject to a greater degree of error and uncertainty than production emissions. Despite uncertainty, there is a consistent finding across studies that the UK's carbon footprint has increased since 1990 and is greater than production emissions. Consumption emissions methodologies are an area of significant ongoing research, which should help narrow the range of uncertainty over time. However, it would currently be both difficult and impractical to set targets and measure progress on the basis of consumption emissions accounting.

We set out our analysis and cover these issues in five sections:

1. How the UK's carbon footprint is measured and key accounting uncertainties
2. Trends in the UK's carbon footprint
3. Key drivers of UK consumption emissions
4. UK progress compared to other countries
5. Scenarios for future UK consumption emissions and key implications

1. How the UK's carbon footprint is measured and key accounting uncertainties

Consumption emissions accounting is a new and emerging area of research, with methodologies evolving rapidly over time as new and improved data become available. As a result, there is a wide range of estimates of the UK's carbon footprint in the existing literature. This section examines the methodologies, data requirements, and uncertainties.

Alternative methodologies for estimating emissions

UK carbon budgets are defined on the basis territorial emissions, or those occurring only within the UK's borders, in accordance with the United Nations Framework Convention on Climate Change (UNFCCC). These include emissions from burning fossil fuels for electricity generation and industrial production, direct emissions from heating in households and businesses, emissions from burning petrol and diesel in cars and other vehicles, and emissions arising from other activities, including agriculture, waste management, and land use, land use change and forestry (LULUCF). Territorial emissions are estimated in the National Atmospheric Emissions Inventory and are used as the basis for the UK's reporting on emissions reduction targets to the European Union (EU) and the UNFCCC.

The UK's national emissions inventory also includes emissions associated with international aviation and shipping. We envisage that these will be included in carbon budgets following agreement on a global approach to regulating these emissions. In this report, we refer to the UK's territorial emissions plus international aviation and shipping emissions as the UK's 'production emissions'.

A third approach accounts for emissions on a 'residents' basis, including emissions by UK residents and industry whether in the UK or abroad but excluding emissions within the UK that can be attributed to overseas residents and businesses. These emissions are estimated in the UK Environmental Accounts, in line with international convention, and published by the Office for National Statistics.

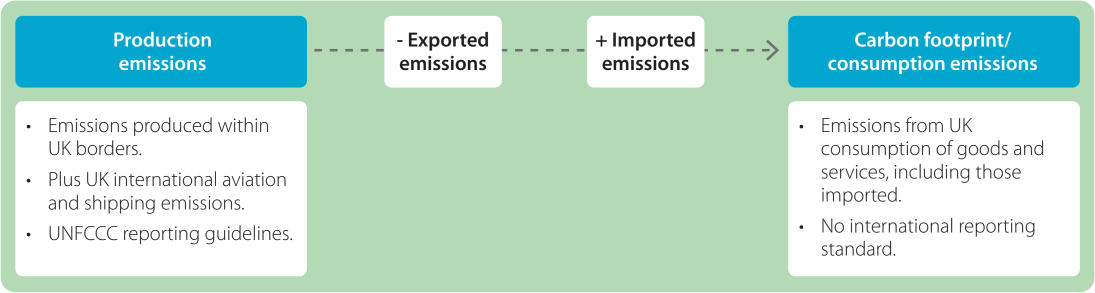
However, these accounting approaches do not include emissions embedded in the goods and services we import (either directly or indirectly), nor do they exclude the emissions embedded in goods and services that are exported. The UK's carbon footprint, or consumption emissions, allows for these emissions, and therefore covers all emissions related to the final consumption of goods and services in the UK.

How consumption emissions are calculated

The UK's carbon footprint refers to emissions that are associated with the spending of UK businesses and residents on goods and services, wherever in the world they arise along the supply chain. For example the UK's carbon footprint includes production and supply chain emissions associated with cars imported into the UK, as well as emissions associated with goods and services that are both produced and consumed in the UK such as electricity. It is therefore calculated as (Figure 1.1):

- UK production emissions (emissions occurring within UK borders, including for the production of goods and services and those directly generated by UK households for heating of homes and private transport);
- Subtracting emissions associated with goods and services that are exported to other countries;
- Adding emissions embedded in imports for final UK consumption.

Figure 1.1: Consumption emissions accounting approach



UK production emissions are relatively straightforward to estimate, relying on annual energy use and other statistics and applying nationally specific emission factors to individual activities (e.g. combustion of natural gas in a boiler). Uncertainties are low in the case of energy-related emissions estimates, for which there is comprehensive data available (e.g. national statistics on energy consumption). Agriculture non-CO_2 and land-use related emissions are somewhat more difficult to estimate but the Government has an ongoing programme to improve data in these sectors[1].

Consumption emissions are much more complex to estimate than production emissions. They require estimates of emissions occurring along international supply chains, and there are no agreed international reporting standards.

Two methodologies have been developed to estimate consumption emissions: a simpler 'production-plus' accounting approach and a more complex method using 'input-output' analysis that links UK demand to complex supply chains across the world. Despite the complexities involved, there is growing international consensus by researchers favouring the use of input-output analysis, in particular multi-regional input-output (MRIO) analysis, to produce the most accurate estimates of a country's carbon footprint:

- **'Production-plus' analysis**. This methodology supplements production emissions by adding estimates of emissions embedded in *net* trade. It has been used by researchers to estimate the UK's carbon footprint[2].
    - Emissions embedded in exports are subtracted from UK production emissions. These exported emissions are calculated by multiplying the total value of UK exports by an average UK-wide emissions intensity, defined as total UK emissions divided by total UK economic output.
    - Emissions embedded in imports are added to UK production emissions. Imported emissions are calculated in a similar manner by multiplying the total value of imports from a UK trading partner by that country's average economy-wide emissions intensity.
    - This approach is relatively simple with few data requirements. It is conceptually straightforward, but has the drawback that it is not possible to track activity and emissions through complex international supply chains, For example, it would not fully account for any intermediary inputs imported to the UK which are used to manufacture products for export.
- **Input-output analysis**. These use very detailed data in 'input-output' tables, which are compiled and published by countries to describe economic flows across sectors and regions (e.g. the amount the UK steel industry spends in other sectors across the UK economy and abroad to support its production of steel). Input-output analysis was originally developed to investigate the inter-dependencies between economic sectors and between trading economies, but has been further developed to perform environmental analysis. For example, expenditures in input-output tables can be linked to emissions occurring across sector and supply chains.

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[1] Defra's Agricultural Greenhouse Gas Inventory Research Platform.

[2] E.g. Helm, D, Smale, R and Phillips, J (2007), *Too Good To Be True? The UK's Climate Change Record.*

- For simplicity purposes and due to a lack of data, input-output assessments have used simplifying assumptions such as aggregating all trading partners to one region. However, approaches have evolved over time, as more data has become available and models have become more sophisticated, to enable **multi-regional input-output** analysis (MRIO) of emissions embedded in trade flows:
    - MRIO analysis enables tracking of UK purchases to emissions arising in supply chains across sectors and countries.
    - Under MRIO analysis, consumption emissions associated with purchasing a German car would account not only for German car manufacturing emissions, but also for emissions associated with inputs shipped to Germany to manufacture that car (e.g. steel from China, and any inputs used in China to manufacture that steel).
    - Similarly, production emissions associated with intermediate goods imported by the UK to produce final goods (e.g. iron ore imported to produce higher value steel products) that are then exported are not allocated to the UK 's carbon footprint.

MRIO is potentially the most accurate method for estimating consumption emissions. However, it has greater data needs, requires complex modelling that is subject to errors and is less transparent.

Key uncertainties and data gaps in estimating consumption emissions

Estimating consumption emissions accurately depends on the availability and accuracy of domestic and foreign production emissions data, UK trade statistics and economic data reported by the UK's trading partners. These data are compiled into global databases but often reflect different time periods, currencies, industrial classifications, and levels of disaggregation and need to be harmonised for use in input-output analysis[3]. Consumption emissions estimates are therefore subject to a greater degree of error and uncertainty than production emissions.

Emissions data

- **UK production emissions data**. The UK has comprehensive and robust CO_2 emission data for energy-related emissions but estimating non-CO_2 and LULUCF CO_2 emissions is not straightforward, evolving, and subject to a wider range of uncertainty[4].
- **International production emissions**.
    - **Global inventories**. There is no single standardised source of global production emissions by country. Parties to the UNFCCC report emissions under Intergovernmental Panel on Climate Change (IPCC) guidelines but there are different requirements for Annex I (industrialised) and non-Annex I (developing) countries. The International Energy Agency reports on CO_2 emissions arising from the combustion of fossil fuels and industrial processes but does not include

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[3] House of Commons Energy and Climate Change Committee (2012) *Consumption-Based Emissions Reporting Volume I*.

[4] For the UK greenhouse gas inventory, it has been estimated that uncertainties are as low as 2% for CO_2 but are 20% for methane and 'very large' for N_2O (see https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/139625/5926-uk-ghg-inventory-national-statistics-user-guide.pdf)

    non-CO_2 gases or CO_2 emissions arising from LULUCF activities. The Emissions Database for Global Atmospheric Research (EDGAR) operated jointly by the European Commission Joint Research Centre and Netherlands Environmental Assessment Agency is one of the most comprehensive sources of global production emissions by country.

  - **CO_2 versus non-CO_2 emissions accounting**. While emissions arising from combustion of fossil fuels are more easily understood, process emissions (e.g. from industrial activities) and emissions arising from land use activities (including greenhouse gases such as nitrous oxide and methane) are imperfectly understood. As such, there is greater confidence in the estimates of CO_2 emissions arising in our trading partners than in non-CO_2 gases.

Economic data

- **UK trade statistics**. Trade statistics published by the UK and other governments and international organisations bear a range of uncertainties (e.g. due to time lags between shipping of exports and receipt of imports, differences in commodity classification and reporting errors).

- **Economic output data** is compiled by government statistical agencies, but is not necessarily standardised nor complete or accurate across all countries, which influences estimates of emissions intensities.

- **Input-output data**. Input-output tables are very complex and require information on how economic sectors link together and trade with each other.

  - They are compiled from surveys by government statistical agencies but often many of the calculations which go into transforming underlying survey data into balanced input-output tables are not publicly available. This makes it difficult to assess many of the underlying uncertainties and data quality issues.

  - The resource-intensive nature of input-output models also gives rise to transparency issues in relation to the countries/regions included. To simplify calculations, studies often aggregate sectors and regions which can reduce the accuracy of results.

  - This data is compiled into various databases for input-output analysis but for countries or years where input-output data are not available, proxies are used. For example, Eora, a new global MRIO database housed at the University of Sydney, provides a time series of input-output tables with matching environmental data for 187 countries. For countries with missing input-output tables, Eora applies a representative economy using tables from the U.S., Japan and Australia. For missing years, a country's input-output table from a previous year is updated using available economic indicators.

Time delays

Economic and emissions data are often infrequently published by national authorities, and are sometimes years out of date. For example, many input-output based assessments of consumption emissions have relied on trade and emissions data from the Global Trade Analysis

Project (GTAP), which produces complete datasets on a three year cycle, typically several years behind the point of publication. As a result most UK studies have focused on estimating the UK's carbon footprint in 2004 which until very recently was the most recent year with complete data available in GTAP (the latest complete dataset made available is for 2007). Over recent years, new MRIO databases have been developed to provide more updated data, with some including times series data. For example, the Government estimates of UK consumption emissions now rely on economic and emissions data from Eora, which is updated annually but with a two-year time lag (e.g. the latest data available for analysis is from 2010).

As with economic data, emissions data are subject to time delays. Moreover, as consumption emissions rely on complete production estimates inventories, there will always be at least a further year delay in producing consumption emissions estimates.

Aligning emissions and economic data to estimate emissions intensities

With no agreed international standard, economic and emissions data differ across countries in terms of quality and sectors/years represented, and must be aligned to create a consistent dataset for input-output analysis (e.g. to estimate emissions intensities associated with a given sector). Moreover, within a given country, emissions data need to be matched to economic sectors, which are often classified on a different basis and scope than emissions data.

Monetary flows as proxy for physical flows

The amount of emissions embedded in a good or service consumed in the UK is determined by multiplying demand (in monetary terms) by the emissions intensity of that good or service. Emissions intensities are calculated by dividing total direct production emissions from that sector by total economic output from that sector. Relying on monetary data rather than energy inputs or physical production (e.g. tonnes) can be problematic as it can distort the real emissions associated with a good and service. For example, economic data for different countries that are compiled into global databases used for input-output analysis is often available at different time periods, and must be adjusted to generate a base year using country-wide consumer price indices. This can introduce error, for example if some sectors are subject to different price changes, which is then carried over into estimating emissions intensities[5].

Conclusions on uncertainty

Consumption emissions accounting is subject to uncertainty present in production emissions accounting, with additional layers of uncertainty due to the availability, accuracy, and aggregation of economic and emissions data used in consumption methodologies. Additionally, consumption-based accounting is subject to modelling and structural uncertainties deriving from the choice of regions and sectors analysed. Using different methodologies and data sets can therefore produce very different estimates of a country's carbon footprint.

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[5] House of Commons Energy and Climate Change Committee (2012) *Consumption-Based Emissions Reporting Volume I.*

Within a given study, it may be possible to estimate uncertainties present in calculations. For example, the model used to develop the Government's estimates of the UK's carbon footprint was subjected to an uncertainty analysis in 2008[6]. This demonstrated that the increase in the UK's carbon footprint was statistically significant within the parameters of the model, thus suggesting that the model was robust enough to provide a reliable indication of the UK's carbon footprint. However, this model has recently been updated with new input data and more regional analysis, showing similar trends to the older estimates but an overall UK carbon footprint that is higher (see Section 2, Box 1.1). Further analysis is required to understand how these revisions have reduced uncertainty.

Consumption emissions are an area of significant ongoing research, which should help narrow the range of uncertainty over time and improve accuracy of estimates. In particular, international standards to ensure consistent reporting practices across countries will be important in future.

Given the reasons outlined above, however, it would be both difficult and impractical to set targets and measure progress on the basis of consumption emissions accounting. However, it is important for the government to continue monitoring consumption emissions to inform policy (see Chapter 3).

We explore trends in the UK's carbon footprint below.

2. Trends in the UK's carbon footprint

Given different methodologies and data sources, there is substantial variation in estimates of the UK's carbon footprint. Even when comparing studies that use input-output approaches and rely on similar datasets for trade and emissions data, there are differences in results reflecting the way in which sectors and regions are aggregated and analysed. For example, estimates of the UK's CO_2 carbon footprint in 2004 vary by around 200 $MtCO_2$ (Figure 1.2).

Despite the variation in methodologies and data, a number of common messages emerge from the various studies:

- Studies that have developed a time series show an increase in UK consumption emissions over time.
- The gap between UK consumption and production emissions has been increasing.

The UK Government first published estimates of UK consumption emissions in 2008, as part of its larger work programme on promoting sustainable consumption and production, and to contribute to its basket of sustainable development indicators. The published estimates now cover a time series of UK consumption emissions going back to 1993.[7] The estimates have been developed using a multi-regional input-out model, which has evolved over the years to reflect improved emissions and economic data (Box 1.1).

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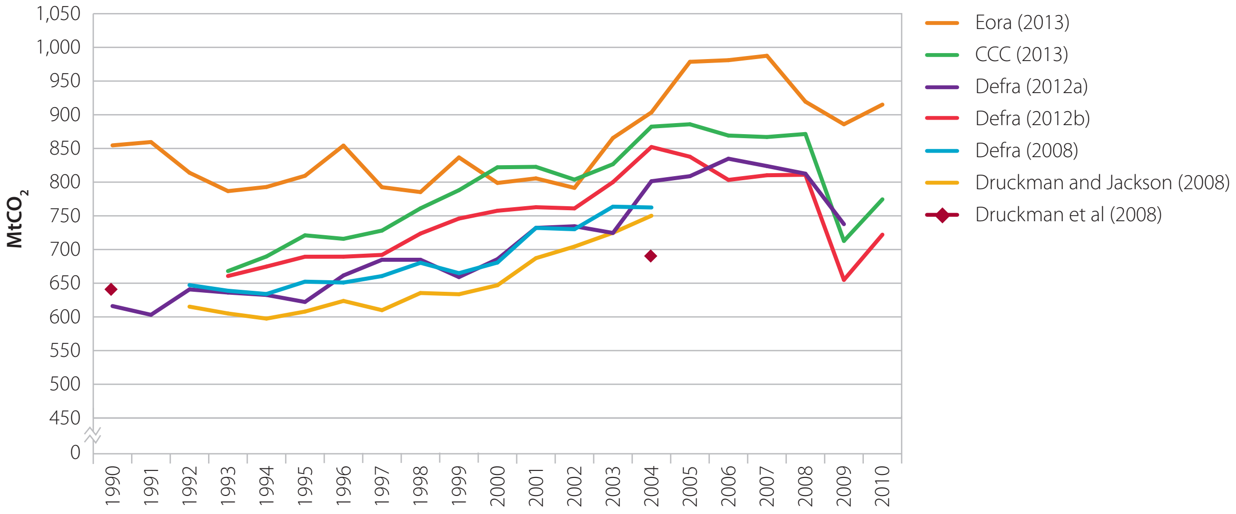
[6] Wiedmann, T., Lenzen, M. and Wood, R. (2008) *Uncertainty Analysis of the UK-MRIO Model – Results from a Monte-Carlo Analysis of the UK Multi-Region Input-Output Model (Embedded Emissions Indicator);* Report to the UK Department for Environment, Food and Rural Affairs by Stockholm Environment Institute at the University of York and Centre for Integrated Sustainability Analysis at the University of Sydney.

[7] Due to data limitations, consumption emissions estimates for the UK are not available pre-1993.

Figure 1.2: Range of estimates for UK consumption emissions (1990-2010)



Source: Various authors and sources.
Notes: Figures are for CO_2 only. This figure provides a representative but not exhaustive summary of UK consumption emission estimates in the literature. All studies use multi-regional input-output analysis with the exception of Druckman et al. (2008) which used a single-region input-output model and Druckman and Jackson (2008) which used a quasi-multi-region input-output model. All studies, with the exception of Eora (2013), Defra (2012b) and CCC (2013) rely on GTAP (a global database) for trade, emissions, and economic output data. Defra (2012b) refers to the latest official Defra estimates published in December 2012.

We have commissioned the University of Leeds to rerun the model used by the Government to estimate the UK's carbon footprint but with a greater disaggregation of trading regions. More detailed regions were chosen in order to explore future scenarios for the UK's carbon footprint in greater detail[8].

Our estimates exhibit a similar trend to the Government's figures but suggest that the UK's carbon footprint was 13% higher than the Defra estimates. This difference reflects that in accounting for a greater number of trading regions (seven versus three), we capture regional emission intensities more accurately, including outlier countries and regions with higher emission intensities (e.g. in Government estimates, emissions intensities are averaged across three trading regions).

We focus below on trends in all greenhouse gases embedded in the goods and services consumed in the UK but note that the estimates of non-CO_2 emissions embedded in imports, accounting for almost 50% of total emissions embodied in imports, are a lot less certain.

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[8] This reflects the rapidly evolving evidence base for multi-regional output analysis (e.g. at the time of publication of UK Government estimates in 2010, data was not readily available for additional regional disaggregation).

Box 1.1: Government approach to estimating UK consumption emissions

The UK Government's consumption emission estimates are developed using a multi-regional input-out model, which has evolved over the years to reflect improved emissions and economic data. The model was first developed by the Stockholm Environment Institute in collaboration with the University of Sydney and is currently updated annually by the University of Leeds:

- UK production emissions intensities are derived by dividing sectoral emissions (as provided in the ONS Environmental Accounts emissions data) by total sectoral output, which are then multiplied by final UK demand for goods and services to estimate the UK's domestic carbon footprint.
- Emissions embedded in imported goods and services are similarly estimated by multiplying demand for imports by carbon intensities of trading partners, which are obtained from global datasets.
- Demand for domestic and imported goods and services and domestic/foreign emissions intensities are inputted into an input-output model to estimate the UK's total carbon footprint.

Evolution of modelling approach

- **Earlier model** (2008-2011). The first UK MRIO model relied on GTAP datasets, which are published with three year time lags. Moreover aligning GTAP sector data with ONS sector data for the UK proved challenging. In addition, some GTAP data is collected via voluntary contributions from researchers around the world in exchange for free access to the database, rather than from scrutinised national statistics. For simplicity purposes, the earlier model applied average world emission intensities to all imported goods and services but was revised in 2011 to enable analysis of two trading regions (EU and the rest of the world).
- **Current model** (2012). The current model uses data from Eora, a global database designed specifically for MRIO analysis. Eora enables more straightforward matching of its sectors with specific UK ONS sectoral emissions and economic output data, and contains a time series of data from 1990 to 2010. The model analyses emissions embedded in imports from three UK trading regions (rest of the European Union, China, and rest of the world).
- **Comparison of results:** While both models estimate similar trends in the UK's carbon footprint, they produce different estimates in absolute terms (e.g. the new model estimates a UK GHG carbon footprint that is 10% higher in 2009).

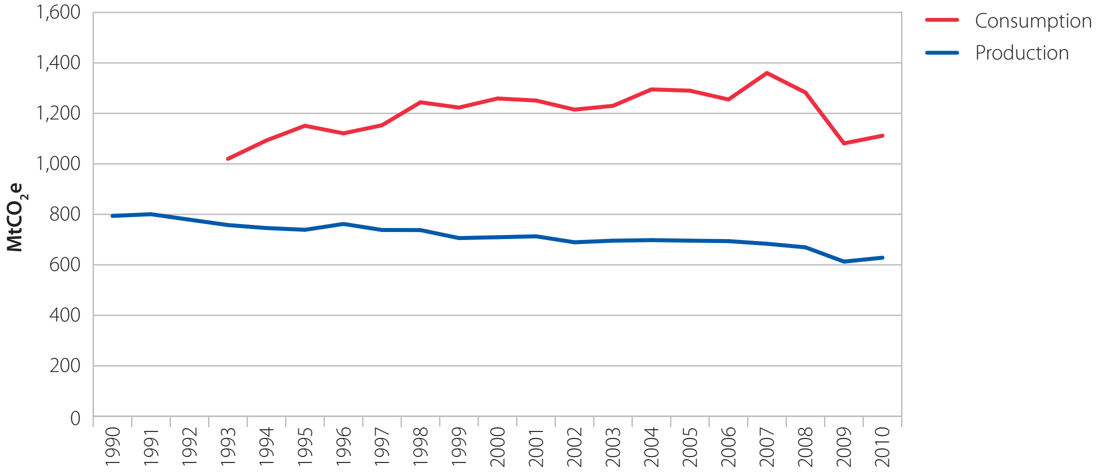
Given the evolving nature of MRIO databases and analysis, it is likely that the model will continue to be revised over time.

Sources: Defra (2011) *UK Consumption Emissions by Sector and Origin;* Defra (2012) *UK's Carbon Footprint 1993 – 2010*; https://www.gov.uk/government/publications/uks-carbon-footprint

Our analysis shows that while UK production emissions have fallen, imported emissions have more than offset this, such that the UK's carbon footprint has increased since 1993 by an estimated 10% (Figure 1.3):

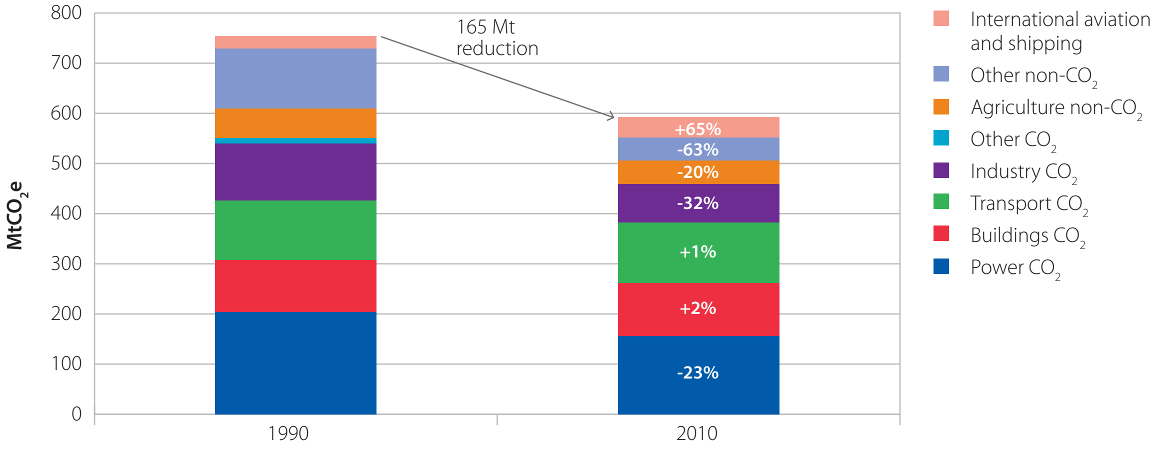
- **Production emissions**: Production emissions fell by 21% between 1990 and 2010 (19% since 1993), mainly due to switching from coal to gas in power generation, reductions in non-CO_2 gases such as waste methane emissions in response to EU landfill policies, and in industry due to switching to less carbon-intensive fossil fuels, energy efficiency improvement, and industrial restructuring (Figure 1.4). More recently, emissions have fallen as a result of the recession.

Figure 1.3: Greenhouse gas emissions associated with UK production and consumption (1990-2010)



Source: CCC consumption estimates developed by the University of Leeds (2013); NAEI (2012).
Notes: Production emissions include emissions from international aviation and shipping. Due to data limitations, consumption emissions estimates are not available pre-1993.

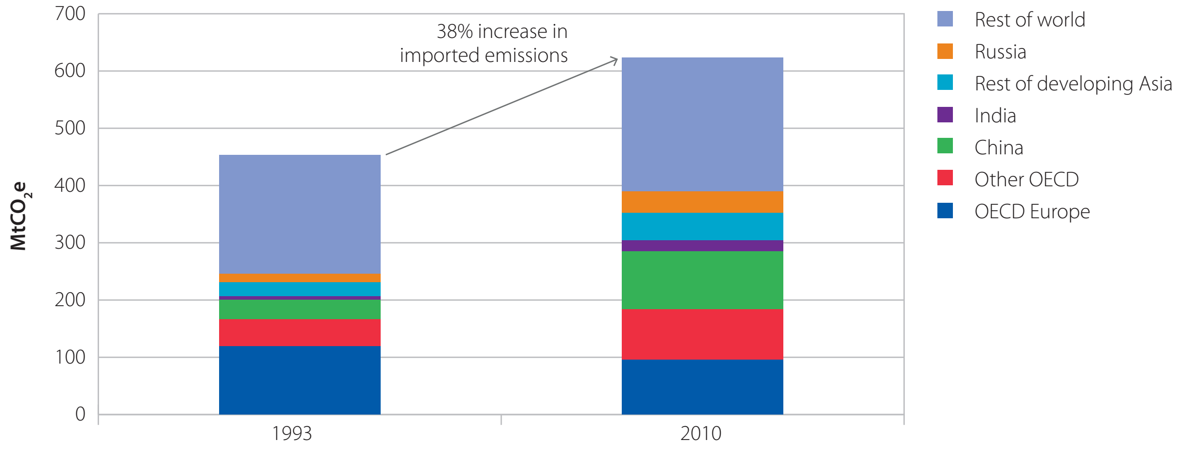
Figure 1.4: UK greenhouse gas production emissions by sector (1990 and 2010)



Source: NAEI (2012).
Notes: Other CO_2 include CO_2 emissions from domestic and military aviation, agricultural energy use and LULUCF. Due to negative LULUCF emissions, other CO_2 emissions were close to zero in 2010 on a net basis. Other non-CO_2 includes non-CO_2 emissions from waste, buildings, industry, energy supply and transport.

- **Imported emissions**. These are emissions that occur abroad and are associated with final UK demand for goods and services. For example, imported emissions associated with purchasing a smart phone in the UK would include emissions associated with material extraction, manufacturing including indirect electricity use and direct industrial emissions, and transport. However, if a raw material is imported into the UK to manufacture a good that is then exported for consumption overseas, the overseas emissions associated with producing and shipping that raw material to the UK would not be added to the UK's carbon footprint. GHG emissions embodied in imports are estimated to have increased by nearly 40% between 1993 and 2010 over which period UK imports increased by over 90% in real terms. We describe trends in imported emissions by region, sector, and product below:

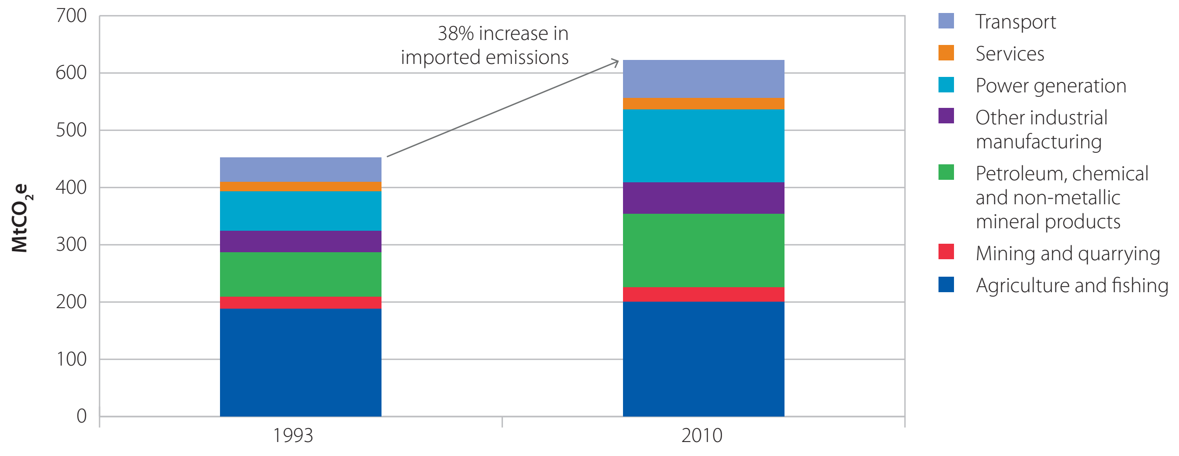
Figure 1.5: UK imported greenhouse gas emissions by region (1993 and 2010)



Source: CCC estimates developed by the University of Leeds (2013).

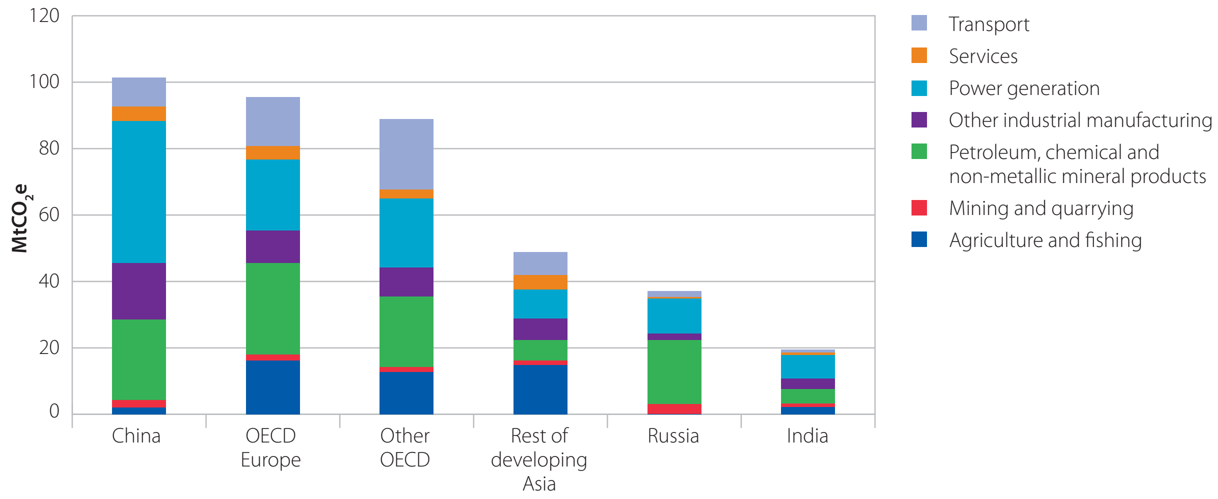
- *Region of origin*. There are significant imported emissions from the rest of Europe (15% of total imported emissions) and the rest of the OECD (15%). Imports from developing Asian economies account for about 30% of imported emissions (half of which come from China) and for the majority of the recent growth in imported CO_2 emissions (Figure 1.5).
- *Sector of origin*. The UK's demand for goods and services results in significant emissions occurring in various economic production sectors overseas, including agriculture (accounting for around a third of imported emissions in 2010), electricity generation (e.g. embedded in industrial products we import), and direct emissions occurring in the manufacturing of petroleum, chemicals, and non-metallic mineral (e.g. cement and glass) products. Together with overseas transport sector emissions (e.g. road, sea, and air freight emissions), these account for the majority of the UK's imported carbon footprint (over 80% in 2010) and growth in imported emissions from 1993 to 2010. (Figure 1.6). When breaking down imported emissions by sector and major trading partner in 2010, power sector emissions, particularly in China, are a major contributor to the UK's imported carbon footprint (Figure 1.7).
- *Product basis*. Consumption emissions data can also be disaggregated on a product basis, showing supply chain emissions associated with a given good or service. On a product basis, the UK's demand for agricultural and petroleum, chemicals, and non-metallic minerals products result in the highest imported supply chain emissions (163 $MtCO_2e$ and 130 $MtCO_2e$ respectively).
- We further analyse trends in imported emissions by sector and product in Box 1.2.

Figure 1.6: UK imported greenhouse gas emissions by sector (1993 and 2010)



Source: CCC estimates developed by the University of Leeds (2013).
Notes: Imported emissions are production emissions occurring abroad associated with producing and transporting goods and services to the UK for consumption. Transport emissions include international aviation and shipping emissions. Services emissions include emissions arising from commercial and public sector services activities.

Figure 1.7: Greenhouse gases associated with UK imports arising in key trading partners, by sector

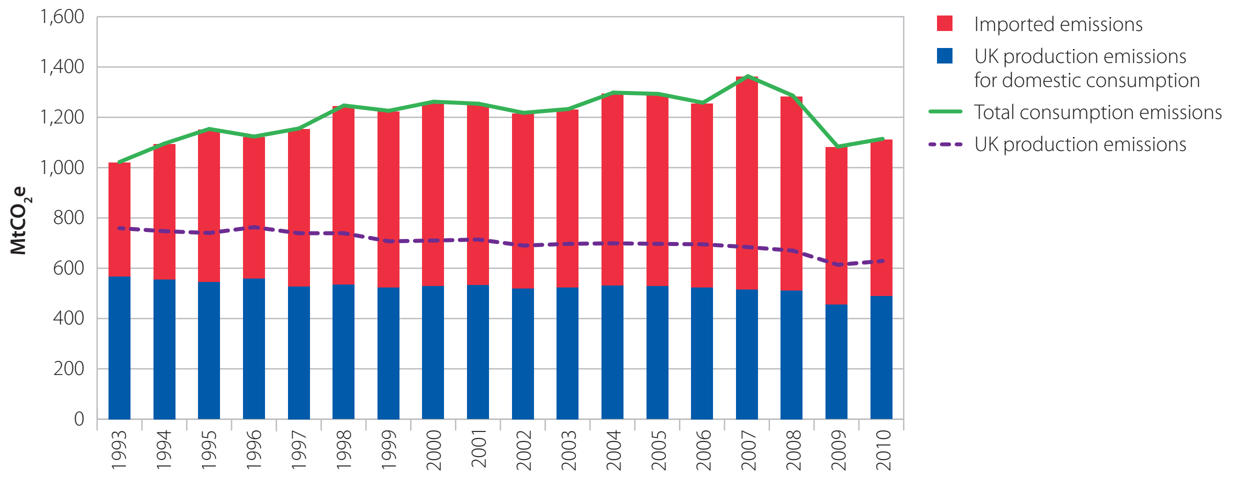


Source: CCC estimates developed by the University of Leeds (2013).
Notes: Transport emissions include international aviation and shipping emissions. Services emissions include emissions arising from commercial and public sector services activities.

- **Exported emissions**. These are emissions embedded in goods and services that are produced in the UK but exported for final consumption overseas. Exported emissions have fluctuated since 1993 but have decreased by 13% overall. Exported emissions related to emissions arising in the UK's petroleum, chemicals and non-metallic minerals, power generation, and mining sectors have fallen significantly, while emissions occurring in agriculture, transport, and retail trade activities have increased.

As noted above, there is greater uncertainty in estimates of non-CO_2 emissions embedded in imports, particularly around agricultural non-CO_2 emissions which arise due to complex biological and ecological rather than fossil-fuel combustion-related processes, and can vary significantly depending on weather, climate and location[9]. CO_2 emissions account for 70% of the UK's total carbon footprint, and are estimated to have increased by around 15% between 1993 and 2010, whereas non-CO_2 consumption emissions have fluctuated but there is no overall trend (Figure 1.8):

Figure 1.8: Greenhouse gas emissions associated with UK consumption – imported and domestic emissions (1993-2010)



Source: CCC estimates developed by the University of Leeds (2013); NAEI (2012).
Notes: The green line shows estimates of total UK consumption emissions and the red and blue bars break down consumption emissions by goods and services produced and consumed within the UK versus imported goods and services. Domestic consumption emissions are estimated to have decreased over time while imported emissions are increasing. The dotted purple line shows trends in UK production emissions (including international aviation & shipping emissions), which have decreased over time. The gap between the dotted purple line and blue bar represents UK production emissions in goods and services for export.

- **CO_2 footprint**. The UK's carbon footprint related to CO_2 emissions increased by around 15% between 1993 and 2010. Imported CO_2 emissions have increased 60% in the same period, with emissions occurring abroad in power generation, transport, and petroleum, chemicals and non-metallic minerals are the most important contributors to the UK's imported CO_2 footprint (60%). Imported agricultural CO_2 emissions are a minor contributor (around 1% of the UK's imported CO_2 footprint).

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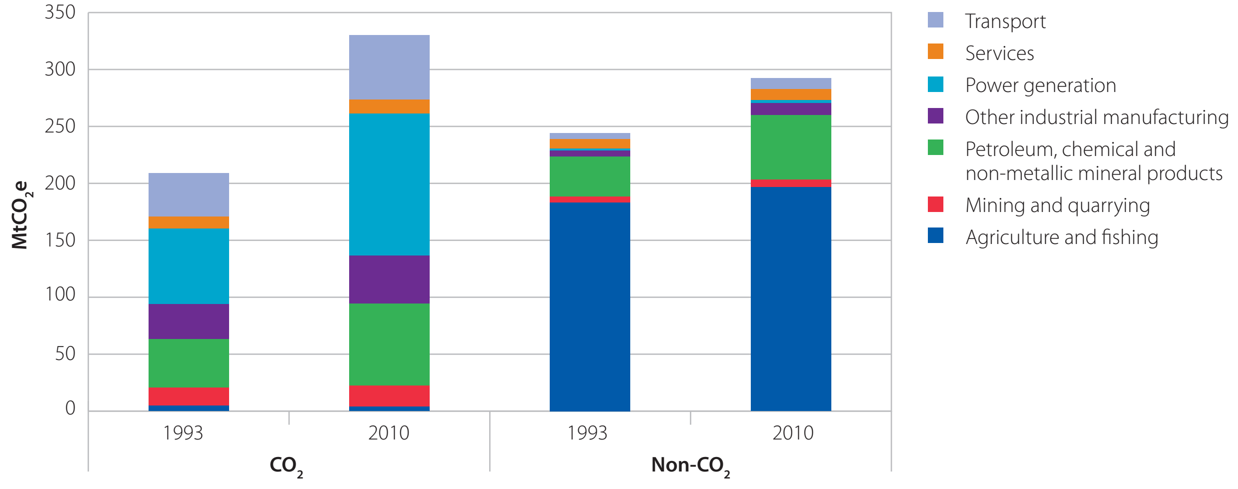
[9] Smith, P., D. Martino, Z. Cai, D. Gwary, H. Janzen, P. Kumar, B. McCarl, S. Ogle, F. O'Mara, C. Rice, B. Scholes, O. Sirotenko (2007): *Agriculture. In Climate Change 2007: Mitigation.* Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.

- **Non-CO_2 footprint.** The UK's carbon footprint associated with non-CO_2 gases has fluctuated between 1993 and 2010 but there has been no overall trend. This is due to reductions in domestic non-CO_2 consumption emissions (nearly 50%) being offset by increased imported non-CO_2 emissions (around 20% increase). Imported agriculture non-CO_2 emissions are estimated to have increased over 80% between 1993 and 2007, but have decreased since the recession such that in 2010 imported agriculture emissions were just 10% higher than 1993 levels.

As a result of production emissions reductions, reductions in exported emissions, and growth in imported emissions, the gap between the UK's carbon footprint and production emissions increased from an estimated 35% in 1993 to around 80% in 2010 (i.e. consumption emissions were nearly 80% higher than production emissions) (Figure 1.9).

In the next section we consider key drivers of increases in the UK's carbon footprint.

Figure 1.9: Trends in the UK's imported consumption emissions by sector, CO_2 versus non-CO_2



Source: CCC estimates developed by the University of Leeds (2013).
Notes: Transport emissions include international aviation and shipping emissions. Services emissions include emissions arising from commercial and public sector services activities.

Box 1.2: Key sectors and products with high imported emissions

The UK's consumption emissions can be disaggregated on a sector or product basis

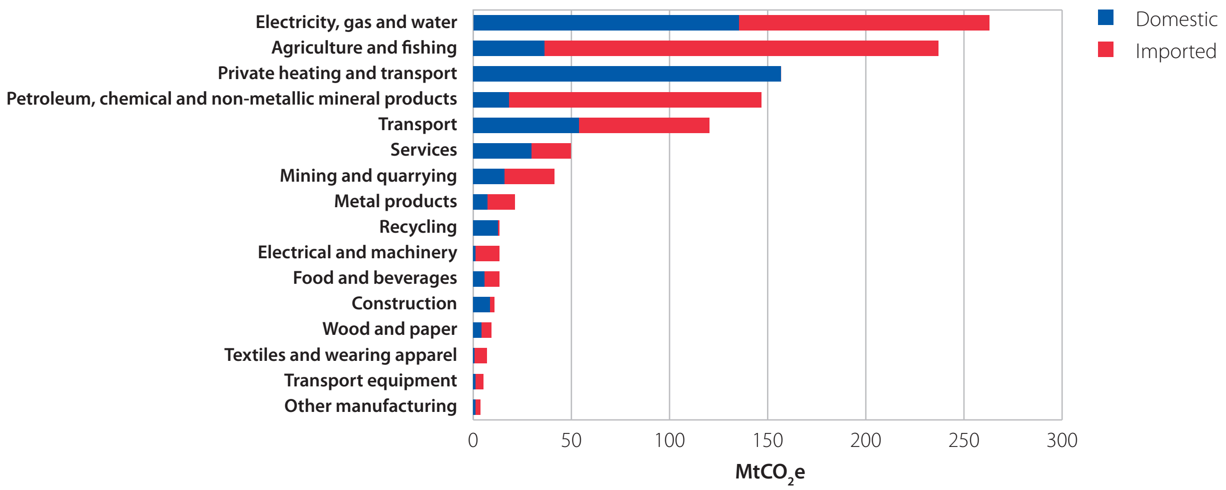
Sectors

As noted above, production emissions occurring abroad in the agriculture, electricity generation, petroleum, chemicals, and non-metallic mineral (e.g. cement and glass) manufacturing sectors, as well as transport service sectors account for the majority of the UK's imported carbon footprint (84%). Sector emissions refer to indirect emissions embedded in the goods and services consumed by the UK. For example, power sector emissions do not refer to direct UK imports of power from other countries, but to emissions associated with power consumed in the manufacture of imported goods.

- **Agriculture.** Imported agriculture missions are mainly non-CO_2, or N_2O emissions arising from the cultivation of crops and methane arising from livestock management occurring abroad. They account for nearly a third of imported GHG emissions (200 $MtCO_2e$ in 2010). They arise due to the UK's demand for goods and services that have embedded agricultural emissions such as imports of crop/livestock commodities, food and drink products, and textiles (which have embodied agricultural emissions related to natural fibre production such as cotton).
- **Power.** The UK's demand for goods and services in 2010 resulted in almost 130 $MtCO_2e$ emissions occurring in the power sector overseas. One-third of these power emissions arose in China, The UK's carbon footprint also includes electricity emissions embodied in foreign business services (for example electricity used in call centres abroad).
- **Petroleum, chemicals and non-metallic minerals.** These emissions are related to production emissions occurring abroad to extract and produce fossil fuels (both crude and refined) and to produce petrochemicals and petrochemical products, other chemical products such as pharmaceuticals, and minerals such as cement, ceramics, glass and lime. This sector covers a broad set of sub-sectors but further disaggregation is not possible given data limitations. In 2010, UK imports were associated with around 130 $MtCO_2e$ of production emissions in this sector.
- **Transport.** These imported emissions relate to emissions arising from land, shipping, and air transport activities, including freight and passenger travel as well as business travel. It excludes private household car travel emissions occurring abroad as these emissions are not linked to the UK's final demand for goods and services. Imported transport emissions totalled 65 $MtCO_2e$ in 2010.

Figure B1.2a provides a breakdown of domestic versus imported UK GHG consumption emissions by sector of origin.

Figure B1.2a: UK greenhouse gas consumption emissions by sector of origin and region (2010)



Source: CCC estimates developed by the University of Leeds (2013).
Notes: Private heating and transport emissions include household heating and personal car travel emissions.

Box 1.2: Key sectors and products with high imported emissions

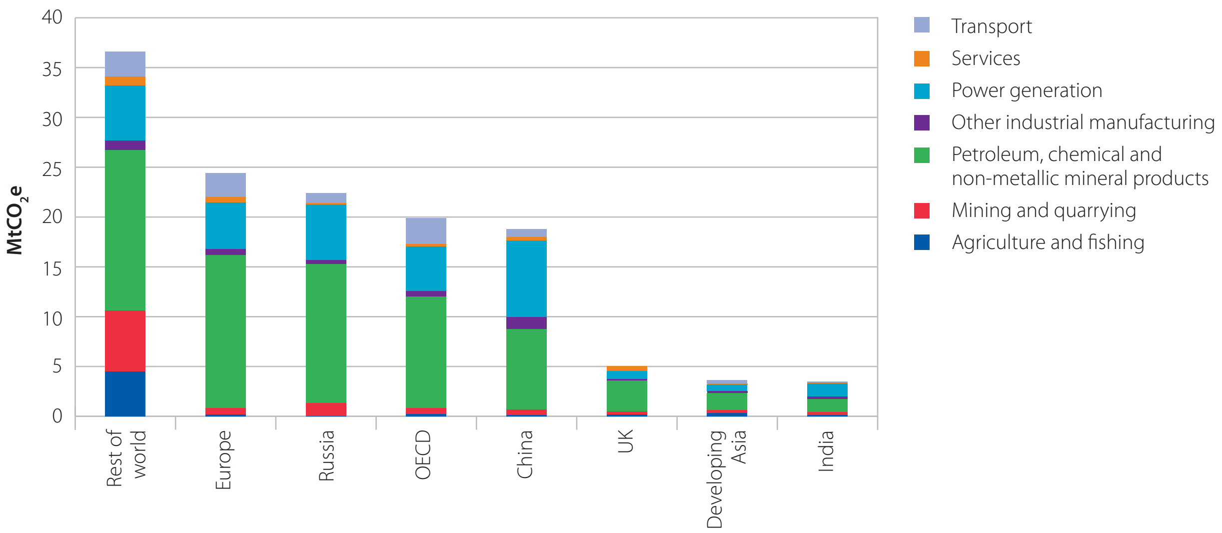
Products

Consumption emissions can also be assessed on a product basis. This type of analysis enables an understanding of how emissions associated with UK demand for goods or services varies by product depending on their supply chain emissions.

For example, the UK's demand for manufactured food and drink products in 2010 resulted in 33 $MtCO_2e$ emissions arising in international supply chains. Of this, only 3.4 $MtCO_2e$ arose from direct food and direct manufacturing processes, 15 $MtCO_2e$ from agricultural production, 5.6 $MtCO_2e$ in electricity generation, and 3.5 $MtCO_2e$ in transport.

On a product basis, supply chain emissions associated with UK demand for petroleum, chemicals, and non-metallic minerals products are a major contributor to the UK's carbon footprint (12%, or around 135 $MtCO_2e$, of which only 5 $MtCO_2e$ arise in the UK). Figure B1.2b provides a breakdown of supply chain emissions associated with the UK's demand for products in this sector, showing the importance of power generation and transport emissions (in addition to direct product manufacturing emissions).

Figure B1.2b: Supply chain greenhouse gas emissions associated with UK consumption of petroleum, chemical, and non-metallic mineral products, by region and sector (2010)



Source: CCC estimates developed by the University of Leeds (2013).
Notes: Transport emissions include international aviation and shipping emissions. Services emissions include emissions arising from commercial and public sector services activities.

3. Key drivers of UK consumption emissions

We considered above broader trends in the UK's carbon footprint. This showed that reductions in production emissions have been offset by increases in imported emissions such that overall consumption emissions have increased. The fact that the UK's carbon footprint has grown as production emissions have been reduced, and that consumption emissions are larger than production emissions, raises several questions including:

- Whether there should be more emphasis on addressing imported emissions and less on production emissions
- Whether production emissions have fallen due to offshoring of industry in response to carbon policies, reallocating emissions within the UK's carbon footprint but not reducing it overall.

In this section, we examine in greater detail the key drivers of consumption emissions (including production emissions, exported and imported emissions) to address these questions.

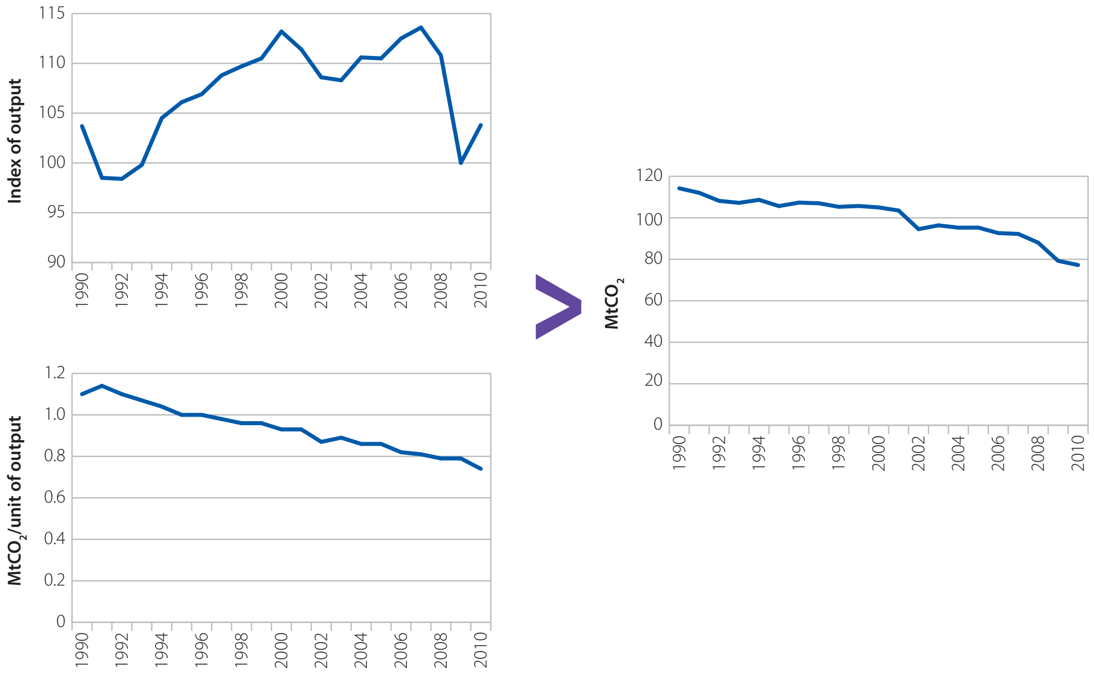
Production emissions

Production emissions have fallen by 21% between 1990 and 2010 (19% since 1993). Our analysis suggests that this decline was not due to significant offshoring in response to low-carbon policies. Rather, production emissions fell due to reductions in emissions from power generation and reductions in non-CO_2 gases (e.g. methane from waste). Additionally, in industry there have been reductions due to switching to less carbon-intensive fossil fuels, energy efficiency improvement and industrial restructuring. More recently, emissions have fallen as a result of the recession (Figure 1.10):

- Reductions in power generation emissions are due to a switch from coal to natural gas.
- Reductions in non-CO_2 emissions are related to a decrease in waste methane emissions in response to EU landfill policies, in industrial processes due to the introduction of low-carbon technologies to abate N_2O emissions, and fugitive emissions from the gas distribution network and coal mines.
- Industrial emissions have declined 32% since 1990 due to energy efficiency improvement and/or fuel switching as well as restructuring.
- More recently emissions have fallen due to the recession.

Industry offshoring cannot be the primary cause of production emission reductions since industry emission reductions only accounted for 22% of total reductions in production

Figure 1.10: UK industry output, carbon intensity and emissions (1990-2010)



Source: ONS (2013) Index of manufacturing production; NAEI (2012); CCC calculations.

emissions between 1990 and 2010. Although in principle falling carbon intensity could also reflect restructuring of energy-intensive industry in response to low-carbon policies, this has had a minor, if any, impact in practice because:

- The divergence between consumption and production emissions pre-dates the introduction of low-carbon policies, therefore suggesting the influence of other factors.
- The impact of low-carbon policies has been limited to date (e.g. carbon price impacts have been limited given the allocation of free allowances to energy-intensive industry under the EU ETS, a low carbon price, and exemption from the Climate Change Levy through Climate Change Agreements).
- The overall output of energy-intensive industries increased between 1990 and the start of the recession, although specific industries such as iron and steel experienced a decline in output due to restructuring.
- Where there are specific examples of restructuring, this is likely to be part of a broader process of globalisation (e.g. based on labour cost differentials).
- More generally, restructuring due to globalisation and a UK focus on service industries has limited industry output growth rather than resulted in reduced output (services now account for 77% of total UK output, growing from 69% in 1997).

Production emissions remain important as they account for more than half of the UK's carbon footprint. Had production emissions not been reduced, then the footprint would be around 10% higher than it currently is. Further reductions of production emissions will be required, as legislated by the Climate Change Act.

Domestic consumption emissions

Emissions associated with domestic consumption of goods and services produced in the UK have decreased around 15% since 1993. This does not reflect a reduction in UK-based consumption, as demand for UK goods and services increased 5% per year between 1993 and 2010. This clearly suggests that UK production emissions intensities have reduced over time (Figure 1.11).

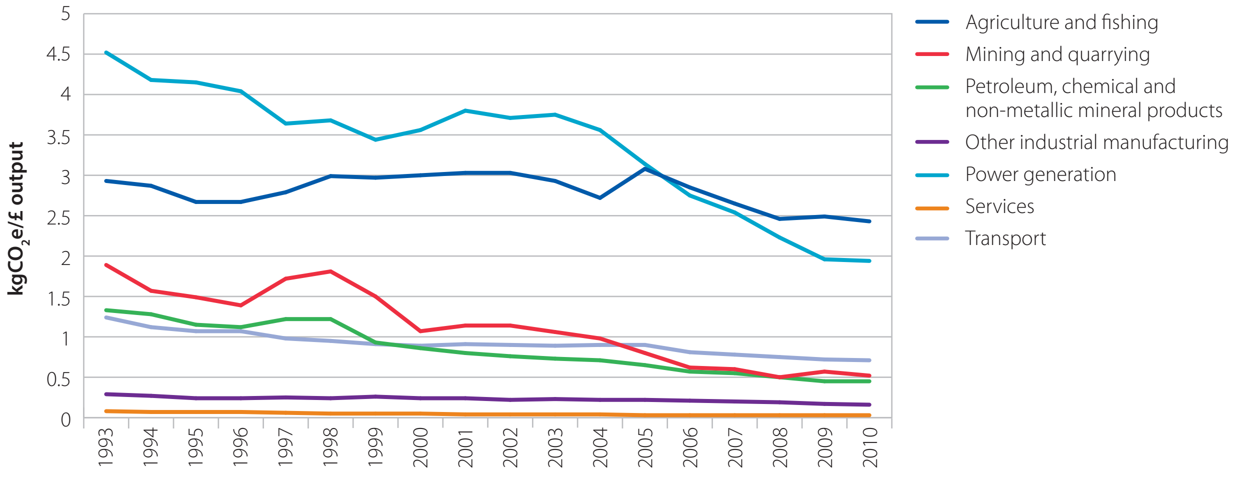
Exports

Between 1993 and 2010, UK exports increased by over 80% (in real value terms) while total exported emissions declined by 13%. This partly reflects the shift in the UK economy, including exports, towards services, which are associated with lower emissions intensities. More generally, reflecting reductions in UK production emissions intensities, the UK has contributed to reductions in the carbon footprint of its trading partners.

Imports

As shown above (section 2), the UK's carbon footprint has increased mainly due to an increase in imported goods and services and partially due to increased imports from countries with high production emissions intensities:

Figure 1.11: UK greenhouse gas emissions intensities of production (1993-2010)

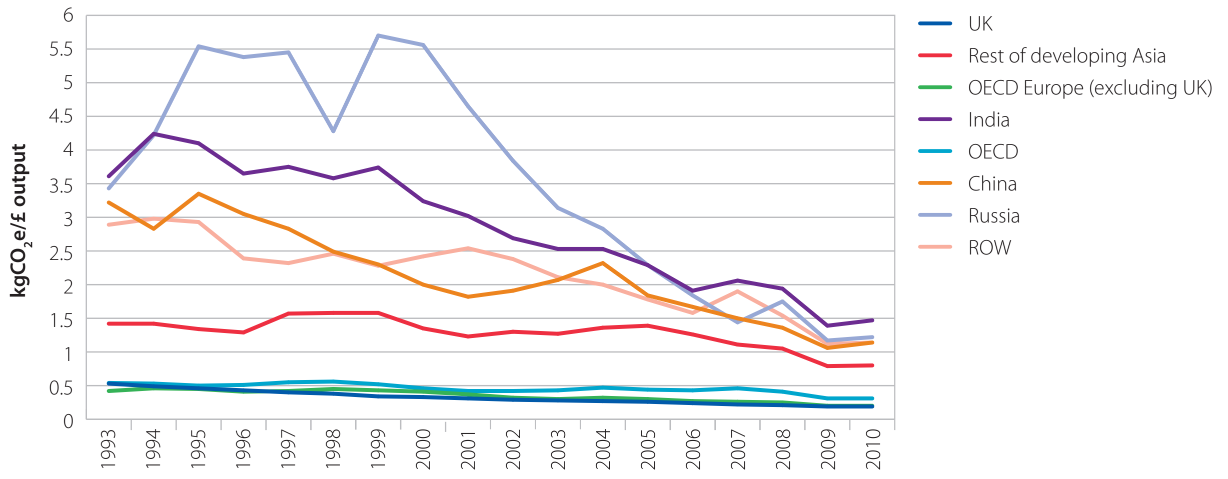


Source: ONS (2012) Environmental Accounts & Supply and Use Tables.
Notes: Emissions intensities calculated by dividing total sectoral emissions by sectoral economic output. Transport emission intensity include international aviation and shipping. Services emissions intensity includes emissions arising from commercial and public sector services activities.

- UK demand for imported goods and services increased by 150% between 1993 and 2010 in real terms
- Emissions intensities in our key trading partners are higher than in the UK's (Figure 1.12).

Growth in imported emissions has therefore more than offset reductions in production emissions. Growth in the UK's footprint reflects import growth due to rising incomes, a growing population and shifts in the UK and global economies (i.e. the UK moving to a more service-based economy). There has been an increase in manufacturing in countries with higher carbon intensities, especially the power sector (for example China's power sector is estimated

Figure 1.12: Greenhouse gas emissions intensities of production in UK trading partners (1993-2010)



Source: Eora World MRIO database (2012).
Notes: Emissions intensities calculated by dividing total sectoral emissions by sectoral economic output.

to emit almost seven times as much CO_2e per pound of economic output as the UK)[10]. As we show in section 5, we expect these intensities to come down in the future.

4. UK progress compared to other countries

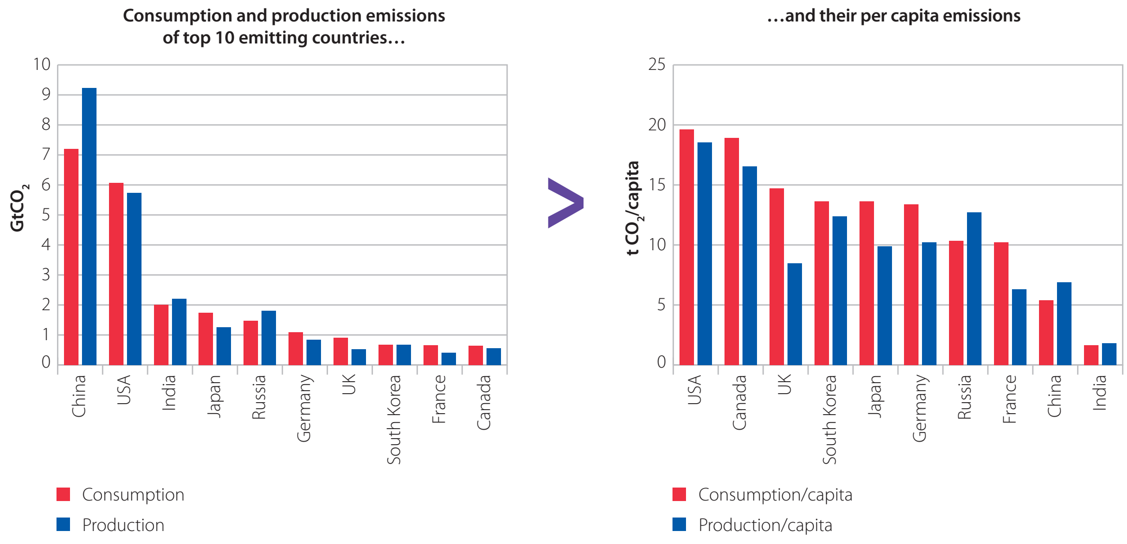
Sections 2 and 3 showed that the UK's consumption emissions are higher than production emissions, driven mainly by imported emissions. In this section, we explore how this compares to other countries in terms of actual and per capita emissions, for emissions in net trade, and for the key drivers over time.

The UK is one of very few countries that publish detailed consumption emissions estimates. Comparing the UK with other countries requires the use of global databases, each with their own uncertainties depending on the methodology used.

Latest data from the Eora[11] emissions database suggests that the UK ranks among the top ten countries by consumption and production emissions but has relatively low emissions compared to other large emitting countries, and is comparable to other major developed countries in per capita terms (Figure 1.13):

- China and the US dominate absolute consumption and production emissions, reflecting the size of their economies and population. UK consumption emissions are around 15% of Chinese and US levels, and similar to other European countries.
- The UK is among the highest per capita emitters on a consumption basis, but broadly in line with other developed countries with service-based economies (e.g. Germany and Japan).

Figure 1.13: Consumption and production emissions of top emitting countries (2010)



Consumption and production emissions of top 10 emitting countries…

…and their per capita emissions

Source: Eora World MRIO database (2013); World Bank.
Notes: Countries ranked by consumption emissions. Estimates from Eora; UK Eora estimates are around 20% higher than CCC and Defra estimates, which use updated and more accurate UK national and emissions account data provided by ONS, as well as different levels of geographical aggregation (e.g. Defra analyses four regions, the CCC eight, and Eora analyses all 187 countries). Per capita chart shows only those countries featured on the left side chart, and therefore excludes some countries with very high per capita emissions (e.g. Singapore, Luxembourg, UAE).

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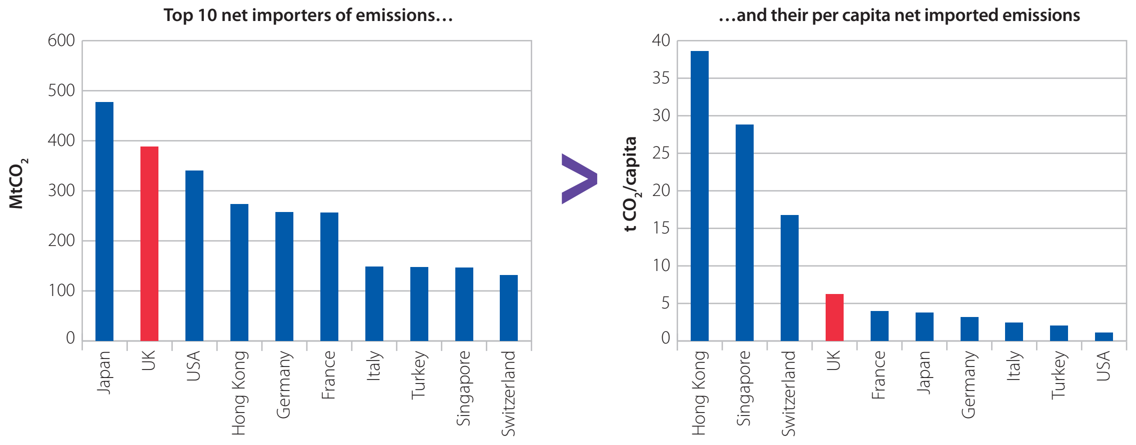
[10] Eora World MRIO database (2012).

[11] Eora estimates of consumption emissions for the UK are around 20% higher than CCC and Defra estimates, both of which use updated and more accurate UK national and emissions account data provided by ONS, as well as different levels of geographical aggregation (e.g. Defra analyses four regions, the CCC eight, and Eora analyses all 187 countries).

Reflecting trade patterns, some countries – including the UK – are *net importers* of carbon (i.e. they import more emissions than they export). In contrast, other countries are *net exporters* of carbon:

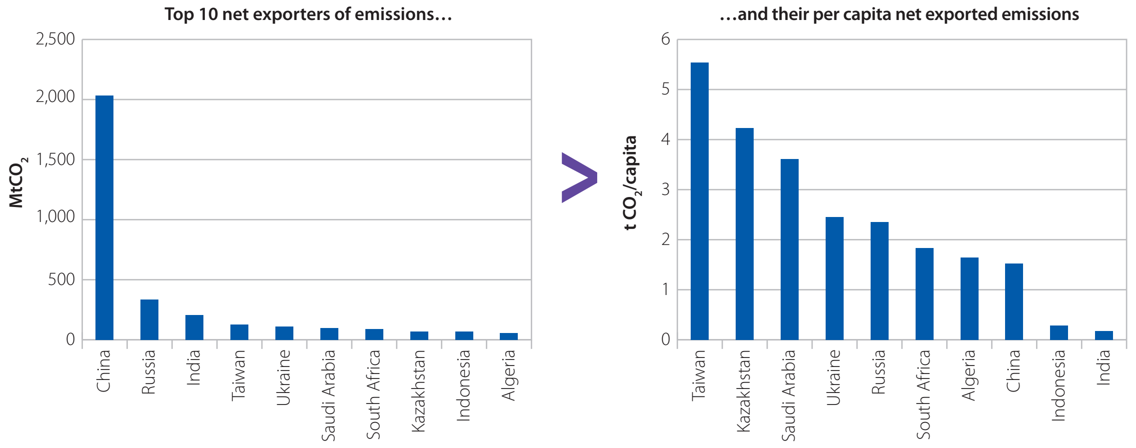
- The UK appears as one of the largest net importers of carbon emissions in absolute terms, and is broadly similar to other European countries on a per capita basis (Figure 1.14). In the UK net imports of carbon emissions rose by 70% between 1990 and 2010. This compares to 15% in the US, 605% in Germany (from a small base) and 55% in France.
- China is the largest net exporter of emissions by a significant margin, and grew by 320% between 1990 and 2010. Other large exporters are Russia and India (Figure 1.15).

Figure 1.14: Major net importers of emissions (2010)



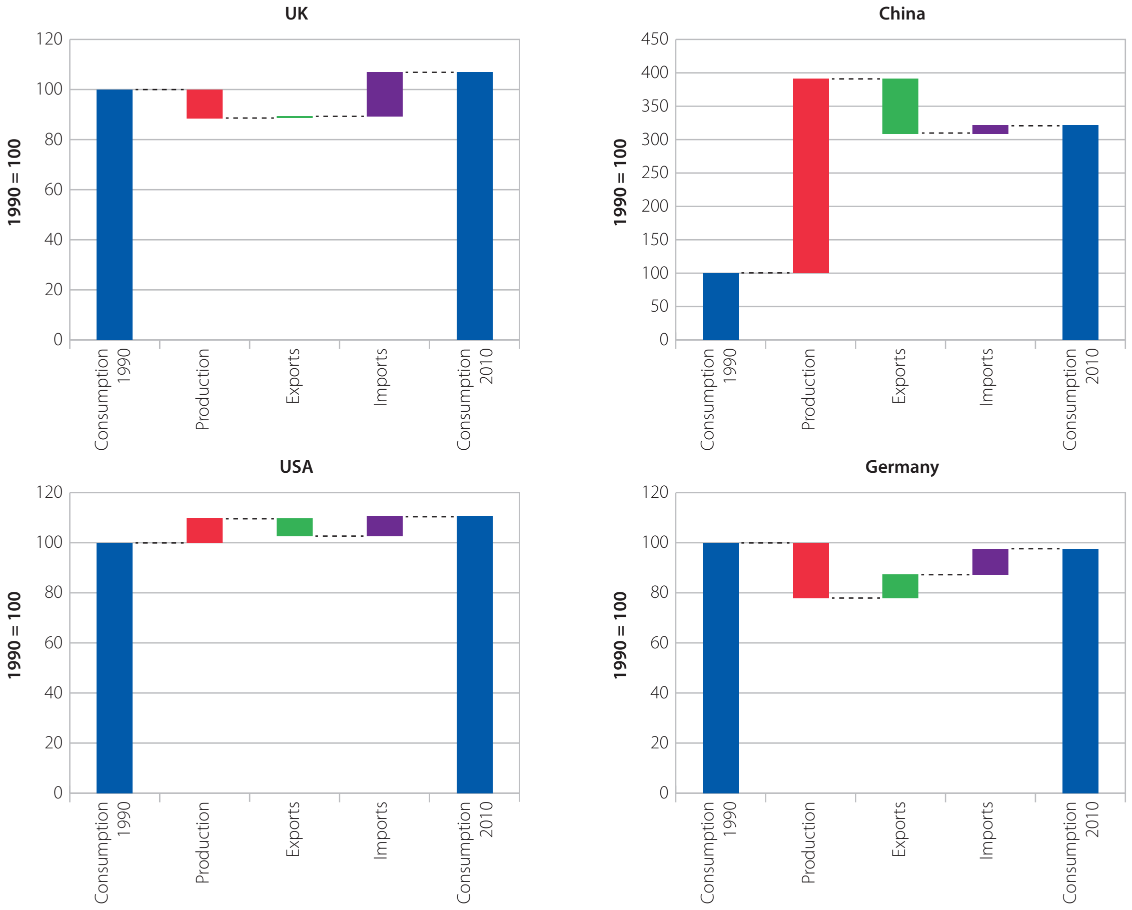
Source: Eora World MRIO database (2013); World Bank.
Notes: Figures are for CO_2 only. Eora estimates for the UK's consumption emissions differ from CCC estimates; please see notes in Figure 1.13.

Figure 1.15: Major net exporters of emissions (2010)



Source: Eora World MRIO database (2013); World Bank.
Notes: Figures are for CO_2 only.

Figure 1.16: Drivers of consumption emissions in the UK and other countries (1990 and 2010)



Source: Eora World MRIO database (2013).
Notes: Figures are for CO_2 only. Eora estimates for the UK's consumption emissions differ from CCC estimates; please see notes in Figure 1.13. Figures are an index, with a base year of 1990 for consumption emissions. Exports contribute negatively to consumption emissions (i.e. increases in exported emissions reduce consumption emissions).

Changes in consumption emissions are explained by changes in production, exported and imported emissions. Examining the drivers of consumption emissions over time shows that they are different across countries (Figure 1.16):

- Eora estimates show that **UK** consumption emissions rose by around 7% between 1990 and 2010, of which the majority was due to increased imported emissions, offset to some extent by falling production emissions.
- **German** consumption emissions were broadly flat between 1990 and 2010. This reflects falling production emissions, offset by both a fall in exported emissions and an increase in imported emissions.
- **US** consumption emissions have increased by 11%, but this was largely due to a 10% increase in production emissions. Changes in imported and exported emissions were broadly neutral. This is in contrast to the UK and Germany where production emissions fell.

- In **China**, consumption emissions rose by around 220%. This reflects a very large rise in production emissions, only partially offset by increased exported emissions. The rise in Chinese production emissions reflects rising domestic consumption due to rising incomes, as well as increased manufacturing for exports.

In future, reducing UK consumption emissions will therefore require reductions in production emissions (which incorporate exported emissions), as well as reductions in imported emissions. In the next section we explore scenarios for the UK's future carbon footprint, taking into account how these factors may change.

5. Scenarios for future consumption emissions and key implications

Consumption emissions accounting is an emerging area of research. While there has been some recent work to develop scenarios for future UK consumption emissions, this has had a focus on improving resource efficiency and changing consumption patterns and has not necessarily been consistent with the wider decarbonisation scenarios required to achieve the UK's 2050 target (Box 1.3).

To date, our own analysis has focused on scenarios for reducing production emissions to 2050 in a way that is compatible with achieving the Climate Change Act 2050 target (i.e. to reduce 2050 production emissions by 80% on 1990 levels).

For this report, we have developed future scenarios for the UK's carbon footprint compatible with achieving the climate objective, which is to keep central estimates of global temperature rise by 2100 close to 2°C above pre-industrial levels, and limit the likelihood of a 4°C rise to very low levels (e.g. 1%). To meet this objective, global emissions need to peak before 2020 and halve by 2050.

As a sensitivity check, we have also analysed the UK's consumption emissions in a world where international actions would not go beyond the pledges made at the United Nations Climate Change Conference at Copenhagen in 2009. This scenario is projected by the International Energy Agency (IEA) to lead to a long-term temperature rise of 4°C.

Box 1.3: Summary of literature exploring UK consumption emissions futures

A few recent studies have used scenario tools to explore potential futures for UK consumption emissions. Key findings and implications for policy are summarised below:

- A 2009 **Waste and Resources Action Programme** (WRAP) study[12] explored options for reducing the UK's carbon footprint by 2050 through adopting supply- and demand-side resource efficiency measures in key UK sectors. Absent the adoption of low-carbon mitigation strategies (e.g. decarbonisation of power and heat), the study found that supply- and demand-side resource efficiency measures would only reduce the UK's carbon footprint by 8% in 2050 relative to 2004. Of resource efficiency measures considered, behavioural changes such as reducing food waste, changing diets to reduce meat/dairy consumption, and extending product lifetimes were found to be more effective in decreasing the UK's carbon footprint than supply-side resource efficiency measures (e.g. materials substitution).
- As part of its investigation into global and UK carbon flows (2011)[13], the **Carbon Trust** used an MRIO model to project UK consumption emissions out to 2025, assuming the UK meets its carbon budgets under the Climate Change Act, varying patterns of emissions reduction in the rest of the world, and projecting future UK demand on the basis of historic patterns. The study found that as the UK decarbonises, the significance of imported embodied emissions in UK consumption emissions could increase (i.e. imported emissions were estimated to be one-third the size of total production emissions in 2004, but by 2025 the UK could import as much carbon as it produces at home).
- The **University of Surrey Sustainable Lifestyles Research Group** has explored scenarios for future UK consumption emissions.
  - A 2011 study[14] projected UK household consumption emissions out to 2030 and concluded that domestic decarbonisation efforts alone were unlikely to reduce UK household consumption emissions significantly. Early action via a global deal was found to be most effective policy to reduce UK's household consumption emissions by 2030, however if a global deal were to be delayed until 2020, the introduction of trade barriers could be an effective interim policy measure.
  - A recent more technical study[15] explores scenarios for future household consumption emissions by varying consumption patterns. Under a low consumption scenario, UK household consumption emissions could fall by over 20% relative to 2010 but under high consumption assumptions, the UK household carbon footprint could increase by as much as 100%.
  - A 2012 study by the **University of Manchester Sustainable Consumption Institute**[16] uses as MRIO model to explore the consequences of climate impacts and emission cuts on the UK food system under global scenarios to meet the climate objective (2°C), as well as less ambitious emissions scenarios. The study finds that to achieve a 2°C objective, growth in food consumption will need to be slowed (e.g. via behavioural change). Under less ambitious global emission reductions, the emissions intensities of imports will need to fall (e.g. via adoption of low-input agricultural practices and other policies abroad).
- Although service industries emit fewer emissions than manufacturing industries (i.e. they have lower direct emissions intensities), service industries consume goods that are emissions-intensive (e.g. the financial sector's consumption of IT equipment) and thus are increasingly contributing to the UK's carbon footprint. A recent **Defra** (2013) study[17] identified the potential contribution the services sector could make to reduce the UK's carbon footprint through improved resource efficiency and demand shift (e.g. less reliance on manufactured goods in service activities). The study concludes that domestic policies combining both strategies could contribute significantly towards achieving the climate objective by 2050, but would require early action in low-carbon and energy efficiency policies.

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[12] WRAP (2009) *Meeting the UK climate change challenge: The contribution of resource efficiency*, prepared by Stockholm Environment Institute and University of Durham Business School.

[13] Carbon Trust (2011) *International Carbon Flows – Global Flows.*

[14] Milne, S. (2011) *Consuming Carbon: RESOLVE Scenarios to 2030 for UK Household Consumption*, University of Surrey.

[15] Chitnis, M., et. al (2012) *Forecasting scenarios for UK household expenditure and associated GHG emissions: Outlook to 2030.* RESOLVE, University of Surrey.

[16] University of Manchester Sustainable Consumption Institute (2012), *What's Cooking – Adaptation & Mitigation in the UK Food System.*

[17] Defra (2013) *Investigation into the CO_2e Emissions of the Service Industries*, prepared by University of Leeds.

Modelling assumptions

Our future consumption emission scenarios incorporate our scenarios for UK production emissions, together with scenarios for demand, imports and emissions-intensity in other countries.

UK production emissions & emissions intensity

In April 2012, we published detailed analysis on how the UK's 2050 target to reduce emissions by at least 80% relative to 1990 levels could be achieved[18].

Our scenarios identified a range of options for reducing emissions across the key emitting sectors of the economy, reflecting 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. They also reflect the UK's expected growth in population from around 63 million now to 75 million in 2050 (+19%). We project UK economic output using Office for Budget Responsibility (OBR) projections.

We developed deployment ranges for key abatement measures in each sector based on detailed modelling of technology costs, deployment constraints and interactions within the energy sectors. We combined these sectoral deployment levels to create economy-wide scenarios. These identified how an 80% reduction target could be met, including when some barriers to deployment of technologies cannot be overcome (e.g. potential consumer resistance to uptake of heat pumps or electric vehicles), or in the absence of key technologies (e.g. carbon capture and storage, CCS).

In our modelling of future consumption emissions, we explore the implications of UK economy-wide scenarios from this earlier work.

Scenarios for UK final demand (domestic and foreign)

Future UK consumption emissions will depend on final demand for domestic and imported goods and services. We constructed three scenarios with reference to historic trends and plausible levels of import penetration. We also explore import scenarios to reflect a shift in UK imports towards emerging economies (e.g. continuing recent trends) and away from fossil fuel goods and services.

Overall import growth demand

- **Low demand scenario.** Demand for imported goods and services increases by 2.25% per year. This is in line with average long-run UK GDP growth, and would keep the share of imports in GDP constant to 2050 at current levels (i.e. around 35%). UK demand for domestic goods and services is assumed to increase just below the rate of imports (2.2% per annum) and the trade balance would be similar to current levels (deficit of less than 10%).

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[18] CCC (2012) *The 2050 target – achieving an 80% reduction including emissions from international aviation and shipping*, http://www.theccc.org.uk/publication/international-aviation-shipping-review/

- **Central demand scenario.** Demand for imported goods and services increases by 2.75% per year. This is halfway between a low demand assumption and a higher demand assumption reflecting historic growth in imports (see below). It would reflect an increase in the import share of GDP to around 40% in 2050. We adjust assumptions for growth in domestic demand to 1.9% per annum.
- **High demand scenario.** Demand for imported goods and services increases by 3.25% per year. This is in line with the historic rate of import growth from 1975 to 2011. Applying this rate forward may not be sustainable in the long run as it reflects a period of strong growth in trade and would imply an increase in imports share of GDP from 34% today to 50% in 2050. We adjust assumptions for UK domestic demand in order to balance net trade in line with historic levels (e.g. UK domestic demand would grow at a smaller rate of 1.6% per annum).

Regional demand

Historically, UK imports have gradually shifted away from the rest of Europe towards emerging economies. For example, in 1990 UK imports from emerging economies comprised less than 20% of total imports, while by 2010 this had increased to 30%. This reflects the growing prominence of emerging economies in global trade and is likely to continue to 2050, with a diminishing role for advanced economies (Europe and other OECD countries). We assume that UK import demand continues to shift towards emerging economies, although at less than recent rates (e.g. import growth from emerging economies might be expected to plateau at some point as wage differentials converge, etc.) such that by 2050, 60% of UK imports are from emerging economies, including China and India.

Sectoral demand

As the UK moves towards a low-carbon economy, we anticipate a decline in demand for fossil fuels and associated products. For example, our scenarios for decarbonising the surface transport sector assume that demand for fossil fuels are reduced close to zero by 2050[19] but there would still be some demand for fossil fuels in aviation and shipping and as for feedstocks in petrochemicals manufacturing. Our assumptions therefore incorporate a shift in demand away from fossil fuels sectors and towards all other economic sectors.

Scenarios for emissions intensity in other countries

We develop scenarios for reductions in emission intensities in the UK's trading partners to meet the internationally agreed climate objective, as well as a scenario where international actions do not go beyond current pledges, based on modelling by the International Energy Agency (IEA) in its *Energy Technology Perspectives* (2012). We explore emissions scenarios in seven regional UK trading partners on the basis of data available in the detailed IEA analysis (rest of Europe, all other OECD, China, India, all other developing Asian economies, Russia, and the rest of the world, Box 1.4).

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[19] CCC (2012) *The 2050 target – achieving an 80% reduction including emissions from international aviation and shipping.*

- **CO_2 emissions.** We use the IEA's scenarios for global emission pathways under an internationally-agreed climate objective, as well as less ambitious pathways. We also explore a scenario where rest of the world emission intensities converge to the UK's by 2050:
  - The **2 degrees (2DS)** scenario implies achieving a globally agreed target of limiting average global temperature increase to 2°C. This climate objective is consistent with the UK's 2050 target and would reduce global energy-related CO_2 emissions by more than half in 2050 compared with 2010. Under a 2DS scenario, global CO_2 emissions decrease from 40 $GtCO_2$ in 2010 to 16 $GtCO_2$ in 2050.
  - The **2 degrees without CCS (2DS no CCS)** scenario runs a sensitivity on the 2DS scenario in which abatement from CCS technologies is not available, and therefore industry emissions are higher. Global CO_2 emissions are 18 $GtCO_2$ in 2050.
  - **Current pledges (4DS).** We also explore emissions under a scenario where international actions do not go beyond current pledges (a 4°C emissions scenario).
  - Under the **UK convergence** scenario, sectoral emissions intensities in the UK's trading partners follow a 2DS trajectory until 2030, after which they start converging to UK 2050 levels. This allows us to explore the extent to which the UK footprint in 2050 might be high because of the level of UK consumption and/or differences in carbon intensity of production.
- **CO_2e emissions.** As the IEA covers reductions in energy-related CO_2 emissions only, we explore scenarios for non-CO_2 emission reductions based on the climate modelling work described in our 2008 report on setting a 2050 target[20]. Due to greater uncertainties about non-CO_2 emissions (particularly around imported agricultural emissions) and abatement options for them, there is less confidence in future estimates of the UK's carbon footprint when including these greenhouse gases.
- **Sectoral economic output.** We use projections for economic output per sector from the International Monetary Fund (IMF), and other sources (e.g. Office for Budget Responsibility (OBR) and DECC) for regional growth.

We derive emissions intensities by dividing sectoral emissions from the IEA by sectoral output projections.

We commissioned the University of Leeds to translate these demand and emissions intensity scenarios into scenarios for the UK's carbon footprint, using its multi-region input-output model developed for Defra.

As outlined above, developing emission scenarios requires a number of assumptions related to long-term economic and demand growth. Translating CCC and IEA emissions scenarios, which explore high-level sectoral emissions pathways (e.g. buildings, industry, transport, power), into the MRIO model specification, which explores emissions in 26 specific economic sectors, also requires disaggregation and realignment. These assumptions and adjustments introduce various uncertainties into modelling results (Box 1.5).

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[20] CCC and Met Office Hadley Centre analysis for CCC (2008), *Building a low-carbon economy – the UK's contribution to tackling climate change*, Chapter 1 Technical Appendix: Projecting global emissions, concentrations, and temperatures.

Box 1.4: IEA global emissions trajectories to 2050

The International Energy Agency's **Energy Technology Perspectives** (**ETP 2012**) publication explores global emission scenarios and strategies to achieve the objective of limiting the global average temperature rise to 2°C (2DS). It also explores less ambitious energy futures including a scenario where international actions do not go beyond the pledges made at the UN Climate Change Conference in Copenhagen in 2009. This scenario is projected to lead to a long-term temperature rise of 4°C (4DS):

- The **2DS scenario** requires reducing global energy-related CO_2 emissions by 50% by 2050 compared to 2009 (to 16 $GtCO_2$). It models changes in technology development, economic structure, and in individual behaviour, as well as decoupling of energy use from economic activity.
- The **4DS scenario** takes into account recent pledges made by countries to limit emissions and improve energy efficiency. Energy-related CO_2 emissions rise by around 30% compared to 2009 to 40 $GtCO_2$.

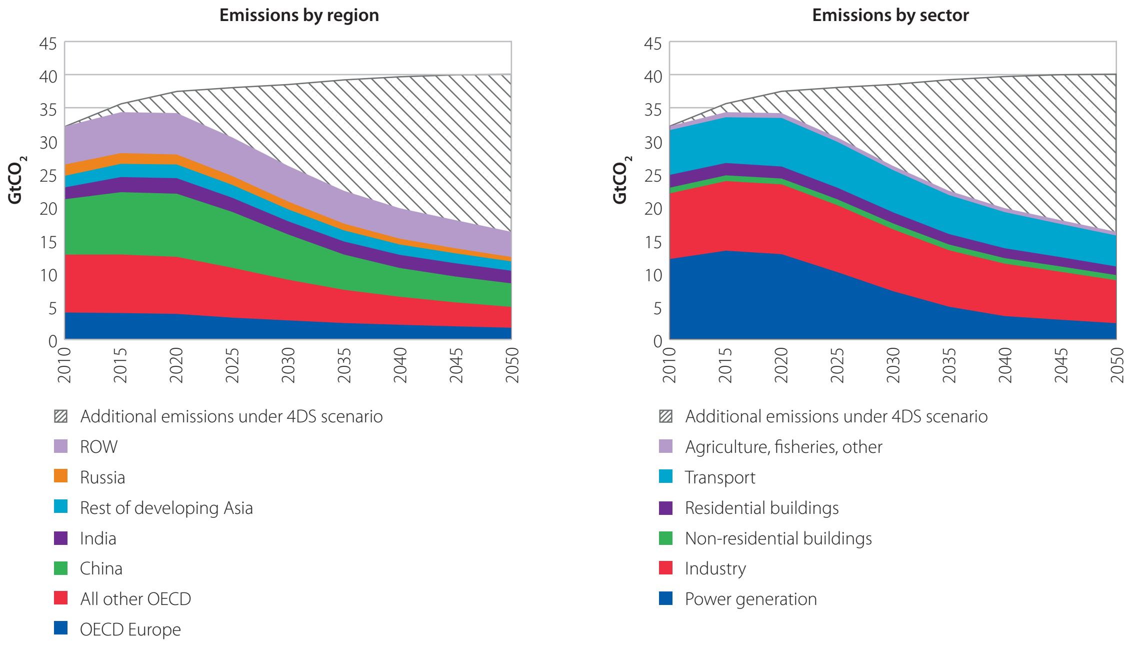
IEA sectors. The ETP model explores pathways for reducing emissions in the following sectors: power generation, industry, transport, residential and commercial buildings, and energy-related emission from agriculture, fisheries, and other activities.

IEA regions. The ETP model covers 28 regions, which for simplicity purposes, were aggregated to seven regions for CCC analysis (including OECD Europe, other OECD, China, India, the rest of developing Asia, and rest of the world).

To estimate future emissions intensities embodied in the UK's imports, the IEA provided the CCC with detailed emissions trajectories by sector and region for the 2DS and 4DS scenarios. These emissions trajectories were aligned with historic emissions data available from the Eora database in order to conduct future consumption scenarios analysis.

Figures B1.4 shows emissions reductions by sector and region under the IEA 2DS and 4DS scenarios.

Figure B1.4: IEA global CO_2 emission scenarios (2010-2050)



Emissions by region

Emissions by sector

Source: IEA (2012) *Energy Technology Perspectives.*

Box 1.5: Developing scenarios for future UK consumption emissions – challenges, caveats and uncertainties

Developing detailed scenarios for future UK consumption emissions required making a number of assumptions regarding future emissions trajectories, economic output, and UK demand, which introduce further uncertainty into estimates.

- **Emissions intensities.** Estimating future sectoral emissions intensities (sectoral emissions divided by sectoral output) required projecting economic growth and emissions:
  - **Emissions projections.** CCC and IEA future emissions trajectories needed to be aligned with historic emissions data by sector in the Eora datasets. As for some sectors there was no 1:1 alignment, we aggregated some CCC/IEA sectors in order to better align with Eora emissions data.
  - **Economic output projections.** We used IMF and OBR projections which may not be necessarily aligned with the bottom-up projections for output in the IEA analysis.
- **Production structure.** The production structure of an economy reveals how various economic sectors are linked to one another through monetary transactions. Due to the speculative nature of projecting changes in the production structure of economies, we held these constant. While we shifted final demand away from fossil fuel products to reflect the world shifting towards a low-carbon economy, we have not changed associated production structure assumptions (i.e. how other sectors purchase fossil fuel-based products to support their own production activities).
- **Import demand projections.** Projecting future demand for imports is also highly speculative and as such generic assumptions were made for changes in import demands based on historical trends. We also shifted demand towards emerging economies in line with recent trends.

Given the exploratory nature of the scenarios, we caution against detailed interpretation of the modelling results.

A detailed description of scenario development and key assumptions is available in the consultancy report developed by the University of Leeds.[21]

Scenarios for future UK consumption emissions

Our consumption emissions scenarios show that the UK's carbon footprint is likely to fall over time, as decreases in emission intensities more than offset the impact of any increase in demand for imports (Figure 1.17). However the gap between production and consumption emissions remains, and widens more significantly under less ambitious global emissions pathways and higher demand for import assumptions (Figure 1.18). The main results suggest that:

- **2DS scenario.** Under a central demand scenario and where the UK meets its 2050 target and global emissions fall in line with the CCC's climate objective, the UK's carbon footprint (CO_2 only) could fall up to 80% below current levels to around 2.4 tCO_2/capita, compared to 1.5 tCO_2/capita production emissions under the existing 2050 target. When including all greenhouse gases, where there is less confidence in estimates, the UK's carbon footprint could fall 70% to around 4 tCO_2e/capita compared to around 2 tCO_2/capita production emissions under the existing 2050 target. Results presented below are for CO_2 only.
  - **No CCS sensitivity.** A sensitivity on the 2DS scenario without CCS technology shows a footprint that is 30 $MtCO_2$ or 17% higher than the 2DS scenario due to higher industrial emissions intensities in the absence of CCS.

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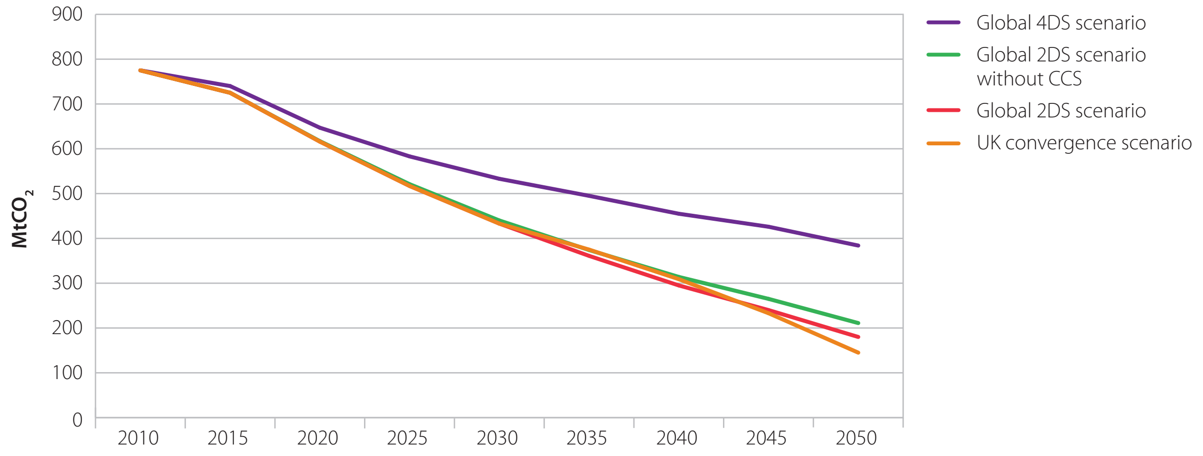
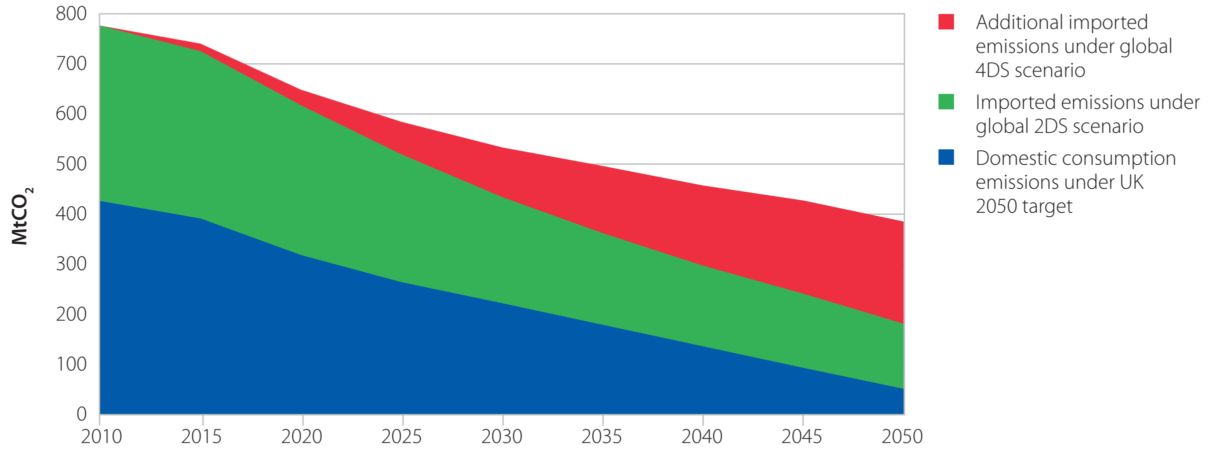
[21] Scott, K., Owen, A., and Barrett, J. (2013) Estimating emissions associated with future UK consumption patterns, University of Leeds; http://www.theccc.org.uk/publication/carbon-footprint-and-competitiveness/

Figure 1.17: Scenarios for UK consumption emissions to 2050 (CO_2)



Source: CCC estimates developed by the University of Leeds (2013); IEA (2012) *Energy Technology Perspectives*.
Notes: Figures are for CO_2 only. Future consumption emissions estimated by using production emission scenarios developed for CCC's 2012 advice on IAS and IEA emissions scenarios.

Figure 1.18: Scenarios for domestic and imported UK consumption emissions to 2050 (CO_2)



Source: CCC modelling (2012); University of Leeds (2013); IEA (2012) *Energy Technology Perspectives*.
Notes: Figures are for CO_2 only. Future consumption emissions estimated by using production emission scenarios developed for CCC's 2012 advice on IAS and IEA emissions scenarios. A linear trend in UK emissions is applied between 2030 and 2050.

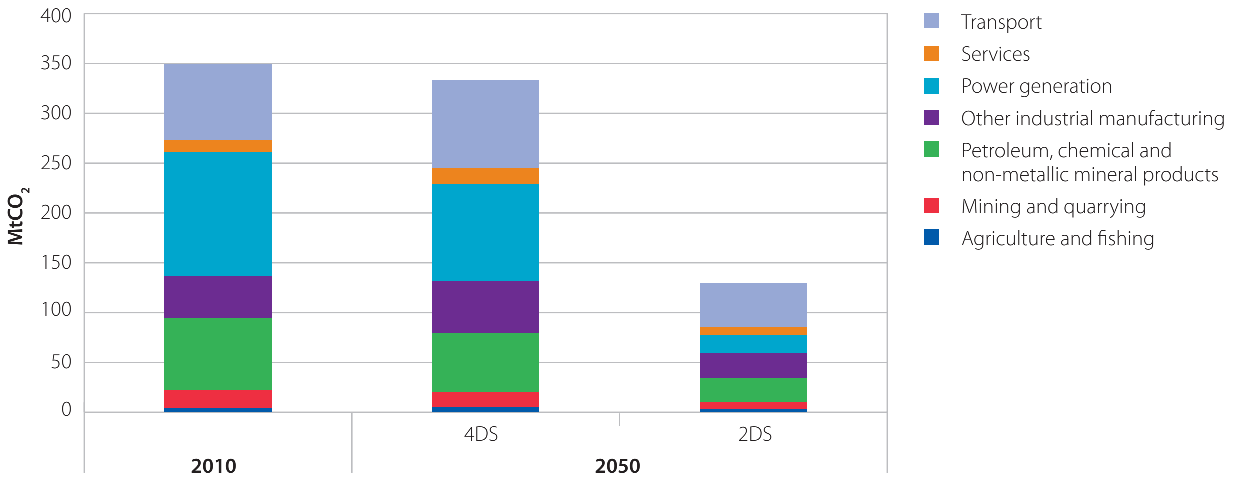
– **Varying demand for imports.** Varying demand scenarios for imported goods and services did not result in significant changes in the UK's carbon footprint (e.g. the UK's carbon footprint was around 5% lower or higher than in the central demand assumption scenario). This partially reflects input assumptions which ensure that imports and exports are broadly aligned over time – whilst any increase in imports would increase imported UK emissions, this also translates to decreased demand for UK produced goods and service and increased exports, effectively lowering the domestic contribution to the UK's carbon footprint. As production emissions intensities across countries are broadly similar to the UK's under a 2DS scenario, even under a high import demand scenario, the UK's carbon footprint is only 5% higher than in the central demand scenario.

- **Sectoral analysis.** Imported CO_2 emissions fall by over 60% from 2010 levels. Due to decarbonisation, power sector emissions overseas are no longer the biggest contributor to the UK's imported carbon footprint (15% of imported emissions in 2050 compared to 35% in 2010). Imported transport emissions are estimated to be the biggest contributor (35% of imported emissions, due to less ambitious emissions reduction in the IEA transport scenarios). Petroleum, chemicals and non-metallic mineral production and other industrial production emissions remain important contributors (40% of imported emissions) (Figure 1.19).

- **4DS.** Under a scenario where the UK meets its 2050 target but the rest of the world does not go beyond current pledges, the UK's carbon footprint (CO_2 only) could be reduced by 50% from current levels, or to around 5 tCO_2/capita (or when including all greenhouse gases, where there is even less confidence in estimates under a 4DS scenario, 9.5 tCO_2/capita).
- **UK convergence.** Under a scenario where emission intensities in the rest of the world converge with the UK's by 2050, the UK's carbon footprint is 20% lower than the 2DS scenario.

Given the exploratory nature of the scenarios and uncertainties (Box 1.5), we focus on broad conclusions rather than specific detailed results.

Figure 1.19: Scenarios for UK consumption emissions in 2050, imported emissions by sector (CO_2)



Source: CCC estimates developed by the University of Leeds (2013); IEA (2012) *Energy Technology Perspectives*.
Notes: Figures are for CO_2 only. Future consumption emissions estimated by using production emission scenarios developed for CCC's 2012 advice on IAS and IEA emissions scenarios. Transport emissions include international aviation and shipping emissions. Services emissions include emissions arising from commercial and public sector services activities.

Key finding 1: the need to reduce both production and imported emissions, and to monitor the UK's carbon footprint

Our analysis suggests that under a global agreement for achieving the global climate objective, the UK's carbon footprint could be reduced by up to 70% in 2050 compared to current levels. With production emissions currently accounting for more than half of the UK's carbon footprint, the reduction in these emissions by 80% (as legislated in the Climate Change Act) is essential.

However, even with an 80% reduction in production emissions, if the carbon intensity of imports were not reduced, emissions embedded in UK imports in 2050 could account for nine times as much as production emissions. Under the current pledges (4DS) global scenario, UK imports would still account for three times as much as production CO_2 emissions (Figure 1.20).

Therefore our analysis highlights the crucial importance of reducing the UK's imported emissions in addition to production emissions, as part of global emission reductions to achieve the climate objective. It implies the need to monitor the UK's carbon footprint together with production emissions, in order to check that this is being reduced in a way that is compatible with achieving the climate objective, or whether further action is required.

Key finding 2: the need for action beyond current global policies

The modelling shows that in a world where global carbon intensity is reduced based on the Copenhagen pledges only (and the climate objective not being achieved), then the UK's carbon footprint could be of the order of five times as much as production emissions per capita allowed under the existing 2050 target. In a world where the climate objective is achieved, the UK's carbon footprint could be up to two times that of production emissions per capita allowed under the existing 2050 target.

We have previously highlighted the need for a step change in the pace at which UK territorial emissions are reduced in order to meet carbon budgets. The analysis in this report highlights the need for further action globally in order that the climate objective is achieved, and as a consequence of which the UK's carbon footprint would be reduced.

In particular, there is a need to reverse the upward trend in the UK's imported carbon emissions in the medium term (e.g. by 2030). UK policies to encourage resource efficiency and sustainable consumption are also important.

We consider policies which could ensure global emissions reductions required to meet the climate objective in chapter 3.

Key finding 3: the UK is likely to remain a net importer of carbon

In all scenarios, the modelling suggests that the UK will remain a net importer of carbon. Even under a scenario of ambitious global emission reductions, the UK could have a carbon footprint that is twice as large as its production emissions, reflecting the fact that it is likely to remain a net importer of manufactured goods (Figure 1.20).

Based on global modelling of emission trajectories[22], we recommended in our 2008 report that the UK should aim to reduce production emissions to around 2 tCO_2e/capita in 2050 (i.e. the basis for the 2050 target in the Climate Change Act) in a context where there are both flows of carbon in traded goods and a market for offset credits (Figure 1.21).

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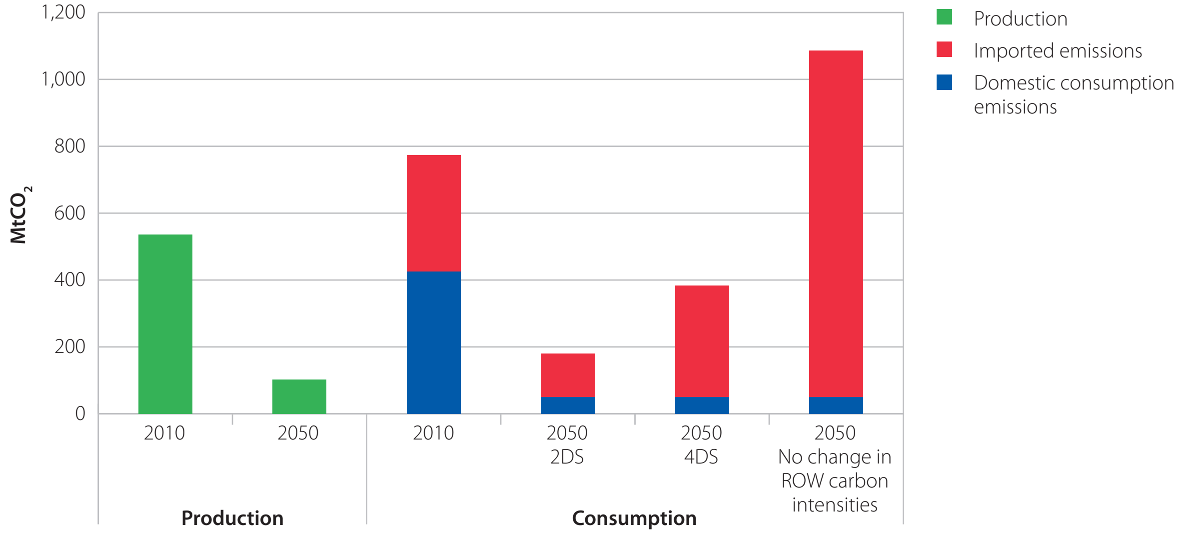
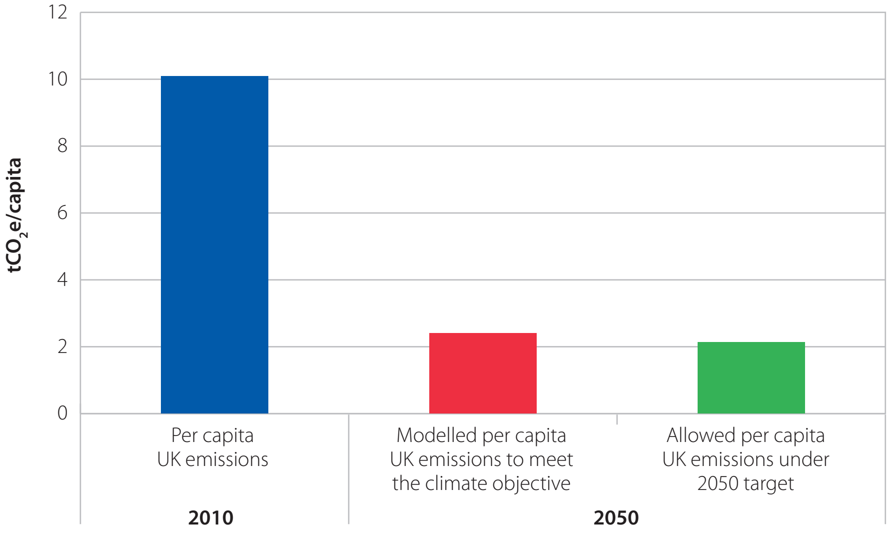
[22] CCC and Met Office Hadley Centre analysis for CCC (2008), *Building a low-carbon economy – the UK's contribution to tackling climate change*, Chapter 1 Technical Appendix: Projecting global emissions, concentrations, and temperatures.

Figure 1.20: UK production emissions and scenarios for UK consumption emissions to 2050 (CO_2)



Source: CCC modelling (2012); University of Leeds and Centre for Sustainable Accounting (2013); IEA (2012) *Energy Technology Perspectives*.
Notes: Figures are for CO_2 only. Future consumption emissions estimated by using production emission scenarios developed for CCC's 2012 advice on IAS and IEA emissions scenarios. A linear trend in UK emissions is applied between 2030 and 2050. Production emissions include emissions associated with exports.

Figure 1.21: Global modelling of per capita UK production emissions in 2050



Source: CCC analysis; UCL-TIAM (2012).
Notes: The UK 2050 target was derived by dividing the global emissions budget in 2050 between countries on a per-capita basis, so that every country has emissions just over tCO_2e per capita in 2050. Modelled UK CO_2 emissions are taken from UCL-TIAM global modelling for the CCC, which allows for the same overall level of emissions globally, but allows trading between regions so that emissions are allocated in a least-cost manner according to the relative costs of reducing emissions in each region. In this modelling, UK 2050 emissions are slightly higher than the 2050 target due to the model's decision to use bioenergy in other regions rather than importing it to the UK. If bioenergy imports are allocated to the UK then UK gross emissions would have been just above the UK target (at 2.4 tCO_2e/capita).

If the UK and some other countries are to continue to be net importers of carbon, this has implications for how we should plan to meet the 2050 target as defined in the Climate Change Act:

- We have said previously that there will be limited longer-term availability of offset credits at low cost if all countries are on a strong downward emissions path consistent with achieving the climate objective. In particular, this will require per capita emissions to reduce to around 2 tCO_2e, which our earlier analysis of UK emissions has suggested will be very challenging.
- Analysis in this report highlights the fact that the UK has a relatively small manufacturing base, while industry emissions are relatively high in other countries, making it more challenging for these countries to meet targets.
- Such countries would have even less scope to sell offset credits into the global carbon market and may need to purchase credits, thus further restricting what is already likely to be limited availability of credits in the market.

This reinforces our previous recommendation that the UK should aim to meet the 2050 target largely through domestic emissions reduction, and not through the purchase of expensive credits, and to reflect this in the design of the fourth carbon budget.

In chapter 3, we consider a range of policies which could ensure global emissions reductions, including policies to promote resource efficiency and sustainable consumption.

Chapter 2: Lifecycle emissions of low-carbon technologies

We have previously discussed lifecycle emissions for certain technologies in our 2011 Renewable Energy and Bioenergy Reviews, but in general, our focus has been primarily on the operating emissions of low-carbon technologies. However, it is important to make a broader assessment of lifecycle emissions to ensure that the measures we have included in our carbon budget scenarios are truly low-carbon and do not have unintended consequences at the global level. If it were the case that these measures have significant lifecycle emissions which we have not accounted for, whether in the UK or overseas, this might suggest a need to develop alternative technologies and/or a need for additional abatement here or abroad.

In this chapter we assess lifecycle emissions of conventional fossil fuel and key low-carbon technologies in power, heat and surface transport; these sectors together account for the majority of emissions reductions required to meet the fourth carbon budget, and need to be largely decarbonised in order to meet the 2050 target.

We assess current lifecycle emissions, together with scope for reducing them through, for example, decarbonisation of electricity and use of different materials. We examine to what extent these emissions occur in the UK (and are therefore already covered by carbon budgets) or outside of the UK (and therefore impact on our overall carbon footprint). Given our assessment of individual technologies, we consider implications of our analysis for approaches to meeting carbon budgets and targets.

Our key messages in this chapter are:

- The key low-carbon technologies (i.e. in power, heat and surface transport) offer significant savings over fossil-fuel technologies even when accounting for lifecycle as well as operating emissions.
- Nuclear and wind power generation have a very low carbon footprint relative to conventional alternatives.
- Compared to nuclear and wind, fossil fuel generation with carbon capture and storage (CCS) has relatively high lifecycle emissions, particularly coal CCS. Therefore CCS with fossil fuels should only be used as part of a portfolio approach (i.e. together with nuclear and renewables), and with gas rather than coal where possible.
- Lifecycle emissions of electric vehicles are significantly lower than those of conventional alternatives when using low-carbon power generation, and could be further reduced through the recycling of batteries.
- Shale gas, like other forms of gas, cannot be regarded as a low-carbon fuel source. It can, however, have lower lifecycle emissions than imported liquefied natural gas (LNG), if transported by pipeline and given appropriate measures to manage methane released during production.

- Lifecycle emissions of heat pumps are significantly lower than those associated with gas boilers when operated with low-carbon electricity, and could be further reduced through the use of low-carbon refrigerants.
- Bioenergy can result in emissions reductions on a lifecycle basis, but stringent sustainability criteria are required to ensure that this is the case. We repeat our recommendation that biomass used in power generation should by 2020 have lifecycle emissions of less than 200 gCO_2e/kWh.

We set out our analysis in 8 sections

1. What are lifecycle emissions?
2. Lifecycle emissions of power generation technologies
3. Gas use and supply chains
4. Lifecycle emissions of heat technologies
5. Lifecycle emissions of surface transport technologies
6. Lifecycle emissions of bioenergy
7. Implications of lifecycle emissions for the UK's carbon footprint and for meeting carbon budget
8. Policies for reducing lifecycle emissions

1. What are lifecycle emissions?

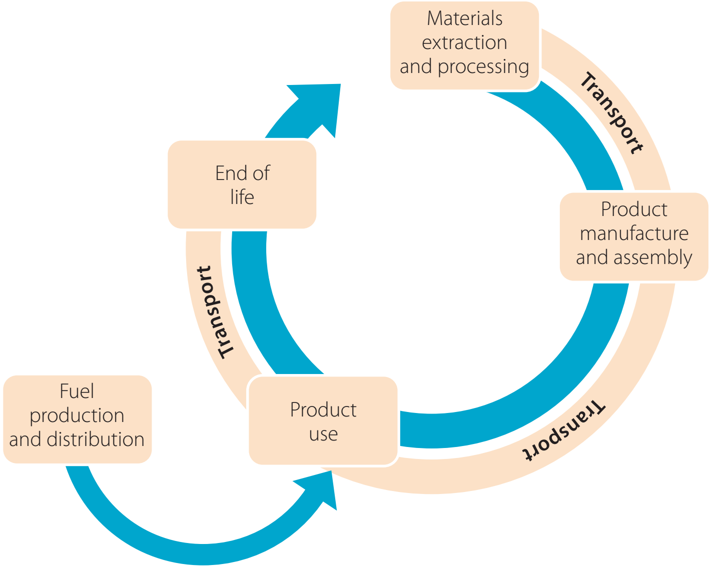
The lifecycle emissions or carbon footprint of a product refers to the total greenhouse gas (GHG) emissions caused directly and indirectly at each stage of its life, from the extraction of raw materials and manufacturing right through to its use and final re-use, recycling or disposal (Figure 2.1). It includes the GHG emissions resulting from any material inputs to, or outputs from, this lifecycle, such as energy use, transportation fuel and direct gas emissions such as refrigerant losses and waste.

Lifecycle emissions can be estimated as part of a wider lifecycle assessment (LCA). Full LCA covers a range of other environmental impacts (e.g. impacts on biodiversity, water resources, landscape etc). While these can be significant, the focus of this study is on GHG emissions only.

LCA is used by many businesses for the carbon footprinting of a variety of consumer products and plays a role in addressing consumption emissions (see Chapter 3). A number of LCA methodologies exist, each with different strengths and limitations (Box 2.1).

Process-based LCA is probably the most commonly used, and forms the basis of a number of standards and guidelines designed to improve the consistency of estimates, including the British Standards Institute's Publicly Available Specification (PAS) 2050, the World Resources Institute's Greenhouse Gas Protocol and the European Commission's International Reference Life Cycle Data System. For example, PAS 2050 is recommended by the Carbon Trust as 'a widely recognised, internationally applied and consistent method for assessing product lifecycle GHG emissions'. In practice, all standards allow for a degree of flexibility. As a result, comparability of studies can be an issue.

Figure 2.1: Product lifecycle stages



Source: CCC.

Box 2.1: Lifecycle methodologies

- Process analysis is a bottom-up method which starts with a process map of all materials, activities and processes associated with the product. Boundaries are then defined for data collection and primary data collected where possible, with gaps filled using secondary data from publicly available databases. Advantages of this method are that it is product-specific and covers the complete product lifecycle. The main limitation is that it suffers from 'truncation error' as a result of the system boundary drawn around the product. This can limit robustness, transparency and comparability of estimates derived from different LCA studies. However, use of product category rules can help alleviate these issues.
- Input-output (IO) analysis is a top-down method for estimating upstream or cradle-to-gate emissions, which combines economic IO tables (see Chapter 1) and estimates of average direct GHG emissions from different sectors to allocation emissions to supply chain. The main advantage of this method is that there is no artificial system boundary, so it captures all emissions from upstream processes in the supply chain. However its top-down nature and associated lack of granularity means that it is more suitable for product groups (sectors) than individual products. Moreover it does not cover the whole lifecycle of a product: emission from use and disposal phases must be estimated separately.
- Hybrid analysis is a combination of process and IO methods. In integrated hybrid analysis, the process method is used to estimate emissions from the most important sources, while other, less important emissions which would otherwise be outside of the system boundary, are estimated using IO averages. An advantage of this method is that it combines the strengths of process and IO analysis, using specific process data where possible but avoiding truncation error. However there is a risk of double counting emissions in the process and IO parts of the analysis (estimates from hybrid analyses are often higher than either process or IO-based estimates). Methods exist for mitigating this risk, but add complexity to the analysis.

In assessing the lifecycle emissions of low-carbon technologies, we have adopted a process-based approach. Our assessment was designed to answer the following questions:

- What are the lifecycle emissions associated with key low-carbon technologies, and their conventional alternatives?
- Will these emissions arise in the UK or be imported?
- How might they change in the future?
- How could they be reduced?

We commissioned Ricardo-AEA Ltd to undertake the following tasks for a range of technologies:

- Establish the range of lifecycle emissions in the literature for technologies (likely to be) deployed in the UK under current conditions
- Identify the key sources of emissions over the technology lifecycle
- Identify the locations of these emissions, through consideration of the supply chain
- Develop scenarios for potential changes in lifecycle emissions to 2050, by developing simple parametric models in which the impact of different factors could be tested: some generic, such as carbon intensity of materials and electricity, others technology-specific (Box 2.2).

Note that, reflecting both context (i.e. to inform the review of the fourth carbon budget) and resources available, this analysis was designed to identify emissions 'hotspots' over the technology lifecycles, and ways in which emissions might change over time, not to provide PAS-2050/GHG Protocol compliant estimates.

Furthermore, our estimates of lifecycle emissions reflect particular examples of technology design and operation. We have tested sensitivities to selected key parameters, but in practice precise lifecycle emissions would vary on a case-by-case basis. However, we can still draw broad conclusions.

Box 2.2: Approach to estimating current and future lifecycle emissions in this report

Technology specifications relevant for the UK, including projected changes over time (e.g. in efficiency), were taken from previous CCC and Government analysis[1].

For each technology, a simple spreadsheet calculation tool was developed to allow estimation of current and future (to 2050) lifecycle emissions.

Data on material and energy requirements for key lifecycle stages were collected from literature studies and adjusted where necessary to reflect the UK situation (e.g. technology specifications, supply chains).

For each of the years 2010, 2020, 2030, 2040 and 2050, these were multiplied by relevant materials and energy emission factors (i.e. relevant to the year in question and the UK supply chain), and summed to estimate total emissions for each lifecycle stage. Based on consideration of supply chains, an estimate of the split between UK territorial and overseas emissions was made.

Base case and alternate (higher) emissions factors for materials and energy were derived from a number of sources including :

- the Inventory of Carbon & Energy (ICE) developed by Bath University
- CCC scenarios for UK power sector and industry production emissions[2]
- scenarios for production emissions for different sectors, regions and over time from IEA Energy Technology Perspectives (ETP) 2012
- Defra/DECC GHG conversion factors for company reporting
- Bottom-up analysis of supply chains for gas, coal and nuclear consumed in the UK

Further details are provided in the accompanying consultancy report.

Note that in general average emissions factors were used the analysis (e.g. reflecting the average power generation mix, and the average gas supply mix). However, where particularly relevant (e.g. for heat pumps), we comment on the sensitivity of our results to the use of marginal emissions factors.

In the following sections, we consider the following technologies (more detailed technology specifications are available in the supporting consultancy report[3]):

- **Power**. Onshore and offshore wind, nuclear, gas CCS, coal CCS (pre- and post-combustion), solar PV and unabated gas generation.
- **Heat**. Solid wall insulation, air- and ground-source heat pumps, and gas boilers in residential applications[4]
- **Surface transport**. Conventional petrol, plug-in hybrid (PHEV) and battery electric (BEV) cars, conventional and hydrogen fuel cell heavy goods vehicles (HGVs).

This list is a clearly a subset of available technology options – finite time and resources meant we focused on those low-carbon technologies with the most significant role in our scenarios for meeting the fourth carbon budget[5], and the conventional technologies most commonly deployed[6].

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[1] CCC (2010) The fourth carbon budget, CCC (2012) Inclusion of international aviation and shipping in carbon budgets, NERA (2010) analysis of low carbon heat to 2030, AEA (2012) A Review of the Efficiency and Cost Assumptions for Road Transport Vehicles to 2050, Element Energy (2012) Cost and Performance of EV Batteries, Parsons Brinkerhoff (2012) Electricity Generation Cost Model – 2012 Update of Non Renewable Technologies, Arup (2011) Review of the generation costs and deployment potential of renewable electricity technologies in the UK. Also Crown Estate (2010) A Guide to an Offshore Wind Farm, Areva and EDF (2012) UK EPR GDA Submission.

[2] From our fourth budget advice, advice on inclusion of international aviation and shipping in carbon budgets and power sector modelling for our 2012 progress report (Redpoint Energy (2011) Modelling the trajectory of the UK power sector to 2030 under alternative assumptions).

[3] http://www.theccc.org.uk/publication/carbon-footprint-and-competitiveness/

[4] Residential applications were chosen due to the size of emissions from residential heat, and because relative to non-residential heat, this is a more homogenous sector, and one for which our characterisation of opportunities is more precise.

[5] with the exception of solar PV, which has a relatively limited role in ours scenarios, but has seen rising uptake in recent years.

[6] In transport, this implied a choice between a petrol and diesel car – our fourth budget scenario implicitly assumes a broadly 50/50 split. However petrol was chosen given greater scope for efficiency improvements in the future (although currently new diesel cars are more efficient than comparable new petrol cars).

For each technology, we recap its role in meeting carbon budgets and then assess current lifecycle emissions together with scope for reducing these through decarbonisation of the supply chain.

We also consider lifecycle emissions of different gas supply alternatives; and we recap the analysis of bioenergy lifecycle emissions from our Bioenergy Review.

2. Lifecycle emissions of power generation technologies

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 the decarbonisation of other sectors.

Power sector CO_2 emissions were 144 $MtCO_2$ in 2011. We proposed a scenario in our advice on the fourth carbon budget where these emissions fell to 16 $MtCO_2e$ in 2030, through reducing direct carbon intensity from 500g CO_2/kWh currently to the order of 50g CO_2/kWh.

We showed that this is achievable through deployment of a portfolio of low-carbon technologies which are or are likely in future to become cost-effective (i.e. cheaper than fossil fuel generation facing a carbon price[7]). In our review of renewable energy in 2011, we considered the generation mix in 2030 in more detail and illustrated a possible mix comprising around 40% nuclear, 40% renewable (mainly wind), 15% CCS and 5% unabated gas- fired generation for balancing the system.

Here we consider the lifecycle emissions associated with each of these technologies. In order to make a like-for-like comparison, we assume that nuclear and CCS operate at baseload and intermittent renewables at load factors reflecting average wind conditions. For each technology, we have estimated emissions in a base case, together with a number of sensitivities specific to each technology.

Before presenting our own estimates, we briefly review previous studies. The results of these studies cover a wide range. reflecting a number of factors including:

- Scope of study (lifecycle stages covered, system boundary)
- Plant characteristics e.g.
  - Plant design and size· These affect materials requirements.
  - Load factor, efficiency and lifetime. These affect the number of kWh over which 'embedded' emissions are spread; efficiency also affects the amount of fuel required and therefore both direct emissions (from combustion) and upstream fuel emissions (e.g. from fuel extraction).
- Fuel cycle assumptions

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[7] Based on DECC's central gas price and carbon price projections.

  - Fuel grade and extraction, processing and transport methods and characteristics. These affect upstream fuel emissions; fuel grade can also affect power plant direct emissions in a similar way to plant efficiency (i.e. a lower fuel grade means more fuel is required to generate each kWh of electricity).

- Assumed carbon intensities of materials and energy used at each lifecycle stage, reflecting supply chains
- End of life treatment (e.g. whether materials are recycled)
- Age of study and location considered, which can have implications for all of the above assumptions

Thus there is no "right" answer: estimates will reflect the specific approach and assumptions used. The assumptions used in our analysis are designed to reflect new, modern plant deployed in the UK (for both low-carbon and conventional technologies). Given technology developments to date (e.g. improvements in efficiency, lifetime, use of materials), this often means that our estimates are at the low end of the range from the literature.

Nuclear

While direct emissions from nuclear generation are zero, emissions arise from the rest of the nuclear lifecycle, including both the plant itself and the fuel used.

Estimates in the literature of lifecycle emissions show a wide range, although most are in the region 5 – 55 gCO_2e/kWh for the type of reactors (i.e. pressurised water) expected to be deployed in the UK. This range is due to a number of factors including plant characteristics (efficiency, lifetime etc), uranium ore grade and enrichment method, mining location and carbon intensity of energy used in mining/milling.

Emissions from nuclear plants deployed in the UK in the near term are likely to be at the lower end of this range (Figure 2.2), reflecting technology specification and fuel processing method, as well as assumed decarbonisation of electricity used for fuel supply in line with our base case[8].

Our analysis suggests that the fuel cycle contributes the largest share of emissions, although embedded emissions in the plant itself also account for a relatively high share:

- Mining and milling of uranium (at source) account for half of total lifecycle emissions, with processing and (centrifugal) enrichment (in the UK) contributing around a further 10%.
- Embedded emissions in the nuclear plant account for around a quarter of the total.

Reflecting this, future lifecycle emissions will largely depend on:

- Fuel supply chains, and measures to mitigate emissions from these supply chains.
  - Mining and milling emissions relate primarily to energy use, mainly electricity, so improving energy efficiency of mining operations and/or reducing carbon intensity of electricity offer scope to reduce nuclear lifecycle emissions.

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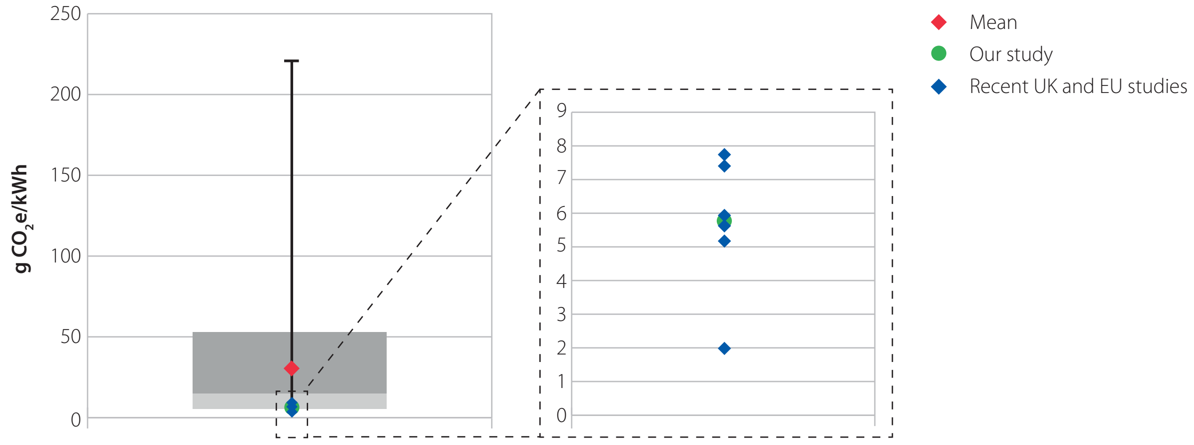
[8] Based on the 2 degree scenario from IEA ETP 2012, and central CCC scenarios for UK power sector and industry emissions.

Figure 2.2: Range of estimates in the literature for lifecycle emissions of nuclear power



Source: Ricardo-AEA for CCC.
Notes: PWR reactor.

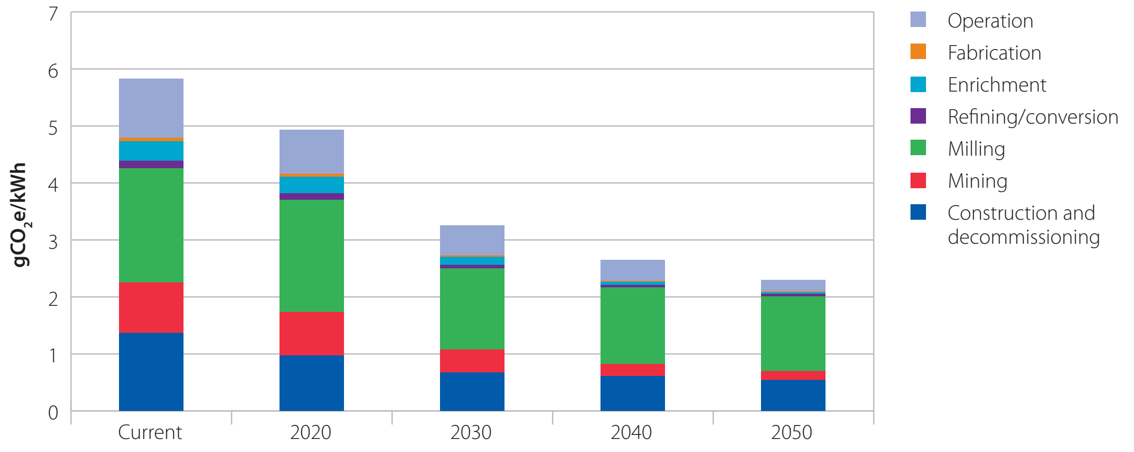
  - The choice of uranium enrichment method could have a significant impact on emissions: centrifugal enrichment is expected for the UK, and has relatively low emissions compared to the alternative (gas diffusion enrichment), which is significantly more energy-intense.
  - All fuel supply chain emissions will be affected by uranium ore grade: the lower the ore grade the more mining and processing required to produce the same amount of uranium.

- Carbon intensity of materials and energy used for construction.
  - Given embedded emissions in the plant accounts for a relatively high share of the total, reducing these emissions will have an appreciable impact on overall lifecycle emissions from nuclear. In particular, emissions from steel, cement/concrete and electricity used in construction together account for around 20% of total g/kWh.

We estimate lifecycle emissions for plant starting operation in 2030 could be between 3 and 10 gCO$_2$e/kWh:

- In a central scenario where ore grades remain at current levels of around 0.1%, centrifugal enrichment is used and carbon intensity of materials and electricity fall in line with our base case, emissions could be 3 g/kWh (Figure 2.3)
- Improvements to fuel utilisation (burn-up) could deliver further reductions, but are likely to be limited to around 10% of current achievable levels; overall nuclear lifecycle emissions would still be around 3 g/kWh in this case.
- Conversely, emissions could be higher (up to 10 g/KWh) in scenarios where lower-grade uranium ores were used, or where gas diffusion was used in instead of centrifugal enrichment.

Figure 2.3: Change in lifecycle emissions from nuclear power over time



Source: Ricardo-AEA for CCC.

Given the significance of the fuel cycle, we estimate that around half of nuclear lifecycle emissions arise outside of the UK currently, and it is likely to be that this will continue to be the case in future, given uranium will always be sourced overseas, reflecting geographic location of reserves.

Wind

As for nuclear, direct emissions from wind are zero. Moreover, wind generation involves no direct fuel use: emissions arise mainly from manufacture and installation of turbines/farms themselves.

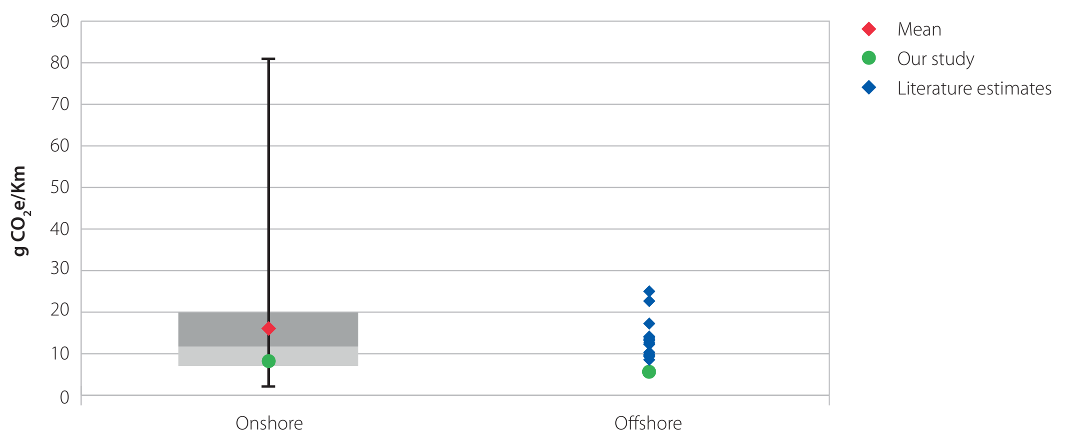
Most estimates in the literature of lifecycle emissions range from 7 – 20 gCO_2e/kWh for onshore wind; estimates for offshore wind are more limited and range from 5 – 24 gCO_2e/kWh for offshore:

- Variation in estimates is often due to differences in assumed lifetimes and load factors (which in turn may depend on wind farm siting and hence wind patterns): the longer the lifetime and higher the load factor, the greater number of lifetime kWh over which the embedded emissions in the wind turbine/farm are spread.
- Other factors which affect estimates will include turbine/farm characteristics (e.g. offshore foundation design and materials used; this again can be dependent on siting, in this case water depth) and supply chains (e.g. source and hence embedded emissions of materials used in manufacture).

We estimate emissions from wind deployed in the UK in the near term to fall within this range (Figure 2.4).

Materials are the primary source of lifecycle emissions, contributing over 80% of the total for both onshore and offshore wind. In particular, embedded emissions of steel account for around 35% of onshore and 50% of offshore emissions.

Figure 2.4: Range of estimates in the literature for lifecycle emissions of wind power



Source: Ricardo-AEA for CCC.

Given the dominance of materials-related emissions, there is scope for wind emissions to fall through reduced emissions from materials production, materials efficiency and/or substitution, and increased turbine size:

- Reducing the carbon intensity of materials currently used (especially steel) in line with our base case could reduce wind emissions by around 25% by 2030.
- There may be opportunities to reduce the amount of materials required (e.g. through use of alternative foundation designs), or to switch to materials which are less carbon-intense, while offering similar structural and other properties. Further work would be needed to explore these options.
- As material requirements do not, in general, scale linearly with turbine capacity[9], use of larger turbines could reduce emissions from offshore wind[10] by increasing kWh generated for the same materials 'investment'. In particular, foundation requirements are relatively insensitive to capacity[11].

We estimate lifecycle emissions in 2030 could be between 4 – 7 gCO_2e/kWh for onshore and 3 – 5 gCO_2e/kWh for offshore wind:

- In a central case, given falling carbon intensity of materials and electricity in line with our base case, we estimate emissions of around 6 gCO_2e/kWh for onshore and 4 gCO_2e/kWh for offshore (Figure 2.5)

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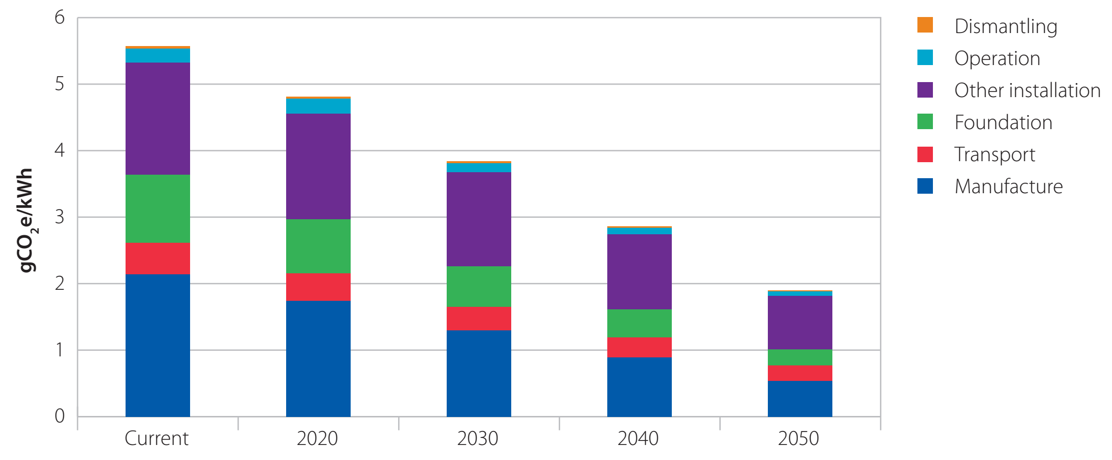
[9] See for example, lifecycle assessments for various Vestas turbines http://www.vestas.com

[10] Planning and access constraints are likely to limit the size of onshore turbines.

[11] *per se* – but they are linked to water depth, which in turn may correlate with capacity (larger turbines may be located in deeper waters).

Figure 2.5: Change in lifecycle emissions from offshore wind power over time



Source: Ricardo-AEA for CCC.

- Reducing tonnes of materials required by 5% per decade could further reduce emissions for onshore wind to around 5 gCO_2e/kWh, while increasing turbine sizes from 5 MW to 8MW could reduce emissions for offshore wind to around 3 g/kWh. Local sourcing of materials and components could also reduce emissions, as a result of shorter transport distances as well as relatively low UK industrial emissions intensities in our base scenario.
- Conversely, emissions could be up to 7 gCO_2e/kWh for onshore and 5 gCO_2e/kWh for offshore, for example if emissions intensities of materials and electricity follow our alternate trajectories[12].

These estimates do not reflect the possible need for back-up generation to provide power when the wind is not blowing: arguably lifecycle emissions from this back-up generation should be allocated to wind[13].However, depending on the mix of capacity on the system, this back-up generation could be provided by unabated gas-fired plant and/or lower-carbon capacity (e.g. gas CCS). As the lifecycle emissions of back-up generation depend on the wider capacity mix, perhaps a more meaningful consideration is the average lifecycle emissions intensity of the power system as a whole; we discuss this below..

In addition, our estimates do not include potential land use change emissions associated with onshore wind, which could be high in some cases (e.g. deployment on peatland), and should be factored in to siting decisions.

In terms of the location of emissions, we estimate that currently around 45 – 55% of lifecycle emissions arise in the UK. Whether this continues to be the case will depend on supply chains. For example, if supply chains for offshore wind are developed in the UK, a greater share of emissions will arise here, but with potential to minimise the size of these emissions (e.g. as result of industrial decarbonisation, as well as shorter transport distances).

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[12] Based on the 4 degree scenario from IEA ETP 2012, and the 'Low Gas Carbon' scenario from our UK power sector modelling with Redpoint Energy (Redpoint Energy (2011). Modelling the trajectory of the UK power sector to 2030 under alternative assumptions).

[13] A similar argument applies to nuclear generation, and the need for 'peaking plant' to complement this relatively inflexible technology.

Carbon capture and storage (CCS)

Unlike nuclear and wind, fossil fuel power generation with CCS produces direct emissions. These depend mainly on the fuel type (gas or coal), power generation efficiency and CO_2 capture rate. In our fourth budget advice we assumed residual emissions of around 45 gCO_2/kWh for gas CCS and around 90 gCO_2/kWh for coal CCS, based on a 90% capture rate.

Other lifecycle emissions of fossil generation with CCS arise from the lifecycle of the plant itself and from production/delivery of the fuel used. Due to the energy penalty involved in CCS (which effectively reduces the plant efficiency), the latter are actually higher than for unabated plant, as more fuel (around 15- 30%) is required per kWh of electricity generated.

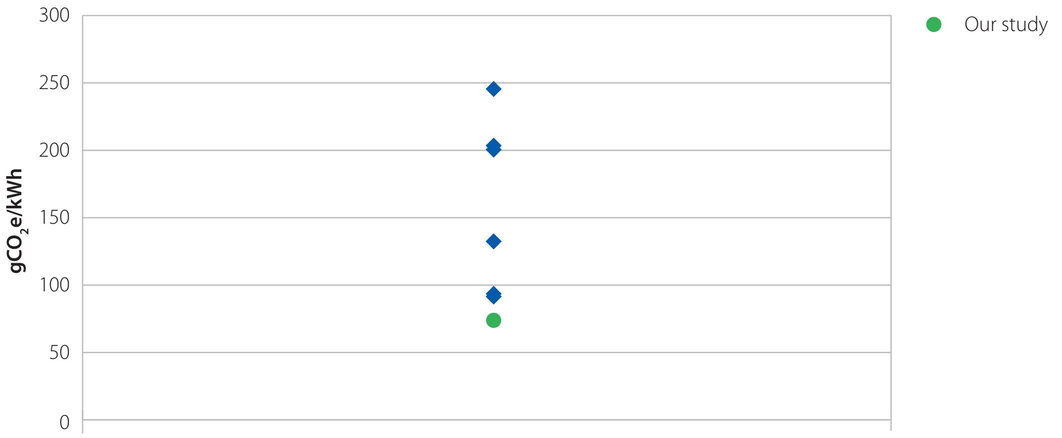
We now consider gas CCS and coal CCS in turn.

Gas CCS

Estimates of lifecycle emissions for gas CCS range from around 90 – 245 gCO_2e/kWh in the studies reviewed. The range is due to number of factors including, most significantly, (net) power generation efficiency[14] and CO_2 capture rate, and characteristics of the gas fuel cycle (e.g. pipeline or LNG, methane leakage during production and transport, energy required for compression/liquefaction – which are all, in turn, affected by source location and distance transported).

We estimate emissions from gas CCS deployed in the UK in the near term to be at the lower end of the range (Figure 2.6), reflecting assumed generation efficiency and capture rate, and UK gas supply chains.

Figure 2.6: Range of estimates in the literature for lifecycle emissions of gas fired power with CCS



Source: Ricardo-AEA for CCC.

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[14] i.e. net of the energy penalty associated with carbon capture.

The key sources of emissions for gas CCS are gas supply and combustion:

- While significantly reduced compared to unabated gas generation, combustion emissions are still a significant source of lifecycle emissions from gas CCS, accounting for half of the total.
- Meanwhile emissions from gas supply (extraction, processing and transport) account for around 40% of the total, given the current UK gas supply mix.
- Embedded emissions in the power and capture plants, and in the CO_2 transport and storage infrastructure, is relatively small.

Future lifecycle emissions will therefore depend mainly on generation efficiency and CO_2 capture rate, and on gas supply chains:

- Generation efficiency and capture rate affect direct emissions, but also, in the case of plant efficiency, the amount of gas used and hence emissions from gas supply. However the extent to which efficiency improvements are possible beyond the ambitious assumptions included in our analysis may be limited. (Plant efficiency here refers to net efficiency, i.e. net of the energy penalty associated with CCS.)
- Emissions from gas supply chains include those related to energy used for production and compression/liquefaction, as well as vented/fugitive methane emissions. These in turn may depend on the source and type of the gas (see section 3 below).

We estimate lifecycle emissions from gas CCS in 2030 could be between around 60 – 120 gCO_2e/kWh:

- In a central case, given our assumptions for plant efficiency and capture rate, and with a continuation of the current UK gas supply mix, emissions in 2030 would essentially remain at near-term levels, i.e. around 70 g/kWh (Figure 2.7).
- A lower capture rate (e.g. 85% rather than 90%) could increase emissions to around 90 g/ kWh, while the impact of gas supply mix can be illustrated with hypothetical cases based on 100% supply from different gas types.
  - A plant using 100% conventional pipeline gas (imported from current sources, with associated energy requirements and methane leakage rates) could have emissions of 60 g/kWh, as could a plant using well-regulated (piped) UK shale gas (see below).
  - A plant using poorly-regulated shale gas[15], or using 100% LNG (again from current sources, and assuming gas-turbine driven liquefaction trains[16]), could have emissions of around 120 g/kWh.

These estimates are based on assumed load factors of 85%. At lower load factors, embedded emissions (in the plant and CO_2 infrastructure) will be higher per kWh of electricity generated. However given the relatively small share of these emissions in the total, this impact is negligible at the load factors of around 55% in 2030 in our fourth budget-consistent scenario.

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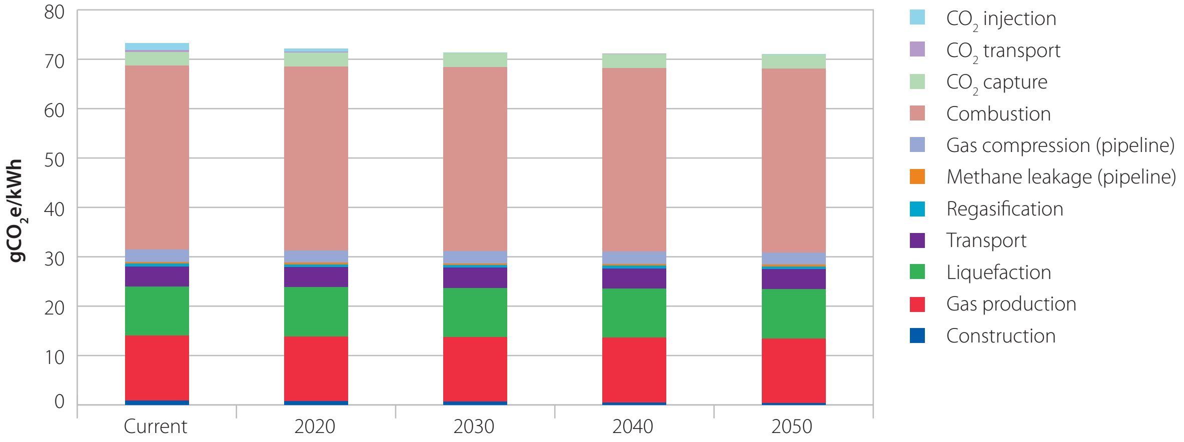
[15] Assuming 2% methane leakage during well completion – see section 3 below.

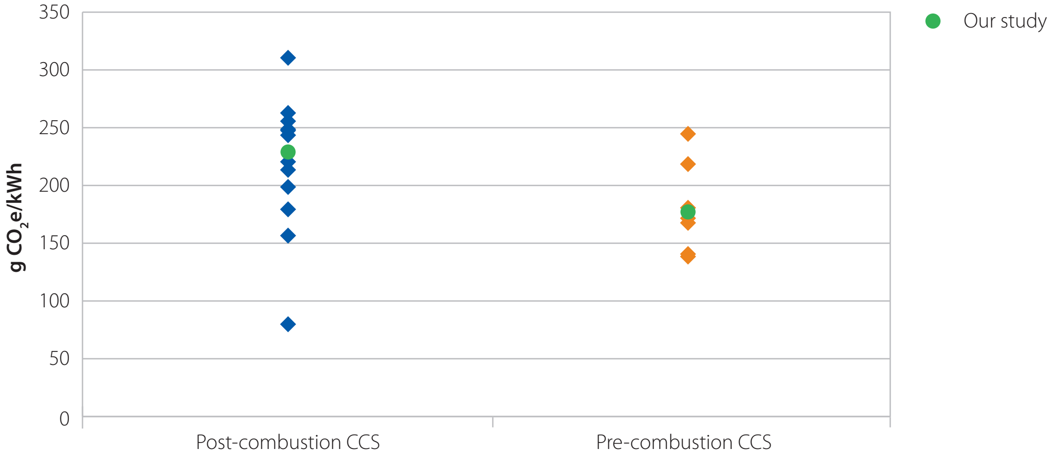
[16] In the longer term, electrical liquefaction trains combined with low-carbon electricity could reduce emissions associated from LNG. However in 2030, carbon intensity of electricity in countries from which LNG is (currently) imported to the UK is still relatively high in the IEA 2DS scenario (e.g. 350 g/kWh direct emissions only).

Figure 2.7: Change in lifecycle emissions from gas fired power with CCS over time



Source: Ricardo-AEA for CCC.

Figure 2.8: Range of estimates in the literature for lifecycle emissions of coal fired power with CCS



Source: Ricardo-AEA for CCC.

In terms of location of emissions, we estimate that for plants deployed in the near term, around 80% of emissions could arise in the UK. These are mainly combustion emissions, together with a share of gas supply emissions (around 50% of current UK gas consumption is UK-produced). In future, the share of gas supply emissions arising in the UK will depend on the balance between falling conventional UK gas production, potential UK shale gas exploitation and levels of imports.

Coal CCS

We have considered two types of coal CCS generation: pre- and post-combustion.

Estimates in the literature of lifecycle emissions range from 140 – 245 gCO_2e/kWh for pre- and 80 – 310 gCO_2e/kWh for post-combustion coal CCS. The range is due to a number of factors including plant efficiency, capture rate and fuel cycle assumptions (coal mining location, type (surface vs deep mining), methane leakage rate, energy use (amount and type) and coal transport distance).

We estimate emissions from coal CCS deployed in the UK in the near term could fall within this range (Figure 2.7).

As for gas CCS, combustion emissions of coal CCS are significant – in this case accounting for around half of lifecycle emissions. Coal supply emissions account for a further 40 – 50%, while embedded carbon in the plant and CO_2 infrastructure is again a relatively small share.

As for gas CCS, future lifecycle emissions will therefore be dependent on generation and capture efficiencies, and on fuel – in this case, coal – supply chains.

- Emissions from coal supply include those related to energy used for mining and transport, as well as methane leakage during mining, which can actually be higher than methane leakage from gas production.
- Measures to mitigate these emissions thus include increased energy efficiency and/or fuel switching for mining and coal transport, and methane capture during mining. However as coal is expected to be imported to the UK, these options would need to be implemented in the country of production.

We estimate lifecycle emissions in 2030 could be between 150 – 195 g/CO_2ekWh for pre- and 195 – 265 gCO_2e/kWh for post-combustion coal CCS:

- In a central case, given our assumptions for plant efficiency and capture rate, and with a continuation of the current UK coal supply mix, emissions in 2030 would essentially remain at near-term levels, i.e. around 155 g/kWh for pre- and 205 g/kWh for post-combustion capture (Figure 2.9)
- The low end of the ranges described above could be achieved through reducing the energy penalty associated with CCS (i.e. improving net generation efficiency) by a fifth, or by capturing a fifth of the methane released during coal mining.
- The high end of the ranges could ensue if capture efficiencies were lower than assumed (85% rather than 90%).

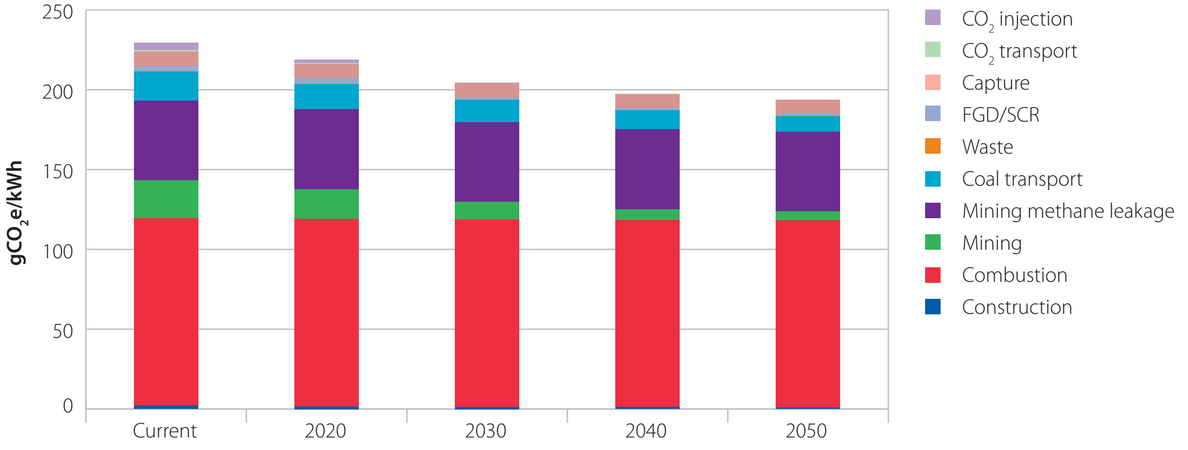
In terms of location of emissions, we estimate that for plants deployed in the near term, around 50 – 60% of emissions could arise in the UK. These are mainly combustion emissions, while the other big contributor – coal supply emissions – arise outside of the UK. This is likely to continue to be the case.

Solar PV

Photovoltaic power generation employs solar panels/modules composed of a number of solar cells containing a photovoltaic material, usually mounted on top of an existing building roof structure or walls.

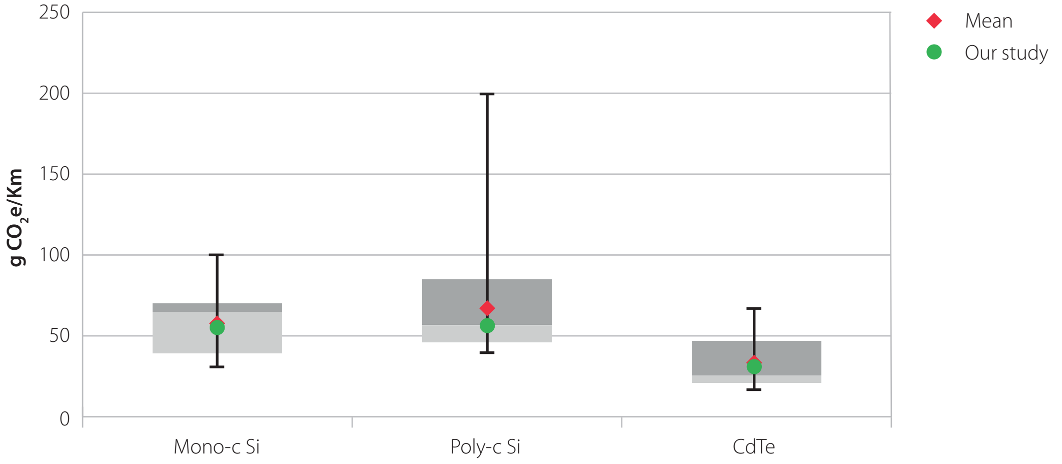
We have considered three types of solar PV: mono-crystalline silicon (mono-c Si), poly-crystalline silicon (poy-c Si) and thin film (cadmium telluride, CdTe). Crystalline silicon

Figure 2.9: Change in lifecycle emissions from coal fired power with post-combustion CCS over time



Source: Ricardo-AEA for CCC.

Figure 2.10: Range of estimates in the literature for lifecycle emissions of solar PV



Source: Ricardo-AEA for CCC.

technologies have historically been most commonly deployed, while thin film technologies offer potential benefits (e.g. in terms of cost, weight, flexibility).

Most estimates of lifecycle emissions in the literature range from around 40 – 70 g/kWh for mono-c Si, 45 – 85 g/kWh for poly-c Si and 20 – 45 g/kWh for CdTe (Figure 2.10). Ranges for each technology arise due to different assumptions for solar radiation (which will vary depending on location), performance ratio[17] and module efficiency, technology lifetime and type of installation is (e.g. rooftop mounted or integrated).

We estimate emissions for new installations in the UK within these ranges (around 55 g/kWh for c-Si technologies and 30 g/kWh for CdTe).

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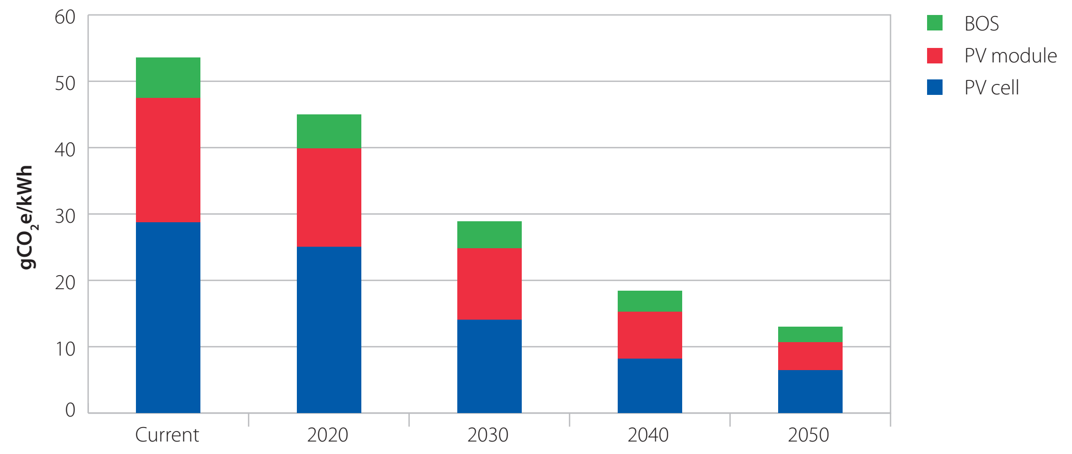
[17] the proportion of solar radiation which is converted to electricity.

Figure 2.11: Change in lifecycle emissions from poly-cyrstalline silicone solar PV over time



Source: Ricardo-AEA for CCC.

Emissions from solar PV stem almost entirely from manufacture – emissions from installation, disposal and maintenance are negligible:

- For c-Si technologies, there are significant energy requirements (including electricity) associated with production of the solar cells[18], which altogether account for around 55% of total lifecycle emissions. Additional materials and energy requirements for the PV module and balance of system (BOS) account for around 30-35% and 10-15% respectively (largely embedded emissions in the aluminium used).
- Production of CdTe modules is less energy-intensive than crystalline silicon ones, resulting in lower overall lifecycle emissions. Emissions embedded in the PV modules as a whole accounts for around 40% of the total, emissions in the BOS for around 60%.
- As emissions are almost entirely 'embedded', this means that g/kWh is essentially inversely proportional to technology lifetime (which determines lifetime output): reducing lifetime from 30 to 20 years increases g/KWh by 50%.

Given that a significant share of emissions is from energy used in manufacture, there is scope for them to fall over time, particularly for silicon technologies (Figure 2.11):

- Assuming manufacture in the EU, and falling EU grid intensity in line with our base case, lifecycle emissions could fall to around 30 g/kWh for c-Si and around 20 g/kWh for CdTe.
- If grid intensity was instead in line with our alternate trajectory, emissions could be higher at around 40 g/kWh for c-Si and around 25 g/kWh. Similar values could ensue if manufacture shifted to non-OECD countries (with grid intensities in line with our base case).
- Conversely emissions could be lower given further technology improvements. For example an increase in efficiency of 2% per decade could lead to emissions of around 20 – 25 g/kWh for c-Si and 15 g/kWh for CdTe.

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[18] from silica through metallurgical then electronic grade silicon, silicon wafer and finally the finished cell.

In terms of location of emissions, this will depend on where cells and modules are manufactured and materials are sourced: currently this is mainly outside of the UK.

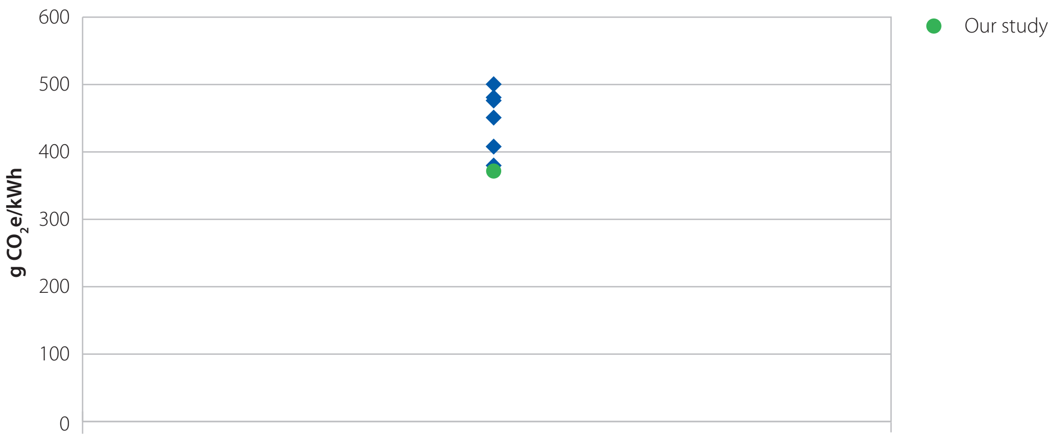
Unabated gas (CCGT)

Emissions from CCGT arise from the lifecycle of both the power plant and the fuel used for generation. Estimates in the studies we have reviewed range from 380 – 500 gCO_2e/kWh, reflecting different assumptions for plant efficiency, and, as for gas CCS, characteristics of the gas fuel cycle. Our estimate for plants deployed in the UK in the near term is at the lower end of this range (Figure 2.12).

Direct emissions from combustion of fuel account for the vast majority of total lifecycle emissions for CCGT. Reflecting this, scope for emissions to fall over time is relatively limited:

- Combustion emissions could in principle be reduced through improved plant efficiency. However, efficiencies are already very high[19].
- Emissions reductions in other parts of the lifecycle are possible but would have minimal impact on overall lifecycle emissions:
  - Emissions from the gas supply chain could be reduced (e.g. through reduced methane leakage, energy consumption and/or carbon intensity of energy used during gas supply), although there is also a risk that gas supply emissions could increase if not properly managed (see below).
  - There is also scope for reducing the carbon intensity of materials and energy used in plant construction.
  - However given the dominance of combustion emissions, the impact of these changes would be small.

Figure 2.12: Range of estimates in the literature for lifecycle emissions of CCGT power



Source: Ricardo-AEA for CCC.

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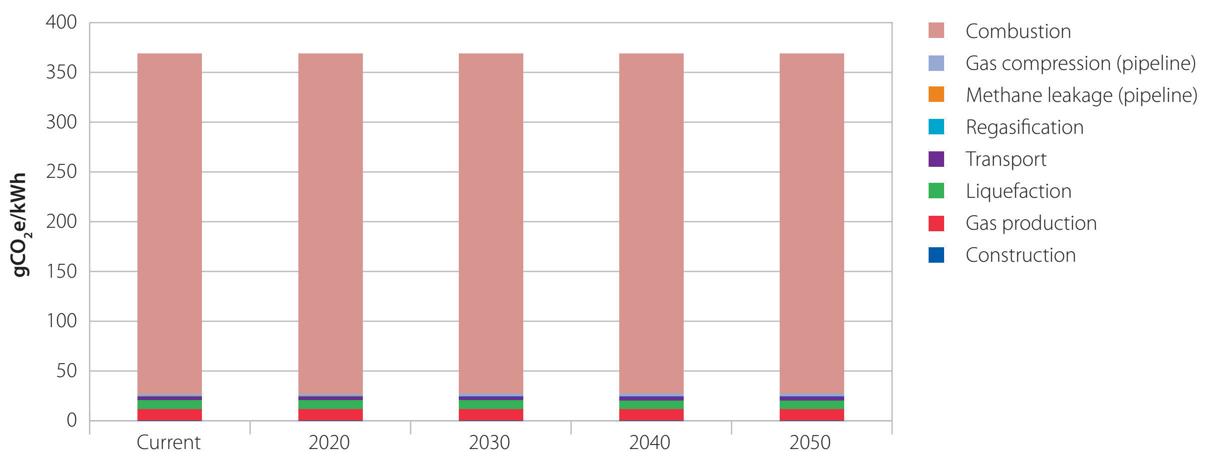
[19] In theory use of biogas, which is counted as zero emissions at point of use under the carbon budget accounting framework, could also reduce combustion emissions. However, biogas is likely to be more efficiently used in other applications – see section 6 below.

Figure 2.13: Change in lifecycle emissions from CCGT power over time



Source: Ricardo-AEA for CCC.

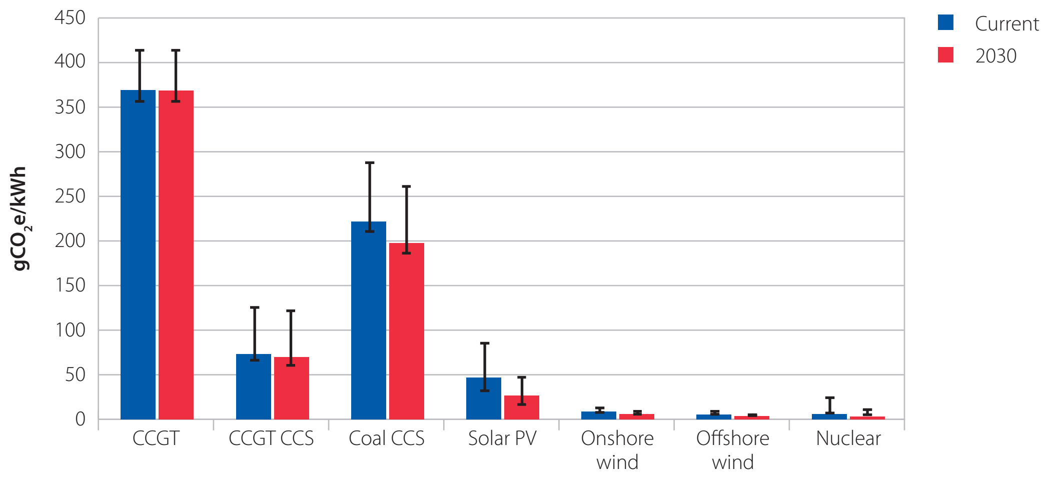
Emissions from CCGT are therefore likely to remain at similar to current levels (Figure 2.13), and continue to arise primarily in the UK.

The dominance of combustion emissions also means that the impact of load factor on lifecycle g/kWh of CCGT is relatively small, even at the levels (e.g. 8% in 2030) modelled in our fourth budget-consistent scenario, where the role of unabated gas is one of system balancing only.

Comparison of lifecycle emissions of power generation technologies

Figure 2.14 compares the lifecycle emissions of different generation technologies. While all low- carbon technologies offer savings relative to CCGT, there is a wide range. Our analysis

Figure 2.14: Estimated current lifecycle emissions of power technologies deployed in the UK, now and in 2030



Source: CCC analysis based on estimates developed by Ricardo-AEA.
Notes: Coal CCS and solar PV base case values are averages across technologies considered. 'Error' bars reflect the range across sensitivities tested.

suggests the biggest savings come from nuclear and wind generation (around 98%), while coal CCS offers savings of only 40 – 45% (compared to 80% for gas CCS).

Applying the generation mix in our fourth budget-consistent scenario suggests that average emissions intensity in 2030 would be around 15% higher on a lifecycle basis than on a direct emissions basis.. In section 7 below, we consider the extent to which lifecycle emissions have already been accounted for in our analysis for carbon budgets.

3. Gas use and supply chains

There has been much recent debate about the role of shale gas in meeting the UK's energy requirements under emissions constraints.

Our analysis suggests that there is a very strong case for early power sector decarbonisation; this is robust across a wide range of scenarios for gas and carbon prices. By 2030, we envisage that unabated gas generation – including from shale gas, if cost-effective – should be limited to balancing the system. However, gas CCS could have a role operating at higher load factors, as part of a portfolio of low-carbon technologies. Moreover, there will continue to be significant demand for gas for heating in residential and industrial sectors.

This raises a question over whether shale gas could play a role in meeting energy demand, for example, substituting for natural gas imported through pipelines or as LNG. In answering this question, it is important to understand the lifecycle emissions associated with shale gas relative to alternative gas sources.

These emissions include:

- Methane emissions from leaks and emissions at well site, processing losses, and losses during transport, storage and distribution
- CO_2 emissions from fossil fuels used to extract, develop and transport the gas

Processing and transport emissions are generally considered to be similar for both conventional and unconventional gas[20], with the debate around shale gas relating to upstream emissions, in particular methane emissions released during fracking (Box 2.3).

While methane leakage during the well completion stage of shale gas extraction is a possibility, options are available to reduce these emissions:

- At a minimum, the methane can be flared rather than vented. This converts methane to CO_2, thus reducing its global warming potential by around 85%[21].

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[20] although estimates of these emissions are uncertain and vary in the literature.

[21] Given a 100-year global warming potential (GWP) for methane of 21, which means a tonne of methane (CH_4) has a around 21 times the global warming effect than of a tonne of CO_2. The combustion of one CH_4 molecule produces one CO_2 molecule, which has a greater mass by a factor of 2.75. Accounting for this effect, flaring one tonne of methane reduces its CO_2-equivalence from 21 to 2.75 tCO_2e.

- Alternatively, it can be controlled through the use of 'Reduced Emission Completions', which involves the temporary installation of equipment designed to handle the high initial flow liquid from well completion. This separates the gas for processing/sale where pipelines are already in place, or storage for a later date. The US Environmental Protection Agency (US EPA) has recently published regulations that would require the use of RECs on new hydraulically fractured gas wells and re-fractured wells.
- In the UK, a recent report by the Environment Agency identified a range of monitoring techniques appropriate at different stages/geographies that could help to manage the risk of methane leakage, including ambient monitoring of diffuse methane emissions.

We therefore conclude that shale gas may be no worse than conventional gas from a carbon perspective if fugitive emissions are appropriately treated.

Box 2.3: Emissions from shale gas production

Hydraulic fracturing is the process by which a liquid under pressure causes a geological formation to crack open. It is used to extract gas from shale formations: continuous deposits over large areas, which have very low permeability and low natural production capacities.

Typically, horizontal wells are drilled in order to maximise access to the gas reserves, following which fluids are injected under high pressure to generate fractures in the rock. Fracturing fluids consist of water and a range of additives including 'proppants', which keep the fractures open after the pressure is released, allowing the natural gas to flow from the pores and fractures in the rock into the well for subsequent extraction.

After fracking is completed, a proportion of the injected fracturing fluid rises to the surface, containing a mix of water, sand, hydrocarbon liquids and natural gas.

A number of recent studies have considered emissions associated with shale (vs. other) gas production, based mainly on data from the US. Variation in estimates is often due to assumptions around methane 'leakage' rate and the global warming potential (GWP) of methane.

Methane leakage is the amount of methane emissions released to the atmosphere as a proportion of gas produced. It depends in turn on three factors:

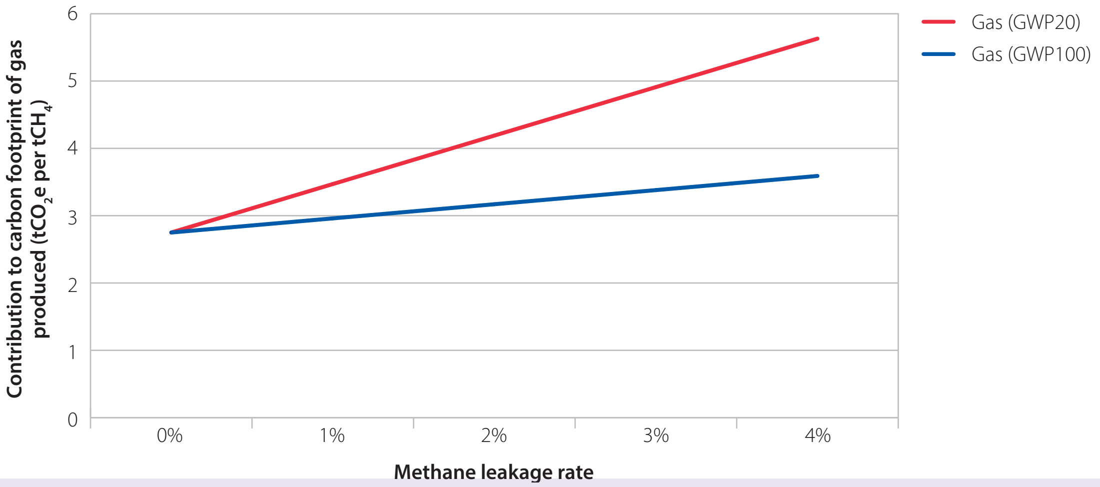
- Amount of methane brought to the surface during well completion
  - This will depend on site-specific factors including concentration of methane in flow-back fluid, quantities of flow-back water and length of flow-back period.
- Venting rate
  - The methane brought to the surface during well completion may be vented to the atmosphere. Alternatively it can be flared (which converts potent methane to CO_2), or controlled through the use of Reduced Emission ('Green') Completions.
- Estimated ultimate recovery of the well (i.e. total amount of gas recovered)
  - This will affect the denominator of the methane leakage rate. It is highly uncertain and varies by well and basin.

The global warming potential of methane relative to CO_2 depends on the timeframe over which it is viewed.

- Methane is a potent greenhouse gas but has a shorter lifetime in the atmosphere than CO_2 (12 years compared to 150 years). Its GWP will therefore be higher if viewed over a shorter timeframe.
- A GWP of 21 over a 100-year period is used as standard for emissions accounting, both globally and within the UK carbon budgets. More recently the U.N. IPPC has assigned methane a GWP of 25 over a 100-year period and 72 over a 20-year period, while some scientists estimate higher values (e.g. 105 over a 20-year period) based on interaction with aerosols.

Figure B2.1 illustrates the effect of methane leakage rate and GWP on the emissions factor for shale gas.

Figure B2.1: Impact of methane leakage rate and GWP on carbon footprint of gas production



Source: CCC analysis.

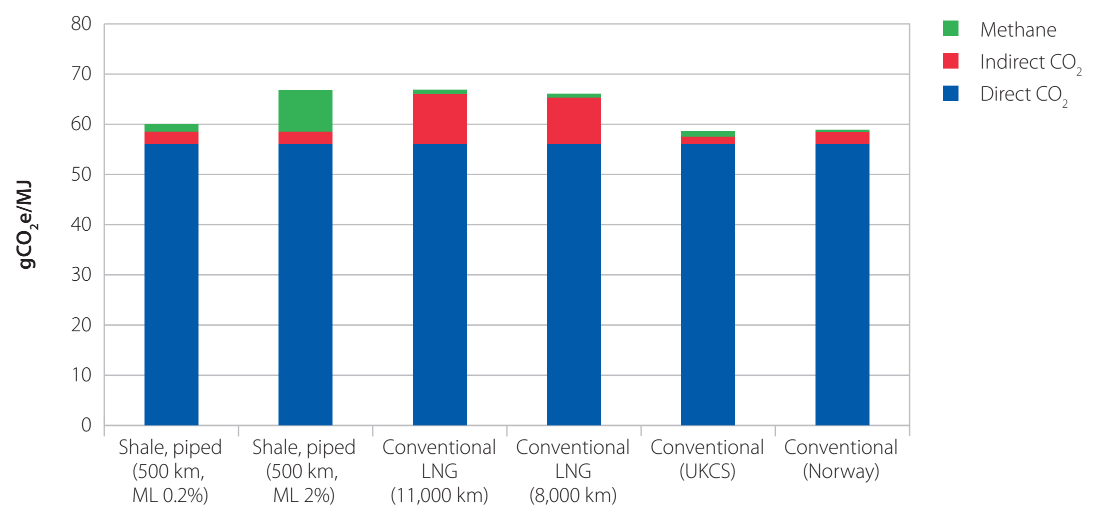
Once gas has been extracted, further emissions are associated with its processing and transport. As noted above, these are generally considered to be similar for conventional and unconventional gas. Of more importance is the form of transport – whether by pipeline or LNG (as well as the distance transported):

- For pipeline gas, key sources of GHG emissions during processing and transmission are energy for compression and fugitive methane from pipelines, both of which are dependent on distance transported. These are opportunities for reducing these emissions, for example through enhanced maintenance, and potentially use of low-carbon energy electricity to drive compressors; further work would be needed to establish the cost-effectiveness of these options.
- LNG is natural gas cooled to a low temperature so that it becomes a liquid occupying a much smaller volume (1/600 of natural gas at atmospheric pressure), which can then be transported over long distances without the need for fixed infrastructure (Box 2.4). Currently the main source of emissions from the LNG lifecycle is energy consumption for liquefaction, with vented/flared and fugitive emissions contributing a smaller share. Potential opportunities for reducing LNG emissions include use of low-carbon electricity and/or capture and storage of carbon arising during liquefaction; further work would be needed to establish the cost-effectiveness of these options.

Looking across the full lifecycle, there are therefore situations where lifecycle emissions of shale gas transported by pipeline could be lower than LNG from conventional sources (Figure 2.15).

Given the still significant role for gas in heating in 2030 (as well as a more limited role in power generation), measures to minimise lifecycle emissions from all types of gas (conventional and unconventional, pipeline and LNG) will be important. In addition to the measures identified above, controls are also available for other sources of emissions which are common to conventional gas extraction (e.g. use of vapour recovery units) and should be encouraged where cost-effective.

Figure 2.15: Illustrative lifecycle emissions of natural gas



Source: CCC analysis based on estimates developed by Ricardo-AEA.
Notes: Emissions per unit energy of gas delivered. Includes transmission but excludes UK distribution. ML = methane leakage from well completion.

Box 2.4: Liquefied natural gas (LNG)

- The LNG process consists of several steps: processing; liquefaction; transport; storage and re-gasification.
- The processing step for LNG is essentially the same as for pipeline gas. The undesirable components (H_2O, CO_2, etc.) are removed, while the higher hydrocarbon fractions (LPG and gasoline) are separated during the liquefaction process. Cooling down to condensation temperature (-162 °C) is done in industrial installations, typically with a number of cooling stages. Boil-off gas and pre-cooling and loading vapours are compressed and used as fuel gas for the liquefaction units or flared.
- Long distance transport of LNG takes place in cargo ships with an insulation system to keep the temperature at -162 °C. Boil-off gas provides a large fraction of the fuel needs for shipping, although a new development is the introduction of a boil-off gas re-liquefaction facility on-board the LNG carriers. At the arrival port LNG is stored, pressurised with a pump, re-gasified and injected into the gas grid.

4. Lifecycle emissions of heat technologies

Direct CO_2 emissions from residential buildings were 66 $MtCO_2$ in 2011, mainly from combustion of gas in gas boilers.

In previous reports we have identified two main opportunities for reducing direct building emissions. These are energy efficiency improvements and the deployment of low-carbon heat, in particular heat pumps. Our core scenario for meeting the fourth carbon budget included insulation of 45% (3.5 million) solid wall properties[22] and deployment of heat pumps to meet 25% of residential heat demand, largely replacing gas boilers.

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[22] We envisage most lofts and cavity walls to be insulated already by the fourth budget period.

Solid wall insulation

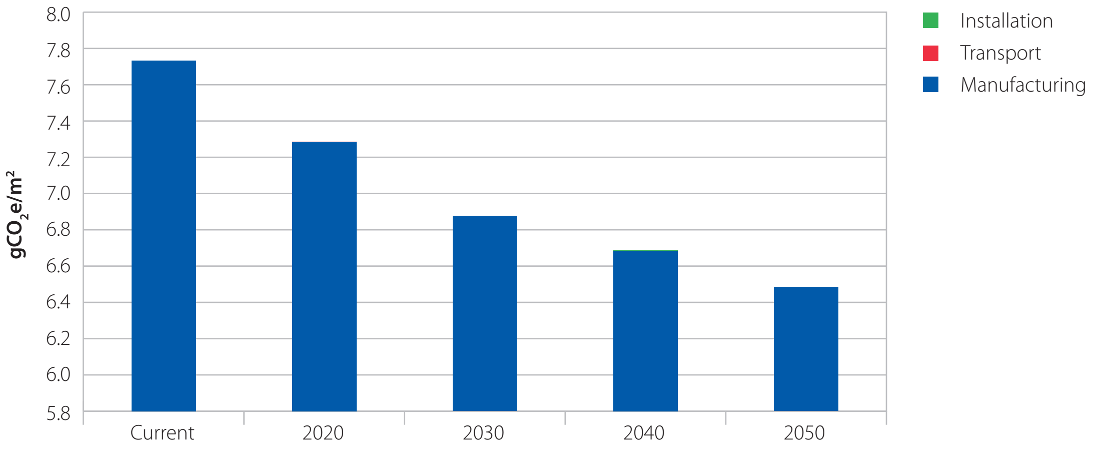
Lifecycle emissions from solid wall insulation stem almost entirely from materials and manufacture. We estimate current values of around 8 $kgCO_2e/m^2$ for rockwool and 10 $kgCO_2e/m^2$ for polystyrene foam insulation[23].

However, there is scope for emissions to fall in future as production processes become less carbon-intense (e.g. through improved efficiency and reduced carbon intensity of energy used) (Figure 2.16). By 2030, emissions could be around 7 $kgCO_2e/m^2$ for rockwool and 8 $kgCO_2e/m^2$ for polystyrene foam.

Given a surface area of around 80 m^2, emissions associated with insulating a typical house would be around 550 – 655 $kgCO_2e$. This compares with total emissions savings of around 20 tCO_2e over the life of the insulation.

Solid wall insulation therefore saves significantly more emissions than are produced during its manufacture and installation and remains an appropriate measure for inclusion in emissions reduction scenarios.

Figure 2.16: Change in lifecycle emissions from solid wall insulation over time



Source: Ricardo-AEA for CCC.

Heat pumps

Heat pumps use electricity to extract heat from the surrounding environment and transmit this for space and hot water heating. One unit of electricity can generate up to 4.5 units of heat (an 'efficiency' of 450%)[24]. There two main types of heat pump: air source heat pumps (ASHP) extract heat from the air, while ground source heat pumps (GSHP) extract it from the ground (via a ground loop or borehole).

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[23] Based on data in the Simapro database, which reflects the use of HFCs for making polystyrene foam. Emissions could be lower where HFC replacements are used as blowing agents. Most solid wall insulation boards available on the UK market have been produced with blowing agents that have a much lower global warming potential (e.g. pentane).

[24] See Box 5.4 in our Fourth Carbon budget report. In this study we assume we assume heat pumps retrofitted to an existing radiator-based heating system in a 'typical' residential building (i.e. a semi-detached suburban house built before 1990), with efficiencies commensurate with this.

Literature on lifecycle emissions from heat pumps is relatively limited; however estimates in the studies reviewed are in the range 60 – 275 gCO_2e/kWh for ASHP and 45 – 235 gCO_2e/kWh for GSHP:

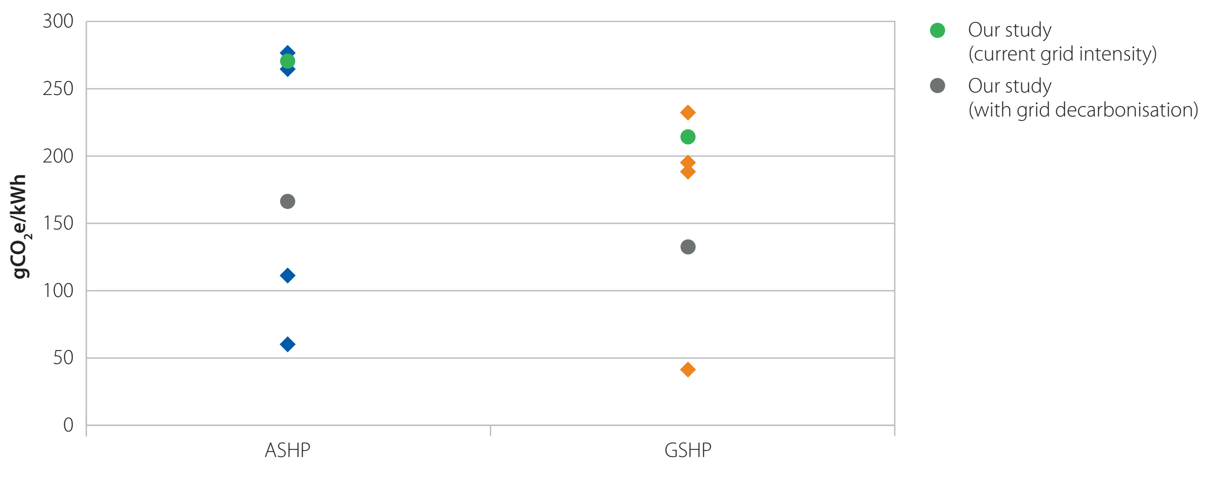
- Emissions from GSHP are generally lower on a per kWh basis given higher efficiencies of GSHPs, notwithstanding additional emissions associated with installation.
- Reasons for the range for each heat pump type include different assumptions for efficiency, lifetime, and, in particular, carbon intensity of electricity during use.

Applying the current average UK grid intensity, we estimate emissions to be around 270 g/ kWh for ASHP and around 215 g/kWh for GSHP (Figure 2.17), based on manufacturers' stated efficiencies, and retrofit to an existing radiator-based heating system.

- A field trial by the Energy Saving Trust[25] found that real-world efficiencies could be somewhat lower, e.g. 220% for ASHP and 240% for GSHP, compared to the 250% and 315% we assumed for the present day. Applying these lower efficiencies would increase lifecycle emissions to around 300 g/kWh for ASHP and 290 g/kWh for GSHP, given current grid intensity. This highlights the importance of best-practice installation and operation.
- Conversely, greater efficiencies may be achievable via use with an underfloor heating system. This would increase absolute lifecycle emissions due to additional materials and energy for installation, but would also increase the heat output over which these emissions are spread. The net result could be to reduce emissions on a per kWh basis (e.g. to around 255 g/kWh for ASHP 195 g/kWh in 2030).

Given current grid intensity, lifecycle emissions are dominated by emissions from electricity generation, which account for around 95% of the total.

Figure 2.17: Range of estimates in the literature for lifecycle emissions of air source heat pumps



Source: Ricardo-AEA for CCC.
Notes: Low values are from Swiss and Norwegian studies and reflect much lower grid intensities in these countries than in the UK currently (Swiss electricty supply mix c. 50% nuclear, 36% hydro, 10% fossil and 4% renewables compared to largely fossil-based UK mix; Norwegian intensity c.18 gCO_2e/kWh compared to c. 500 g/kWh in the UK).

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[25] Energy Saving Trust (2010) Getting warmer: a field trial of heat pumps.

These estimates assume no change in the emissions intensity of electricity used for charging over the lifetime of the heat pump. However, there is scope for emissions to fall dramatically, given decarbonisation of the power sector (Figure 2.18):

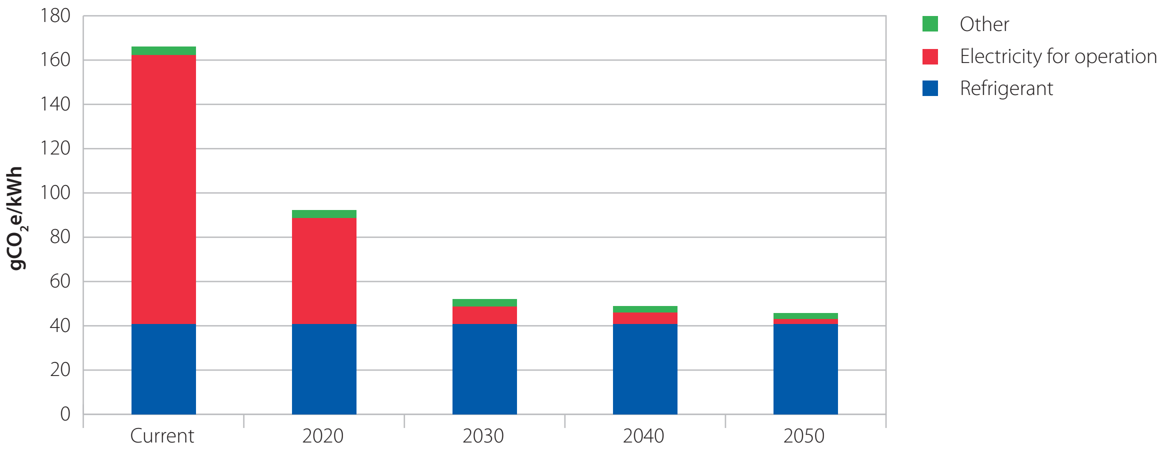
- Given falling average grid intensity over the heat pump lifetime, reaching around 50gCO_2/kWh$_e$ in 2030, emissions from air source heat pumps installed today would be reduced to around 165 g/kWh (135 g/kWh for ground source) [26].
- Emissions from heat pumps installed in 2030 would be even lower (around 50 g/kWh for air source and 45 g/kWh for ground source) as a result of further reductions in grid intensity post-2030 (e.g. to around 10 g/kWh by 2050, as set out in our International Aviation and Shipping advice[27]).

For heat pumps installed in 2030, emissions from other parts of the lifecycle become much more important:

- In particular, emissions associated with the refrigerant could account for up to 80% of the total in 2030 if HFCs continue to be used and leakage rates (during manufacture, operation and disposal) remain at current levels.
- With a switch to CO_2 or other low-GWP refrigerant, emissions could be further reduced to around 10 g/kWh for air source heat pumps (16 g/kWh for ground source) – i.e. emissions associated with heat pump materials (mainly steel), manufacture and installation.

Given the current dominance of emissions from electricity generation and HFC refrigerant leakage, most heat pump lifecycle emissions (over 95%) arise in the UK. With power sector decarbonisation and a switch to low-GWP refrigerants, the proportion of emissions arising in the UK or overseas in future will depend on the location of heat pump manufacture (mainly continental Europe for heat pumps sold in the UK at present) and associated supply chains.

Figure 2.18: Change in lifecycle emissions from air source heat pumps over time



Source: Ricardo-AEA for CCC.

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[26] The seasonal, and to a lesser extent diurnal, pattern of heat demand means that a proportion of the additional demand for electricity from heat pumps will be served by marginal generating plant. In our fourth budget advice, this was assumed to be CCGT. Applying the corresponding emissions factor trajectory would result in lifecycle emissions of around 215 g/kWh for ASHP and 170 g/kWh for GSHP installed today.

[27] http://www.theccc.org.uk/publication/international-aviation-shipping-review/

Gas boilers

Emissions from gas boilers are currently around 255 g/kWh and are dominated by combustion of gas during operation:

- Combustion emissions currently account for 90% of total emissions. Upstream emissions from gas production account for much of the remainder; emissions from the lifecycle of the boiler itself are negligible.
- The majority of emissions therefore arise in the UK.

Given the dominance of combustion emissions, there is relatively limited scope for lifecycle emissions of gas boilers to fall in future:

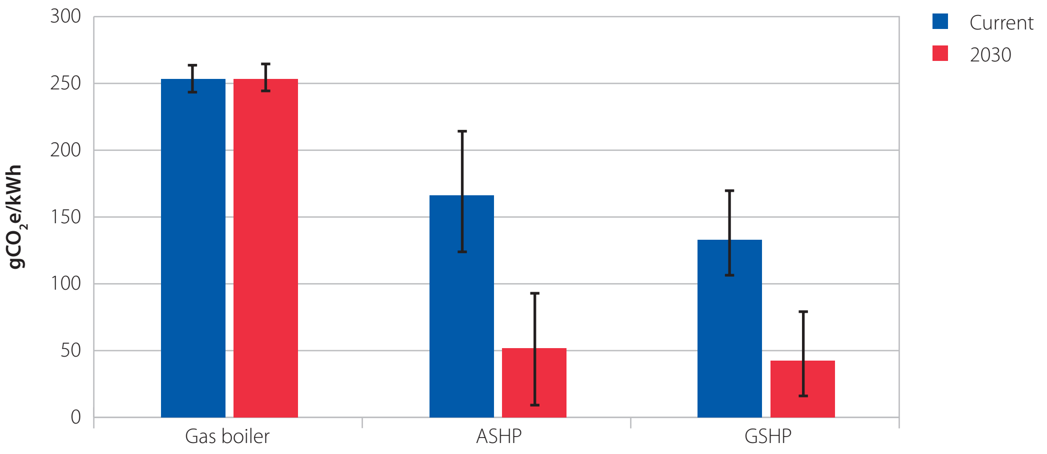
- Combustion emissions could in principle be reduced through improved boiler efficiency, but efficiencies are already very high[28].
- Emissions from gas supply could be reduced (e.g. through reduced methane leakage, energy consumption and/or carbon intensity of energy used during gas supply), although there is also a risk that emissions could increase if not properly managed (see section 3 above). However, the impact on overall boiler emissions would be relatively small.
- Similarly, reducing the carbon intensity of materials used to manufacture the boiler would be have limited impact.

Emissions from gas boilers are therefore likely to remain similar to current levels, and continue to arise in the UK.

Comparison of lifecycle emissions of residential heat technologies

Figure 2.19 compares the lifecycle emissions of different heat generating technologies. Given power sector decarbonisation in line with our scenarios for carbon budgets, heat pumps

Figure 2.19: Estimated lifecycle emissions of heat technologies deployed in the UK



Source: CCC analysis based on estimates developed by Ricardo-AEA. 'Error' bars reflect the range across sensitivities tested.

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[28] In theory use of biogas, which is counted as zero emissions at point of use under the carbon budget accounting framework, could also reduce combustion emissions. However, biomethane will only be a fraction of gas supply even in the longer term, therefore the marginal source of gas will always be fossil natural gas.

installed today could offer savings relative to gas boilers of around 35 – 50% over gas boilers over their lifetime, with savings of around 80 – 85% for heat pumps installed in 2030.

Meanwhile, as noted above, our analysis suggests that solid wall insulation saves significantly more emissions than are produced during its manufacture and installation.

We consider the extent to which lifecycle emissions have already been accounted for in our analysis for carbon budgets in section 7 below.

5. Lifecycle emissions of surface transport technologies

Direct CO_2 emissions from surface transport were 110 $MtCO_2$ in 2011. Our analysis for the fourth carbon budget envisaged a 39% reduction by 2030:

- In the near to medium term, these emissions can be reduced through improved efficiency of conventional (internal combustion engine) vehicles, some use of biofuels, as well as demand-side measures.
- In the longer term, wide-spread deployment of ultra-low carbon vehicles will be required to achieve deeper emissions cuts with minimal reliance on scarce bioenergy (see section 6 below). In our advice on the fourth carbon budget, we included a scenario in which 60% of new cars and vans are either battery electric (BEV) or plug-in hybrid (PHEV) in 2030, and there is some deployment of hydrogen fuel cell buses (as a precursor to HGVs), in preparation for a fully electric (battery or fuel cell) vehicle fleet by 2050.

Here we consider lifecycle emissions from a range of technologies, specifically petrol, plug-in hybrid petrol and battery electric cars; diesel and hydrogen fuel cell HGVs.

For all technologies, estimates in the literature typically depend on assumptions for:

- Vehicle size – affecting material requirement and associated emissions
- Vehicle efficiency (dependent on assumed technology and/or drive cycle) – affecting the amount of fuel required per km, with implications for direct and/or indirect emissions
- Lifetime activity – affecting the number of km over which embedded emissions in the vehicle (and refuelling infrastructure) are spread
- Carbon intensity of materials and energy used at each lifecycle stage
- End of life treatment (e.g. recycling)
- In addition, estimates can vary depending on the scope of the study (i.e. lifecycle stages covered), its age and location.

BEV cars

While direct emissions from BEVs are zero, emissions arise from the rest of the BEV lifecycle. This includes the vehicle itself and the electricity used for charging.

Estimates of BEV emissions in the studies reviewed range from around 70 – 220 gCO_2e/ kWh (Figure 2.20). A key factor driving this range is the assumed carbon intensity of electricity during use.

Applying the current average UK grid intensity, we estimate real-world[29] emissions for BEVs to be around 175 g/km.

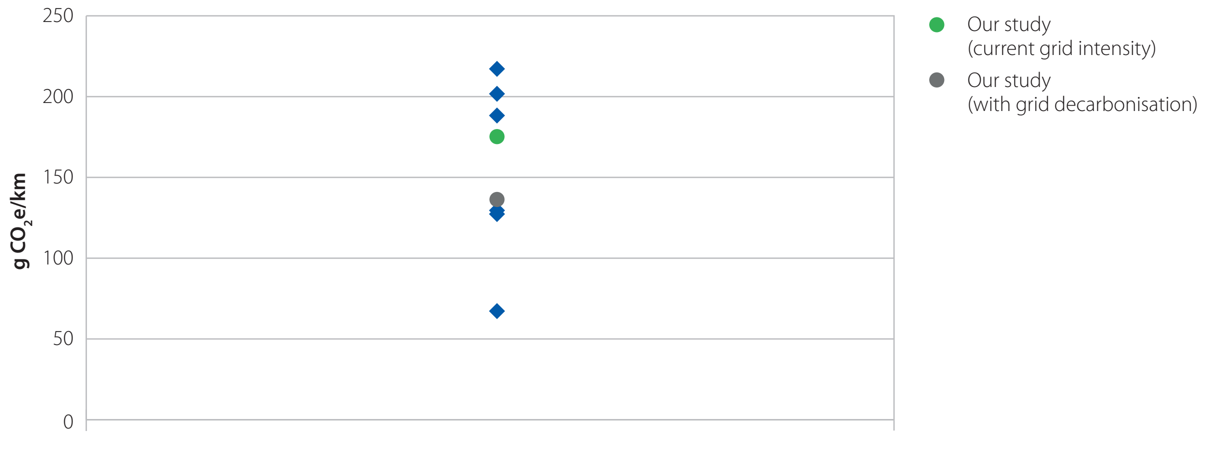
- This assumes lifetime kms for BEVs are the same as for conventional cars. In practice, BEVs are currently range-constrained compared to conventional cars and thus may have lower lifetime kms. For example, given a halving of lifetime kms, current lifecycle emissions would be around 35% higher, at around 235 g/km.
- It also assumes the battery lasts the lifetime of the vehicle. Current manufacturer warranties suggest this is the case; however should the battery need to be replaced within the vehicle lifetime both total BEV lifecycle emissions, and the share of battery production emissions within these, would be higher.

Emissions from electricity generation account for around 65% of the total, while emissions from manufacture account for around 30%, of which a significant proportion are emissions from battery manufacture. Emissions from other parts of the lifecycle, including charging infrastructure[30], each account for less than 3%.

However, there is scope for emissions to fall dramatically, particularly given decarbonisation of the power sector:

- Given our trajectory for grid intensity (reaching around 50g/kWh in 2030 and 10 g/kWh by 2050), emissions would be around 20% lower (135 g/km) for BEVs taken up today, and 60% lower (70 g/km) if the same vehicles were taken up in 2030.

Figure 2.20: Range of estimates in the literature for lifecycle emissions of BEV cars



Source: Ricardo-AEA for CCC.

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[29] i.e. based on real-world efficiency around 25% lower than test-cycle efficiency, reflect driving patterns.

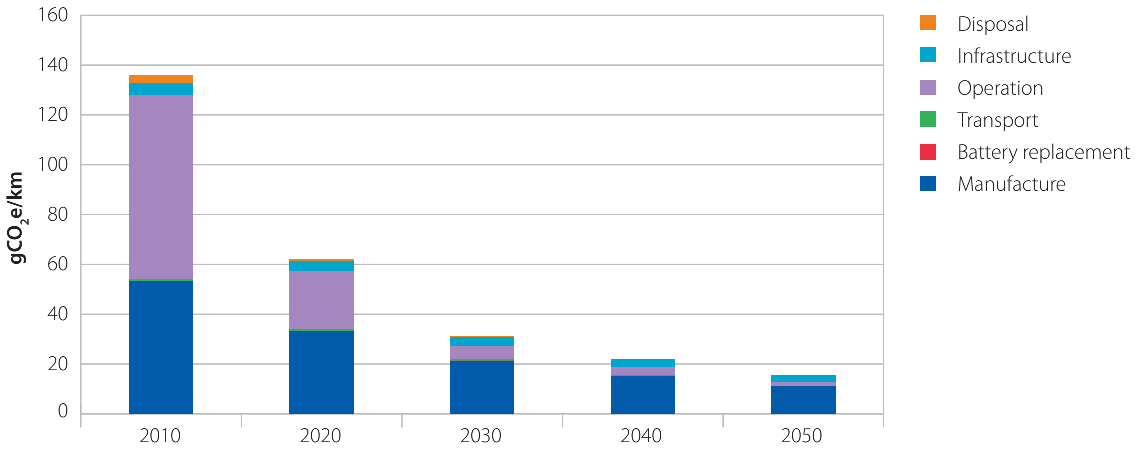
[30] Based on a mix of home (79.5%), public slow (15%) and public fast (5.5%) charging.

Emissions from other parts of the BEV lifecycle then become much more important, in particular emissions associated with the battery. However, there is significant scope for battery emissions to fall too:

- Significant improvements in battery energy densities are expected by 2030, meaning less material required for a given range. Our previous analysis for the fourth budget assumed a doubling of energy density between now and 2030.
- We estimate that around 30% of battery production emissions are associated with energy use (mainly electricity) in manufacture, and would therefore fall with power sector decarbonisation (envisaged for all regions in our base case).
- Around 70% of battery emissions are associated with materials. Battery recycling could therefore reduce battery lifecycle emissions, by avoiding emissions associated with materials extraction.
- An alternative to recycling could be to use EV batteries in 'second life' power storage applications. Further work would be needed to examine the relative emissions savings from and costs of these options (e.g. building on recent work for the Technology Strategy Board[31]).

Together with other improvements in vehicle efficiency and carbon intensity of materials and energy used in manufacture, we estimate that BEV lifecycle emissions could fall to around 30 g/km by 2030 (Figure 2.21) (20 – 60 g/km across a range of individual sensitivities tested[32]).

Figure 2.21: Change in lifecycle emissions from BEV cars over time



Source: Ricardo-AEA for CCC.

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[31] http://www.innovateuk.org/

[32] Lifetime activity, grid intensity, manufacturing location and emissions, use of recycled material, and need for battery replacement. Combining all best (worst) case assumptions *simultaneously* leads to emissions of around 15 (280) g/km; however it is unlikely that this would ensue in reality. See consultancy report for more details.

The vast majority of these emissions would be embedded emissions in the vehicles (including battery), with emissions embedded in charging infrastructure contributing a smaller share (e.g. less than 15%).

Reflecting the share of emissions from electricity generation, around two-thirds of BEV emissions are estimated to arise in the UK currently. However by 2030, if supply chain locations remain similar to today's, then the share of BEV emissions arising in the UK could fall to around a third. On the other hand if supply chains for vehicles and batteries were developed in the UK, a greater share of emissions would arise here, but with potential to minimise the size of these emissions (as result of industrial decarbonisation as well as shorter transport distances).

PHEV cars

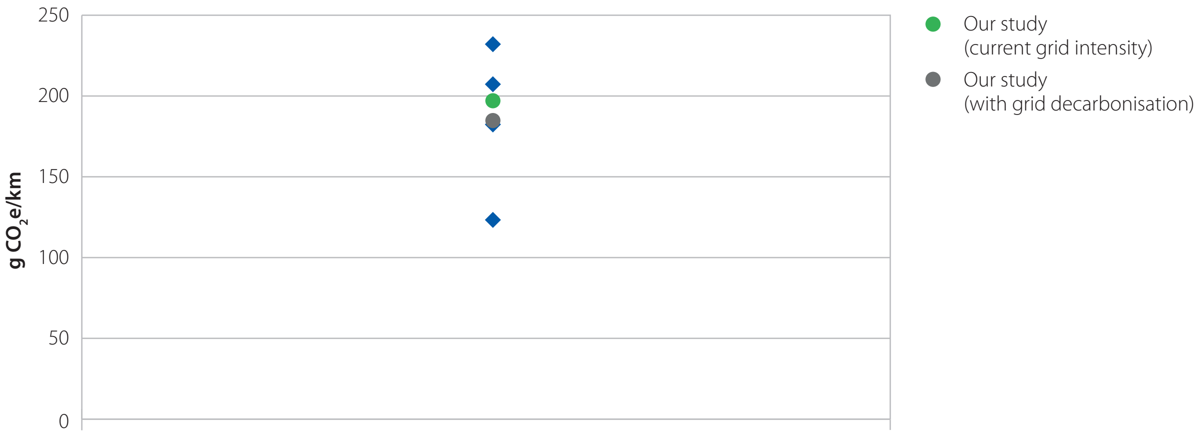
In contrast to BEVs, PHEVs produce direct emissions from combustion of fuel. Like BEVs, emissions also arise from the rest of the PHEV lifecycle including the vehicle itself and the electricity used for charging.

Estimates of PHEV emissions in the studies reviewed range from around 125 – 230 gCO_2e/kWh (Figure 2.22), given different assumptions for, in particular, carbon intensity of electricity during use and proportion of kms travelled in electric mode.

Applying current average UK grid intensity, we estimate PHEV emissions of around 195 g/km, assuming 31% of miles are travelled in electric mode (based on an electric range of 30 km).

Emissions are dominated by those relating to energy use in vehicle operation, i.e. emissions from combustion of fossil fuel used for the share of miles travelled in non-electric mode, and generation of electricity used for the remaining miles. Emissions from manufacture contribute a smaller share than for BEVs (around 15%).

Figure 2.22: Range of estimates in the literature for lifecycle emissions of PHEV cars



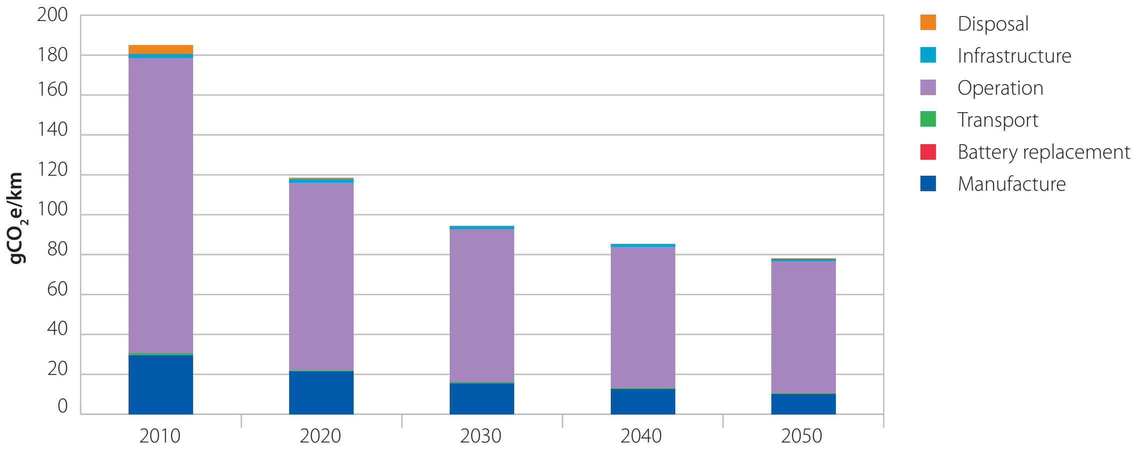
Source: Ricardo-AEA for CCC.

There is some scope for reducing combustion emissions in future (e.g. through improvements in vehicle efficiency). On the other hand, there is scope for emissions from electricity generation to fall dramatically, given power sector decarbonisation. The share of miles travelled in electric mode – already an important factor currently – then become even more important for overall lifecycle emissions:

- Given our trajectory for grid intensity, together with improvements in vehicle efficiencies and carbon-intensity of manufacture (including battery production) similar to those described for BEVs, we estimate that emissions could fall to around 95 g/km by 2030 (Figure 2.23) (85 – 110 g/km across a range of individual sensitivities tested[33]). This assumes an increase in the share of miles travelled in electric mode to 43%.
- The majority (e.g. 80%) of these emissions would be associated with the fuel used in non-electric mode. Increasing the number of miles travelled in electric mode could therefore further reduce overall PHEV emissions, notwithstanding increased emissions associated with a larger battery.
  - To increase the share of electric miles to 62%, for example, would require a doubling of the electric range of the vehicle (to around 60 km) based on current trip patterns. This would in turn require a doubling of the battery size, with a proportional increase in battery production emissions. However, these additional emissions would be more than offset by the reduction in fuel combustion emissions, reducing overall lifecycle emissions to around 70 g/km.

These estimates exclude the potential impact of increased biofuel blends on PHEV lifecycle emissions[34]. In our Bioenergy Review we identified limited scope for use of biofuels in road transport in the longer term (see section 6 below).

Figure 2.23: Change in lifecycle emissions from PHEV cars over time



Source: Ricardo-AEA for CCC.

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[33] Lifetime activity, grid intensity, manufacturing location and emissions, use of recycled material, and need for battery replacement. Combining all best (worst) case assumptions *simultaneously* leads to emissions of around 85 (170) g/km; however it is unlikely that this would ensue in reality.

[34] For the purposes of this analysis, bioethanol/petrol blends were assumed to remain at the levels assumed in the Defra/DECC 2012 GHG conversion factors for company reporting, i.e. 3.1% by volume.

Given the current dominance of operational emissions, most PHEV lifecycle emissions (e.g. around 85%) are estimated to arise in the UK. This could continue to be the case for PHEVs deployed in 2030: operational emissions will fall given power sector decarbonisation, but so too will emissions from vehicle manufacture (largely outside of the UK). In practice, the share of UK emissions will largely depend on the share of miles travelled in electric mode (hence operational emissions), as well as supply chains for vehicles and batteries.

Conventional cars

Estimates for lifecycle emissions from conventional cars in the studies reviewed ranged from around 165 – 330 g/km (Figure 2.24).

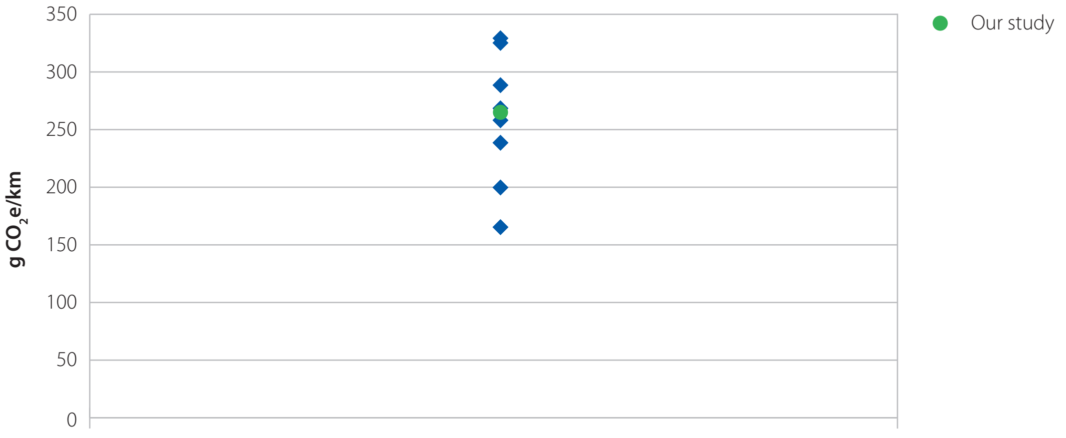
For a medium sized petrol car sold recently in the UK, with real-world tailpipe emissions of 190 g/km[35], we estimate that other parts of the lifecycle could add around 75 g/km, bringing total lifecycle emissions to around 265 g/km.

Emissions from combustion of fuel during operation therefore account for around 70% of the total. Upstream emissions from fuel production account for around a further 15%, with emissions from vehicle manufacture accounting for much of the remainder.

Combustion (i.e. tailpipe) emissions of conventional cars are expected to fall in future, largely driven by EU targets:

- In our analysis for the fourth budget we assumed that test cycle tailpipe emissions for an average conventional new car would fall to around 110 g/km (on a test-cycle basis) by 2020 and 80 g/km by 2030, through a range of measures including through increased hybridisation, downsizing of engines with turbocharging and use of advanced light weight materials.

Figure 2.24: Range of estimates in the literature for lifecycle emissions of petrol cars



Source: Ricardo-AEA for CCC.

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[35] Corresponding to test-cycle efficiency of 160 g/km. Estimates are for a car sold in 2010, as this is the year our technical data for all vehicle technologies relate to. However, average tailpipe emissions of new cars have fallen by around 8% between 2010 and 2012. Assuming the same reduction for medium sized petrol cars specifically, and holding embedded emissions in the vehicle (which are a small share of the total) constant, our estimate of total lifecycle emissions would fall to around 250 g/km for a car sold in 2012.

Our analysis assumes that upstream emissions from petrol production remain constant over time; in practice there may be scope for these emissions to fall (e.g. through process improvements in refineries), but also a risk that they rise as high oil prices drive development of more costly and energy-intensive reserves (e.g. tar sands). Further work would be needed to explore this.

Changes in emissions from other parts of the lifecycle can be expected too, but these will have a more limited impact on overall g/km:

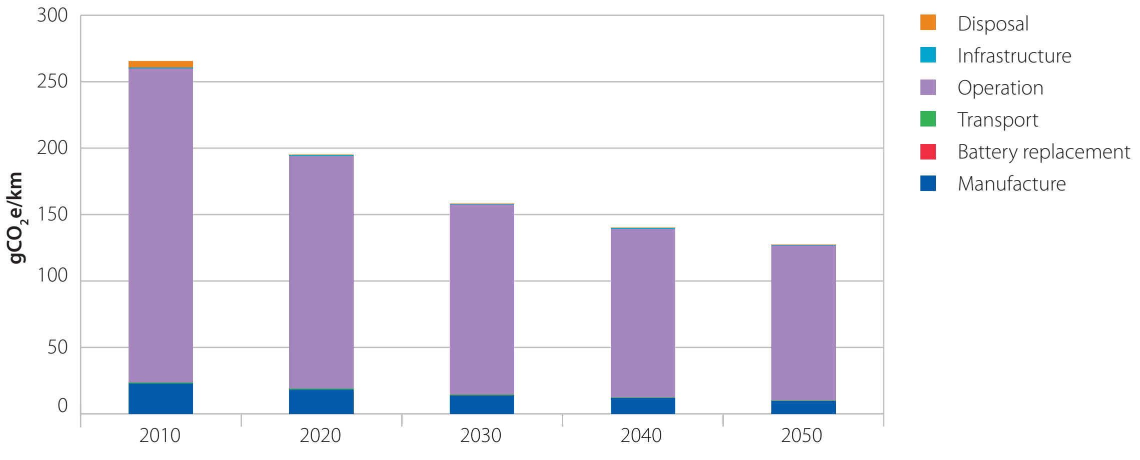
- Measures to reduce tailpipe emissions could imply changes to emissions from manufacture. For example, light-weighting will require less use of steel and greater use of materials such as aluminium and carbon fibre reinforced polymer, with implications for embedded emissions in the vehicle.
- There will be changes in embedded emissions even where the same materials continue to be used, given falling carbon intensity of materials production processes (e.g. due to energy efficiency and/or fuel switching), and of energy used in vehicle manufacture.
- However, the impact on overall lifecycle emissions will be limited as embedded emissions account for a relatively small share of the total.

We estimate that emissions of conventional cars deployed in 2030 could be around 160 g/km (150 – 195 across a range of individual sensitivities tested[36]) (Figure 2.25). Combustion emissions will continue to account for the majority of the total.

Note that, as for PHEVs, these estimates exclude the potential impact of increased biofuel blends on lifecycle emissions.

Given the dominance of combustion emissions, around 90% of emissions are estimated to arise in the UK currently and will continue to do so for vehicles deployed in 2030.

Figure 2.25: Change in lifecycle emissions from petrol cars over time



Source: Ricardo-AEA for CCC.

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[36] Lifetime activity, manufacturing location and emissions, and use of recycled material Combining all best (worst) case assumptions ***simultaneously*** leads to emissions of around 150 (195) g/km; however it is unlikely that this would ensue in reality.

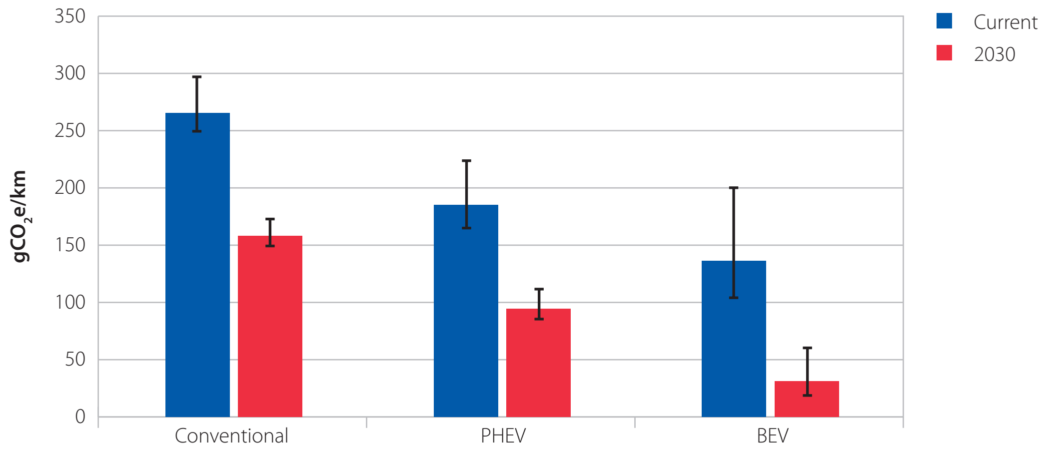
Comparison of lifecycle emissions of car technologies

Figure 2.26 compares the lifecycle emissions of different car technologies. Given power sector decarbonisation in line with our scenarios for carbon budgets, BEVs taken up today could offer savings relative to conventional cars of around 50% over their lifetime, with savings of around 80% in 2030 (PHEVs offer savings of around 30% currently and 40% in 2030).

Electric cars are associated with higher 'upfront' emissions than conventional cars but significantly lower operating emissions, given use with low-carbon electricity. Our analysis suggests a 'payback distance'[37] of around 37,000 kms for BEVs taken up today (16,000 kms for PHEVs) and 14,000 kms for BEVs taken up in 2030 (7,000 kms for PHEVs)[38].

We consider the extent to which lifecycle emissions have been accounted for in our analysis for carbon budgets in section 7 below.

Figure 2.26: Estimated lifecycle emissions of car technologies deployed in the UK



Source: Ricardo-AEA for CCC. 'Error' bars reflect the range across sensitivities tested.

Hydrogen fuel cell HGVs

While direct emissions from hydrogen fuel cell HGVs are zero, emissions arise from the rest of their lifecycle. This includes the lifecycle of the vehicle itself and the hydrogen fuel used.

We could find no studies in the literature on emissions from hydrogen fuel cell HGVs, but drew on information for conventional HGVs, and for hydrogen fuel cell cars, to produce our own indicative estimates.

Our analysis suggests that the emissions intensity of hydrogen is the most important determining factor in the lifecycle emissions of hydrogen fuel cell HGVs, with scope for reductions in future (Figure 2.27):

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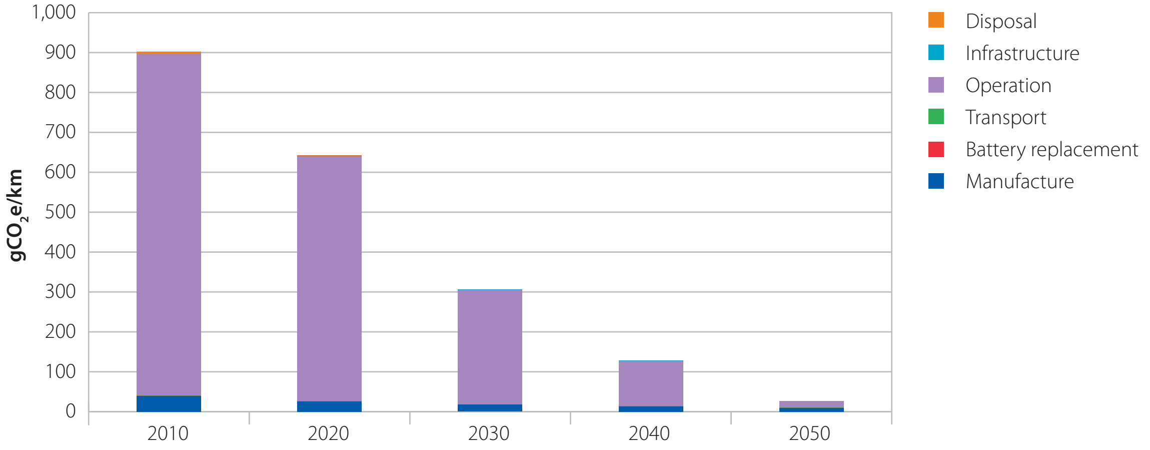
[37] i.e. the number of km after which the higher upfront emissions are offset by the cumulative emission savings during operation.

[38] NB shorter payback distances do not imply greater lifetime savings.

Figure 2.27: Change in lifecycle emissions from hydrogen fuel cell HGVs over time



Source: Ricardo-AEA for CCC.

- Hydrogen produced via steam methane reforming (i.e. current practice), has an emissions intensity of around 460 g/kWh. Emissions of hydrogen fuel cell HGVs using liquid hydrogen from this route could be around 900 – 1150 g/vehicle-km, with the vast majority (around 95%) coming from hydrogen production.
- However, with a move to low-carbon production such as CCS or electrolysis using low-carbon electricity, there is scope for the emissions intensity of hydrogen to fall significantly in future (e.g. to around 260 g/kWh in 2030 and 15 g/kWh in 2050[39]). As a result, emissions of a hydrogen fuel cell HGV deployed in 2030 could fall to around 300 – 590 g/v-km.

Even with 50% low-carbon hydrogen production by 2030, operational emissions could continue to dominate overall g/v-km of hydrogen fuel cell HGVs:

- Embedded emissions in the vehicle itself, and also the hydrogen refuelling infrastructure[40], could account for a relatively small share (e.g. 5%) for vehicles deployed in 2030. Not until 2045 (with 75% low-carbon hydrogen production, rising to 100% by 2050) might emissions from other parts of the lifecycle become significant (e.g. more than 20%) on a per km basis.
- This reflects the high lifetime activity of an HGV, which means that embedded emissions are spread over a very large number of km, and that operational emissions will be continue to dominate until the emissions intensity of hydrogen is at very low levels (e.g. less than 50 g/kWh on average on the vehicle lifetime).

Given the dominance of operational emissions, the majority of lifecycle emissions from hydrogen fuel cell HGVs would arise in the UK.

The ranges above reflect a number of uncertainties, including around the performance of hydrogen fuel cell HGVs, which are currently at a relatively early stage of development:

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[39] Based on 50% production via electrolysis by 2030, and 100% by 2050, combined with our trajectory for power sector decarbonisation.

[40] Based on preliminary analysis. Further work on hydrogen refuelling infrastructure would be needed to confirm this.

- The efficiency of the vehicle (along with the emissions intensity of hydrogen) is a key driver of emissions: a 25% reduction in efficiency could lead to a broadly proportional increase in g/v-km for vehicles deployed in 2030 given the continued dominance of operational emissions.

In addition, the lower energy density of liquid hydrogen means more space will be required for fuel storage thus reducing payloads relative to conventional HGVs. Lifecycle emissions savings on a g/tonne-km basis would thus be lower than savings on a g/vehicle-km basis (discussed below). However, our analysis suggests that by 2050 these savings would still be significant, given the lower fuel-cycle emissions of hydrogen from low-carbon routes.

Further work on hydrogen fuel cell HGVs would be beneficial.

Conventional HGVs

For an articulated HGV sold in the UK today, with tailpipe emissions of around 1015 g/v-km, we estimate that other parts of the lifecycle could add around 260 g/km, bringing total lifecycle emissions to around 1275 g/v-km.

Emissions from combustion of fuel during operation therefore account for around 80% of the total. Upstream emissions from fuel production account for around a further 18%, with emissions from vehicle manufacture accounting for around 2%.

There is scope for combustion (i.e. tailpipe) emissions of conventional HGVs to fall in future, through measures including improved powertrain efficiency, lower rolling resistance and better aerodynamics. Our most recent analysis suggests that conventional new HGV tailpipe emissions could fall by around 15% by 2020 and a third by 2030.

As for conventional cars:

- Our analysis assumes that emissions from fuel production remain constant over time; further work would be needed to explore potential changes in different parts of the fuel supply chain.
- Changes in emissions from other parts of the lifecycle (e.g. embedded emissions in the vehicles) will have a limited impact on overall lifecycle emissions given their small share in the total.

We estimate that emissions of conventional HGVs deployed in 2030 could be around 855 g/v-km (845 – 870 g/v-km across a range of individual sensitivities tested[41]) (Figure 2.28). Combustion emissions will continue to account for the majority of the total.

Given the dominance of combustion emissions, most lifecycle of emissions of conventional HGVs are estimated to arise in the UK currently and will continue to do so.

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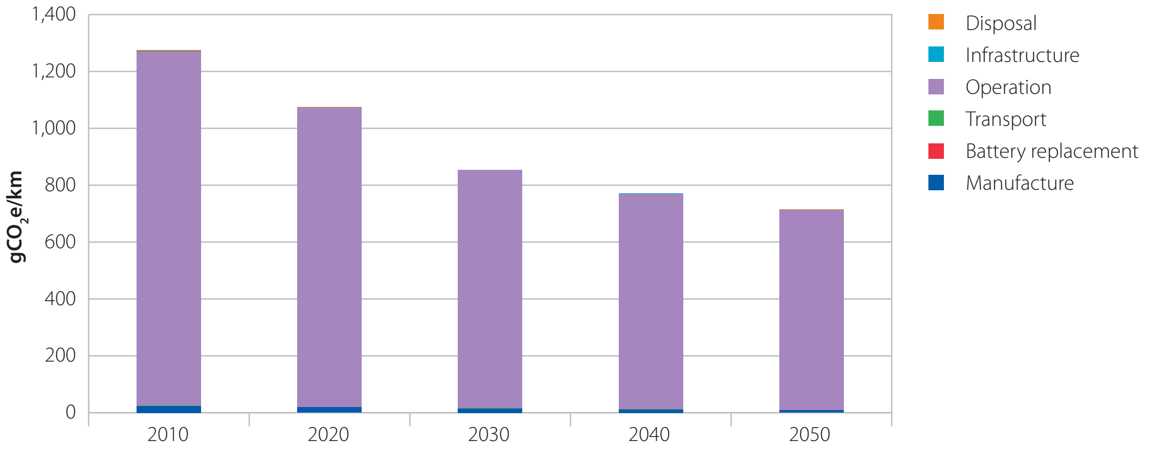
[41] Lifetime activity, manufacturing location and emissions, and use of recycled material. Combining all best (worst) case assumptions *simultaneously* leads to emissions of around 845 (905) g/v-km.

Figure 2.28: Change in lifecycle emissions from conventional HGVs over time



Source: Ricardo-AEA for CCC.

Note that, as for conventional (and PHEV) cars, these estimates exclude the potential impact of increased biofuel blends on lifecycle emissions[42]. They also exclude the potential use of natural gas as a fuel for HGVs:

- In terms of embedded emissions in the vehicle, estimates for HGVs running on natural gas are likely to be broadly similar to those for diesel HGVs.
- Emissions related to the fuel cycle would be different: combustion emissions of gas are over 20% lower than diesel, although lower vehicle efficiencies and potentially higher emissions from gas supply could partly offset this saving.
- A study for the Low Carbon Vehicle Partnership[43] estimated well-to-wheel emissions savings of up to around 15% compared to diesel vehicles[44]. However, while this suggests a potentially useful role for natural gas HGVs in the near term, greater savings could be achieved in the longer term via hydrogen fuel cell HGVs with low-carbon hydrogen production.

Total lifecycle emissions from key low-carbon HGV technologies

Figure 2.29 compares the lifecycle emissions of different HGV technologies deployed in 2030 and 2050. Hydrogen fuel cell HGVs could offer savings of around 30 – 65% over conventional HGVs in 2030 and up to 97% in 2050.

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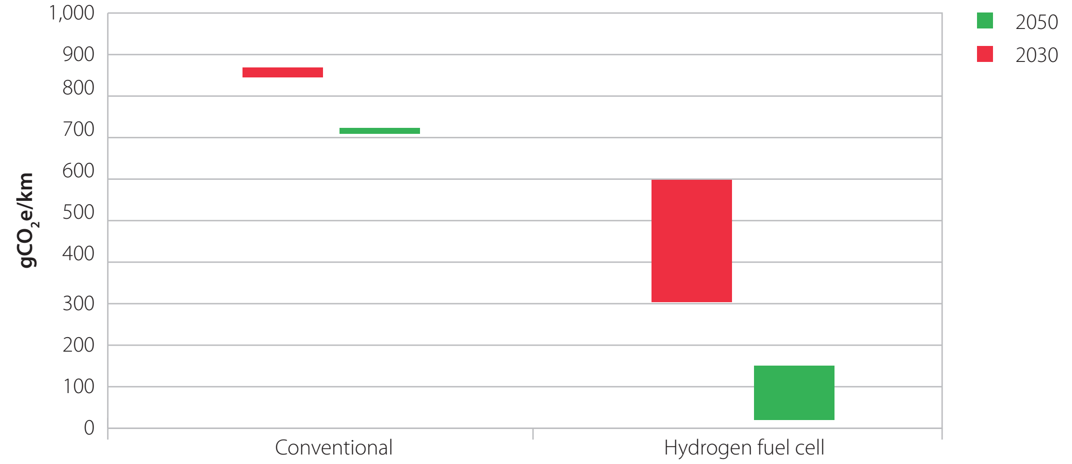
[42] For the purposes of this analysis, biodiesel/diesel blends were assumed to remain at the levels assumed in the Defra/DECC 2012 GHG conversion factors for company reporting, i.e. 3.5% by volume.

[43] Ricardo-AEA (2012) Opportunities to overcome the barriers to uptake of low emission technologies for each commercial vehicle duty cycle

[44] Use of biomethane from wastes could further reduce fuel cycle emissions. However, biomethane will only be a fraction of gas supply even in the longer term, therefore the marginal source of gas will always be fossil natural gas.

Figure 2.29: Estimated lifecycle emissions of HGV technologies deployed in the UK



Source: Ricardo-AEA for CCC.

6. Lifecycle emissions of bioenergy

Bioenergy currently meets around 2% of UK energy demand. In our 2011 Bioenergy Review[45] we assumed that this could increase to around 10% of primary energy demand in 2050. This would be through using bioenergy to generate heat for industry and – if CCS is available – using it in power generation and/or to produce hydrogen. Without CCS, aviation biofuels are likely to be a better option.

Whilst bioenergy could in principle be zero carbon, as carbon is absorbed in the growth phase of feedstocks and released when these are combusted, in practice this is not the case. This reflects lifecycle emissions associated with cultivation, processing and transportation of biomass feedstocks and products, and emissions linked to possible direct and indirect changes in land use. These can be significant and some feedstocks exceed the emissions of fossil fuels:

- GHG savings for different liquid biofuels range widely. In the best case (e.g. when made from waste or growing a dedicated energy crop on previously degraded land), savings can be 80% or more compared to fossil fuels, while in the worst cases lifecycle emissions are actually higher than for petrol or diesel.
- Emissions associated with indirect land-use change (i.e. when a bioenergy crop displaces another crop which is then grown on newly converted land) can erode savings significantly but are difficult to calculate. Modelling for the European Commission suggests that nearly half of the potential gains of switching from fossil fuels to biofuels vanish due to indirect land-use emissions, with some feedstocks (soybean and rapeseed) even increasing emissions compared to fossil fuels.

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[45] http://www.theccc.org.uk/publication/bioenergy-review/

- For forest biomass (used in power and heat), there is also a large variation in lifecycle emissions between feedstocks, with waste feedstocks and thinnings from managed or neglected woodlands offering emissions savings of more than 60% compared to natural gas, while biomass from whole trees (which would be best used for timber, e.g. in construction, Box 2.5) or old-growth forests risks emissions higher than those from gas. Indirect land-use change and its associated emissions is also a potential problem if feedstock production causes deforestation elsewhere.
- In general, there is a high level of uncertainty about the lifecycle emissions associated with different feedstocks.
- In our Bioenergy Review, we assumed that in the future low-lifecycle emission feedstocks would be available provided feedstock production was restricted to degraded or abandoned agricultural land, sustainable forestry, agricultural residues, and the use of wastes.

The current accounting framework for carbon budgets reflects lifecycle emissions only for domestically-produced bioenergy feedstocks. Combustion emissions are counted as zero and emissions embedded in imported feedstocks are not considered, although they are reflected in government support mechanisms for biofuel and biomass:

- **Biomass** for use in power will have to meet sustainability criteria from October 2013 under proposals currently under consideration by the Government. In order to qualify for support under the Renewables Obligation:
  - Feedstock has to meet a maximum carbon emissions limit of between 240 gCO_2/kWh (new and existing dedicated biomass plants) and 285 gCO_2/kWh (converted coal plants). Potentially, this will be reduced to 200 and 240 gCO_2/kWh respectively by 2020.
  - In addition, solid wood fuel would have to meet the UK Government's public procurement policy for wood (i.e. being certified under a scheme such as the Forest Stewardship Council).
  - We wrote to the Secretary of State in November 2012 urging that a 200 gCO_2/kWh standard should be set from 2020 for all plant.
- **Biofuels** have to conform to the carbon and sustainability criteria of the EU Renewable Energy Directive (RED):
  - Biofuels must achieve at least a 35% GHG emissions saving compared to petrol/diesel, increasing to at least 50% from 1 January 2017, and 60% from 1 January 2018 for biofuels produced in installations which started production on or after 1 January 2017.
  - Additionally, biofuel may not be made from raw material obtained from land with high carbon stock or land that was undrained peatland.

- The EU Commission published proposals in December 2012 to address indirect land-use change. This would limit the role of food-based biofuels to current levels (5% of transport fuel mix) and require the reporting of indirect land-use factors. However, as proposed these factors would not be used for measuring compliance with the RED carbon and sustainability criteria.

It is important that the role of bioenergy in low-carbon strategy reflects realistic estimates of total lifecycle emissions for different types of feedstock. We concluded in the Bioenergy Review that EU and UK regulatory approaches should be strengthened, in particular in relation to indirect land-use change emissions.

Box 2.5: Use of wood in the construction sector

In the construction sector, there is the potential to use wood products to replace concrete, steel and bricks, for example in building structures and cladding. If wood is used in construction, the carbon is stored in the buildings, making it preferable to burning the wood and releasing this carbon as CO_2 back into the atmosphere.

Notwithstanding the potential for existing construction materials to reduce their emissions intensity (e.g. through CCS in the cement sector), the use of woody biomass in construction is still likely to be a preferred low-carbon option given that it generates negative emissions through a very efficient form of carbon capture.

However, further work is required to compare options on a full lifecycle basis. For example, emissions associated with transport of wood to construction sites and maintenance during use would have to be included. This was beyond the scope of the present study which focused on energy options.

7. Implications of lifecycle emissions for meeting carbon budgets and for UK carbon footprint

Using our base case estimates, we estimate that total lifecycle emissions from deployment of the key low-carbon technologies in our scenarios for meeting carbon budgets are around 260 $MtCO_2e$ over the period to 2030, of which around 40% are energy-related operational emissions and around 60% arise in the UK[46].

- Lifecycle emissions from low-carbon power generation technologies are estimated to be around 90 $MtCO_2e$ over the period to 2030, of which around 30% are operational emissions (i.e. combustion emissions from fossil fuel generation with CCS), and around 60% arise in the UK.

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[46] Note these estimates are for actual emissions arising during the period to 2030: they include all embedded emissions from technologies deployed, and use actual operational emissions factors (e.g. grid intensity) for the years in question. The g/kWh (or g/km) estimates presented in the previous sections are 'levelised' over technology lifetimes, i.e. they allocate embedded emissions over lifetime outputs, and use average operational emissions factors over lifetimes.

- Lifecycle emissions from low-carbon residential heat technologies are estimated to be around 45 $MtCO_2e$ over the period to 2030, of which around 40% are operational emissions, and around 80% arise in the UK[47].
- Lifecycle emissions from low-carbon transport technologies are estimated to be around 125 $MtCO_2e$ over the period to 2030, of which around 45% are operational emissions, and around 55% arise in the UK.

It is important to understand whether these emissions have already been accounted for in our modelling. If they had not, then extra abatement would be required to meet the carbon budgets and emissions targets that we have recommended.

Our modelling of both UK and global emissions has already substantially allowed for lifecycle emissions of low-carbon technologies:

- Our UK modelling to 2030 and 2050 explicitly includes energy-related operational emissions from all technologies, including residual combustion emissions from CCS. Additional emissions, arising in the UK, from key-low carbon technologies are around 55 $MtCO_2e$ over the period to 2030 (around 0.5% of allowed emissions under carbon budgets[48]).
- Our modelling also includes ongoing industry emissions. While these are not explicitly linked to the demand for industrial products (e.g. steel and cement) created by deployment of different technologies, the additional demand in a low-carbon vs. reference scenario is small compared to total projected output (e.g. <5%).
- The global models used in our analysis (e.g. TIAM[49]) also include energy-related operational emissions from all technologies as well as emissions from industrial sectors producing both materials and fuels. As these emissions are based on exogenous demand assumptions, this may lead to underestimates in some sectors (e.g. nuclear fuel supply) relative to an estimate explicitly linked to technology deployment; however these are likely to be offset by overestimates in other sectors (e.g. refineries).

Therefore we can be confident that no additional abatement is required to meet carbon budgets and emissions targets as long as lifecycle emissions are reduced from current levels, and with CCS applied to fossil fuel power generation used as part of a portfolio approach alongside other low-carbon technologies with lower lifecycle emissions.

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[47] This estimate does not reflect the diversity of building types which exist and would in practice affect emissions of heat technologies; however it provides a sense of the order of emissions involved.

[48] Excluding international aviation and shipping, and assuming a 2030 target of a 50% reduction in emissions on 1990 levels.

[49] See http://archive.theccc.org.uk/aws/IA&S/UCL%20(2012)%20Modelling%20carbon%20price%20impacts%20of%20global%20energy%20scenarios.pdf

8. Policies for reducing lifecycle emissions

We have shown that most low-carbon options, with the exception of CCS, already have very low lifecycle emissions and they can be expected to reduce further over time, as the UK and other countries take action to decarbonise the power sector and take other measures to reduce emissions in industry (including fuel supply sectors).

There are a number of policies which will or could provide incentives for reduction of lifecycle emissions:

- **CCS**. Demonstration of CCS is important to verify and improve technology performance at commercial scale. It is important that both residual combustion emissions and fuel supply emissions are minimised, through optimised capture rate and minimised energy penalty. However, lifecycle emissions of CCS are likely to remain high relative to other low-carbon power technologies. This suggests CCS should only be used as part of a portfolio approach (i.e. together with nuclear and renewables).
- **Shale gas**. The Environment Agency is the environmental regulator for unconventional gas operations in England and Wales. Similar to landfill permitting, their permitting regulations for shale gas exploration require use or flaring of methane emissions from fracking (which can be interpreted as a waste under the Mining Waste Directive). Additional requirements (e.g. for fenceline monitoring) could further help to ensure fugitive methane emissions from shale gas exploration in the UK are minimised, especially when scale up from exploration to commercial production is considered.
- **Heat pumps.** Leakage of HFC refrigerants during use and end of life is covered by the existing EU F-Gas Regulation. Beyond this, the EC is considering options to further reduce F-gas emissions in future including both a phase-down mechanism and an outright ban for placing F-gases on the market in sectors where appropriate alternatives are available. Use of CO_2 or other low-GWP refrigerant in heat pumps could be considered one such alternative and Government should support this where cost-effective.
- **Vehicles.** Support for R&D and for EVs more generally will help drive improvements in battery energy density, reducing the size of battery required for a given range. Battery recycling is mandated under the European Waste Battery and Accumulator Directive; however requirements for material recovery (50% for the Lithium-ion batteries used in EVs) are not based on emissions considerations and current recycling practices tend not to recover the materials which would offer greatest benefit for lifecycle emissions. In future, improved recycling efficiency and use of less energy-intensive recycling processes (e.g. closed-loop recycling) could further reduce the lifecycle emissions of EV batteries, and measures to incentivise this should be supported.

- **Bioenergy.** Policies should incentivise the development and use of low-lifecycle feedstocks, e.g. through progressively tightening the greenhouse gas thresholds for the support of biomass under the Renewables Obligation (in our Bioenergy Review we recommended 200 gCO_2/kWh, compared to the current threshold of 285 gCO_2/kWh). Consideration should also be given to introducing a sustainability standard for all wood to avoid indirect deforestation.

More generally, our analysis highlights the need for an economy-wide approach to emissions reduction in order that lifecycle emissions are reduced. It also emphasises the need for a comprehensive policy framework to cover emissions arising in both the UK and abroad. A global deal to reduce emissions would be the most effective means for achieving this. Meanwhile, many lifecycle emissions of low-carbon technologies will be covered by UK carbon budgets and/or the EU ETS, while others (e.g. those arising outside of the EU) would require additional policies (e.g. sectoral agreements, see Chapter 3) to ensure they are minimised.

With supporting policies and economy-wide approaches in place, the fourth carbon budget and means we have recommended to meet it remain appropriate in light of our assessment of lifecycle emissions.

Chapter 3: Options for addressing the UK's carbon footprint

As we have shown in chapter 1, overall consumption emissions are currently high but these can be expected to decrease over time provided a global climate deal can be agreed. Some lifecycle emissions from low-carbon technologies (chapter 2) would also reduce as a result of action in response to a global deal. In addition, other measures focused on supply chains and consumer behaviour can help achieve emission reductions.

In this chapter, we consider a range of international and domestic options to reduce consumption and lifecycle emissions. In addition, we assess the implications of consumption emission trends for carbon budgets and emissions monitoring.

Our key messages are:

- Production emissions remain the most appropriate basis for carbon budgets, as (i) they account for more than half of the UK's carbon footprint and (ii) consumption accounting is uncertain and impractical. However, it is important for the government to continue monitoring consumption emissions to inform policy.
- There is a need for a global deal to substantially cut global emissions over the next decades and achieve the climate objective. A consequence of this would be that the UK's carbon footprint would fall. The UK government should continue to play a leading role in reaching an international agreement.
- Support for developing countries to implement mitigation and adaptation measures through international climate finance is an important aspect of the emerging global deal, and can contribute to reducing carbon intensities in the UK's trading partners.
- Sectoral agreements can play a supporting role in a global deal; border carbon adjustments are not an alternative to a global deal but should not be ruled out as a possible transitional measure.
- Policies to encourage resource efficiency and sustainable consumption (e.g. business carbon footprinting to reduce supply chain emissions, consumer information provision, regulation, and measures to promote reuse and recycling) could help to reduce our carbon footprint.

Carbon budgets and consumption emission monitoring

It remains appropriate to account for carbon budgets on the basis of production emissions given accounting conventions and available policy levers:

- Moving to a consumption-based accounting methodology would be disruptive and impractical given international accounting conventions (which are based on territorial emissions and aim to avoid double counting) and uncertainties over consumption emissions.

- Production emissions account for more than half of the UK's carbon footprint and we have the levers to reduce them; there is less scope for reduction of imported emissions through UK levers.

However, consumption emissions should be monitored to check whether these are falling in line with global action required to achieve the climate objective, or whether further action is required. If monitoring of consumption emissions were to reveal that these are falling too slowly, this would suggest the need for further action. We will report periodically on consumption emissions as part of our broader reporting to Parliament on progress reducing emissions.

As we discussed in chapter 2, consumption emission estimates are highly uncertain, due to data and methodology issues. The Government therefore asked us to consider the merits of a two-stage approach for monitoring consumption emissions (i.e. to supplement input-output data with lifecycle analysis data for specific product groups). However, as with input-output based consumption-emissions estimates, there are data and methodology limitations associated with lifecycle analysis (see chapter 2). Furthermore, lifecycle emission databases are only updated on an ad hoc basis, which would make regular monitoring of specific products difficult. We therefore recommend that the Government continues to base its consumption estimates on input-output analysis. It should support further improvements to UK and international consumption emission datasets.

Lifecycle analysis for specific products is however very useful for identifying carbon 'hotspots' in supply chains and can help businesses reduce their emissions (see section 2).

International measures

Global deal to reduce emissions

The key to meeting the climate objective is to get agreement on a strong global deal. This would ensure that all nations implement effective policies to reduce their carbon intensities, which would also result in lower embedded emissions in their exports (and hence the UK's imports). This should reflect production-based accounting. Moving to a consumption accounting basis would be unnecessary and difficult to implement:

- If all nations make commitments under a global deal and fully account for their territorial emissions, there is no need to further account for consumption emissions, given that these emissions will already have been covered (with some countries likely to continue as net emission exporters, while others will be net importers).
- It is important that all countries follow the same accounting approach so that all emissions are covered and none are double counted.
- Individual countries have policy levers to reduce production emissions, but less scope to reduce imported emissions, short of introducing border carbon adjustments (see below).

- There is substantial uncertainty in consumption data and it is not feasible to produce robust and up-to-date annual estimates, as would be required under a global deal with mandatory targets.
- Introducing a new accounting basis into the on-going negotiations on the global deal would create unnecessary complications.

There are also a number of polices and measures which could support the implementation of a global deal.

International climate finance

Support for developing countries to implement mitigation and adaptation measures is an important aspect of the emerging global deal. Low-carbon power and industrial energy efficiency projects are priority areas for international climate finance and such projects can contribute to reducing carbon intensities in the UK's trading partners:

- Developing world trading partners have higher emission intensities of production than the UK (e.g. in Asia, the average emission intensity of industry is 44% higher than in the UK, with Chinese industry having an emission intensity 65% higher than the UK's).
- Emissions embedded in the UK's import of goods from developing countries have risen over the past two decades (e.g. embedded emissions from China more than doubled between 1993 and 2010).
- There is some scope for reducing these high emission intensities through the targeted use of international climate funding (e.g. through investment in manufacturing industry energy efficiency measures or renewable energy, or technology transfer).

Currently, the UK's climate finance is mainly channelled through the International Climate Fund[1] (ICF) with smaller bilateral contributions made through the Department for International Development:

- The Climate Investment Funds (CIFs), and within these the Clean Technology Fund (CTF), are the largest recipient of UK climate finance. The ICF also contributes to the Global Environment Facility (GEF).
- Most of the mitigation finance available through the CTF and GEF is spent on renewable energy projects or energy efficiency measures (primarily electricity and industrial processes) in a number of rapidly developing economies such as India, Thailand, Malaysia and Indonesia (all of which also have high carbon intensities).

Since 2008, the UK has been the largest contributor (around £1.5 billion) to international climate finance and has some leveraging power. Globally, climate finance is a source of substantial funding for developing and emerging economies. However, the impact on production emissions in these countries, and through this on UK consumption emissions, is limited:

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[1] The Department for International Development, DECC, and Defra contribute to this fund, and have pledged to disburse £2.9 billion (for mitigation and adaptation) between April 2011 and March 2015.

- Publicly funded climate finance to developing countries amounts to $14-21 billion annually. This compares with investments of $524 billion in non-OECD countries, estimated by the IEA as necessary to be on track to a 2°C scenario.
- While additional private finance is needed, there are specific barriers to uptake of energy efficiency or renewable energy investments in recipient countries (e.g. projects are considered as highly complex by financiers, high upfront costs for renewables are difficult to finance, and small-scale energy efficiency projects have high transaction costs).
- Climate finance reflects global commitments on a wide set of objectives. Thus funds cannot be specifically targeted to schemes which will reduce UK (or any developed country) consumption emissions.

Therefore, the most important aspect of climate finance is its key role in securing a global deal, with the added benefit (especially if there is sufficient private and domestic leverage of funds) of achieving some emission reductions in key recipient countries. The UK Government should continue to play a leading role in international climate finance.

Sectoral agreements

Sectoral agreements can refer to a wide range of possible measures, including:

- Multilateral agreements between governments to regulate emissions from a sector
- Unified product/efficiency standards for sectors or technologies across countries
- Co-operation on research or deployment of technologies
- Industry initiatives to reduce emissions

There are numerous examples of sectoral agreements in practice (Box 3.1).

Sectoral agreements could be linked over time to support a global deal. For example, a system of sector cap and trade schemes could become part of a global carbon market.

Box 3.1: Sectoral agreements in practice

A range of sectoral agreements and policies can be found, reflecting a mix of regulatory and voluntary approaches at international, regional and national levels:

- **International aviation and shipping**. The Kyoto Protocol delegated regulation of international aviation and shipping emissions to the International Civil Aviation Organisation (ICAO), and the International Maritime Organisation (IMO). The IMO has recently agreed a global energy efficiency standard for new ships (the Energy Efficiency Design Index). The ICAO has agreed an aspirational fuel efficiency improvement of 2% per year, with carbon neutral growth from 2020.
- **EU ETS sector benchmarks**. In the EU ETS, industrial operators are granted free allowances up to a level of emissions consistent with the average greenhouse gas emission performance of the 10% best performing installations in the EU producing that product. This therefore gives incentives to adopt more efficient technologies.
- **Cars**. The EU has agreed emission standards for new cars, and these apply to all Member States. Other countries have adopted stretching new car fuel efficiency targets with similar implied reductions to the EU (e.g. CAFE standards in the US).
- **Industry energy efficiency**. In the UK, many industries have Climate Change Agreements. These include negotiated targets between industry sectors and government, with a 90% discount on the Climate Change Levy for participating sectors. The latest targets have been set out to 2023.

In principle, sectoral agreements can address consumption emissions by setting a common framework across regions and firms, and therefore giving incentives to reduce emissions in all covered countries. To the extent that the UK consumes goods from countries covered by such agreements, UK consumption emissions would be reduced.

However, the effectiveness of any agreement would depend on overcoming a number of barriers:

- The difficulties of reaching multilateral agreement between countries and/or industries
- Incentives to enter into binding sectoral agreements on a voluntary basis are likely to be weak
- The need for avoiding product substitution to other sectors which are not covered by an agreement

Although it is possible that these barriers could be overcome, it is unlikely that sectoral agreements would have extensive coverage. Therefore, these could support the implementation of a global deal, as part of which incentives to enter into sectoral agreements could be strengthened, but not substitute for it.

Border carbon adjustments

Border carbon adjustments aim to create a level playing field by adjusting for carbon costs embodied in trade (e.g. through a carbon tax on imports, or the purchase of emission allowances by importers).

This would ensure all consumption – both domestic and imported – is covered by a carbon price. It would give incentives to reduce emissions to consumers (by discouraging consumption of relatively carbon intense goods) and to foreign firms (where they are not covered by a carbon price domestically).

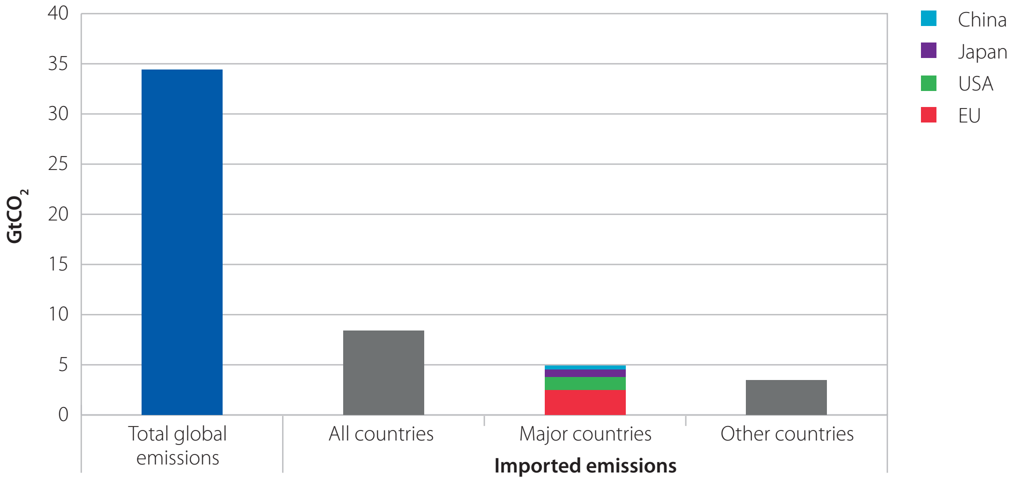
Border carbon adjustments could be imposed unilaterally by countries, by blocs of countries (e.g. the EU) or by all countries as part of a global deal to levelise carbon costs.

While, in principle, border carbon adjustments can address consumption emissions, in practice there are likely to be challenges regarding design and implementation:

- **Legality**. While border carbon adjustments already exist for some taxes (e.g. VAT), and it may be feasible to design a scheme which could comply with WTO trade rules, a clear answer on the legality of border carbon adjustments is unlikely until a test case is brought.
- **Geopolitical implications.** Border carbon adjustments are politically contentious – as shown by the inclusion of aviation emissions in the EU ETS (this involved the regulation of aviation emissions outside EU territory) – and may be seen as an illegal barrier to trade. In addition, it is not clear what impact they would have if implemented outside the UNFCCC negotiation process.
- **Measurement of embodied carbon**. Border carbon adjustments should reflect the embodied carbon in imported products, but this is difficult to measure accurately.
- **Coverage**. Ideally all internationally traded goods would be covered in order to send correct signals to consumers and foreign producers. However, this could impose significant informational and administrative burdens on regulators, particularly around measurement.

In addition, given limited potential coverage (e.g. traded emissions account for less than 25% of global emissions, Figure 3.1), together with the need for other policies in addition to a carbon price, border carbon adjustments are not an alternative to a global deal.

Figure 3.1: Coverage of traded emissions compared to global emissions (2010)



Source: Eora (2013).
Notes: Traded emissions shown on an import basis for country breakdown. On an export basis the total traded emissions are the same (since imports and exports are equal at the global level) but country breakdown differs in line with trade patterns. Figures are for CO_2 only.

Border carbon adjustments could be useful as a possible transitional measure and, while they should not be ruled out, a cautious approach is appropriate. For example, if border carbon adjustments were introduced, this should be with the support of blocs of countries rather than unilaterally, and in light of a full analysis of possible trade impacts and associated costs.

Domestic measures

A number of drivers can explain the UK's rising carbon footprint (see chapter 1). These include rising incomes which increased demand for manufactured goods (e.g. for electronic goods and textiles). As a result of globalisation, these are now mostly produced elsewhere, often in countries where the emissions intensity of manufacturing is higher than in the UK. In addition to a global deal, a range of domestic supply and demand-side abatement options could play a role, carried out at the company (i.e. supply chain) level or as a result of individual consumer choices. Many of these can be implemented in the short-term and thus already achieve some results in reducing emissions while negotiations for a global deal are on-going:

- Supply-side options include various resource efficiency measures (Box 3.2)
- Demand-side options include informed choices by consumers about the goods and services they buy and how to use them (Box 3.3)

Box 3.2: Supply-side options

A wide variety of measures are potentially available:

- **Material reduction.** Businesses can reduce material inputs into production processes through 'right-weighting' or designing lighter and leaner products. For example under various corporate voluntary responsibility deals, the amount of materials used in retail packaging in the UK has been reduced by 35% (in weight terms). There are other opportunities for material reduction, including the use of high strength steel in construction of building foundations, vehicles, and long span bridges.[2] There are additional opportunities for reducing the use of raw materials in packaging, structural metal products, electrical products, household goods such as furniture, and transport vehicles.[3]
- **Material substitution.** Carbon-intensive materials such as steel and cement can be substituted with more sustainable materials such as wood in construction. In our 2011 Bioenergy Review we noted that the use of wood in the construction industry is not common in the UK but is widespread in other countries. For example, in Finland 84% of the housing stock is built from wood. Wood is also a carbon store, therefore reducing emissions relative to burning of biofuels.
- **Waste reduction in supply chain processes.** Reductions in waste at the production stage will reduce material requirements. The UK consumes 680 million tonnes of material per year, of which half ends up as waste. Of this waste, 25% is commercial and industrial waste, which has a high embodied carbon impact. Although some waste is unavoidable, there are potential opportunities to reduce materials wastage along the supply chain.

Box 3.2: Supply-side options

- **Diversion of waste from landfill towards material recovery.** Under the EU Landfill Directive and the UK landfill tax, 33% of waste generated in the UK is diverted from landfill towards recycling and other materials recovery. Working with businesses to increase the recyclable contents of products/packaging can help increase recycling rates, as can targets for businesses and households (or material specific landfill restrictions). The increased recycling of inert materials such as metal and glass will reduce upstream emissions while the recycling of biodegradable materials such as paper/card and textiles will prevent upstream emissions as well as avoid methane emissions arising from decomposition in landfills.
- **Lifetime optimisation.** This includes both a supply-side and a demand-side aspect. On the supply side, products can be designed to last longer or be more easily repaired. On the demand-side, changes of attitude may be needed as at present products such as clothes or personal electronics can become prematurely obsolete due to peer pressure/fashion and the availability of newer products.

Box 3.3: Demand-side options

- **Reducing food waste.** Half of the food thrown away by UK households is still edible. When discarded food is landfilled it biodegrades in the absence of oxygen and produces methane, a greenhouse gas 20 times as potent as CO_2. WRAP's Love Food Hate Waste campaign has encouraged reductions in household waste (e.g. by 1 Mt between 2007 and 2011) and the landfill tax has encouraged composting and/or treatment of food waste via anaerobic digestion.
- **Dietary change.** Dietary change away from carbon intensive food such as meat and dairy could improve overall health in the UK and would reduce methane emissions that arise from livestock production (meat and dairy account for less than 25% of weekly average food intake but generate nearly 60% of food related GHG emissions). Current UK diets are on average higher than the Department of Health's recommended calorific intake and high in meat, dairy, fat and sugary foods while low in fruit and vegetable intake.
- **Shift from goods to services.** Changing use patterns from ownership of goods towards services (e.g. through shared ownership of cars) can increase the resource productivity of a given product. For example, as shown in chapter 3, lifecycle emissions of electric vehicles (i.e. mainly those associated with batteries) per km travelled are lower if total lifetime km travelled are higher. The rising popularity of car clubs in recent years demonstrates that there is already growing consumer demand for such shared ownership.
- **Lifetime optimisation.** See Box 3.2.
- **Public sector procurement efficiency.** Government can lead by example through reducing emissions in its procurement of goods and services.

Delivery of these abatement options will require actions from businesses and individuals, with a role for government in encouraging voluntary engagement and, in some cases, regulating and setting standards. In the next section, we focus on scope for product regulation at EU level, and discuss business approaches to carbon footprinting, as well as options for consumer engagement.

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[2] Yagi, K. and Halada, K. (2001) Materials development for a sustainable society, Materials and Design, 22, 143-146.

[3] Raw materials include wood, pulp and paper, plastics and synthetic resins, rubber, glass, ceramics, cement, lime and plaster, iron and steel and non-ferrous materials.

Supply-side options

1. Regulation

There is scope under the EU Ecodesign Directive to regulate the lifecycle emissions of products. Currently, the Directive applies only to energy-related products and has been almost exclusively applied to in-use energy consumption (i.e. resulting in the setting of energy efficiency standards). In a few cases, other lifecycle aspects have been addressed (e.g. refrigerants).

A 2012 evaluation of the Ecodesign Directive for the European Commission[4] considered the feasibility of extending the Directive to non-energy using products, focusing on a number of products that have a high savings potential (e.g. textiles, food and cars). It concluded that an extension of the Ecodesign Directive would be premature:

- Given that only very few energy-using products have been covered so far, priority and resources should focus on extending the coverage of the existing Directive.
- For many non-energy related products, the most significant environmental impacts occur in the early lifecycle stages and methodologies to identify and set the relevant requirements are either missing or at an experimental stage.
- Enforcement would be difficult (e.g. for textiles, due to the international character of the supply chain and a large number of small producers).

While it makes sense at present to focus the implementation of the Directive on the energy efficiency of energy-using products, in the future (i.e. once electricity use becomes less significant in the lifecycle through electricity sector decarbonisation) it could become a useful tool for addressing the carbon emissions of other (non-use) lifecycle stages for some key products.

Several EU Directives (Waste from Electrical and Electronic Equipment Directive, Battery Directive and the End-of-Life Vehicles Directive) set requirements for the collection, recycling and re-use of key products. While not specifically focused on reducing carbon emissions, the promotion of re-use, recycling and more efficient design (i.e. by encouraging lower material use to reduce the need for collection and recycling) will reduce carbon at different stages of the lifecycle chain.

The EU is the most appropriate level for regulating product standards and the UK Government should actively promote improvements to these Directives, so that they are used to their maximum benefit for reducing consumption emissions.

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[4] http://ec.europa.eu/enterprise/policies/sustainable-business/ecodesign/review/index_en.htm

2. Voluntary measures by business

Carbon footprinting

In this context, carbon footprint refers to the total GHG emissions caused directly and indirectly by an organisation, business, event or product:

- Organisational carbon footprints refer to the measurement of emissions from all the activities across an organisation, including buildings' energy use, industrial processes and company vehicles.
- Value chain carbon footprints refer to the measurement of emissions occurring inside and outside an organisation's own operations, meaning emissions from both suppliers and consumers, including use and end-of-life emissions.
- Product carbon footprints refer to the measurement of the emissions arising over the whole life of a product or service, starting from the extraction of raw materials and manufacturing up until its use and final reuse, recycling/disposal. Product carbon footprints are produced by using lifecycle analysis (see chapter 2).

Carbon footprinting gives firms a better understanding where the actual sources of emissions lie. It has been taken up by many UK companies, using the PAS 2050 framework methodology for product carbon footprinting provided by the British Standards Institution (see chapter 2). The Carbon Trust (one of the UK's main carbon footprinting organisation) has awarded its Carbon Trust Standard (based on PAS 2050) to approximately 200 UK companies since 2010, and certifying the carbon footprint of around 25,000 products sold in the UK. Product carbon footprinting can both reduce emissions and bring wider benefits (e.g. cost savings):

- According to the Carbon Trust, footprinting frequently leads to reductions of 20-50% of product-level emissions.
- Lifecycle analysis allowed Coca Cola Enterprises to identify the significance of carbon emissions associated with their packaging, and that switching to recycled plastics could cut emissions by up to 60% and also save costs.
- Comparing footprints of similar products delivered by different supply chains can help firms shape their sourcing decisions. For example, supermarket chain Asda decided to sell bananas from the Canary Islands after comparing footprints, thus reducing transport emissions by around 80%.
- Footprinting can reinforce relationships with suppliers, incentivising them to share best practice within a sector (e.g. Tesco's online hub for suppliers to share their experience in reducing their carbon footprint) and helping them identify cost saving opportunities up the supply chain.
- Product footprinting can also link to carbon labelling (see below), thus offering potential for consumer engagement.

However, while footprinting can assist companies in their carbon reduction strategies, it is resource-intensive and complex. As a result, some businesses (e.g. Tesco and Marks & Spencer) have scaled-down their footprinting ambitions. (Box 3.4).

Box 3.4: Costs and complexities of carbon footprinting

Footprinting costs: Costs are particularly significant for small and medium-sized enterprises without in-house capacity. Access to LCA datasets, hire of consultant and third part verification of LCAs can all be expensive (e.g. according to the OECD, data costs are commonly in the order of $3,500-15,000 but can be up to $70,000 for complex products, plus verification costs of $1,000-6,000 for on-site audits). The EU is supporting a free lifecycle database to help reduce some of these costs.

Abatement costs: Questions can arise over who should pay for the costs of the improvements; suppliers may be reluctant to incur the upfront investment that would lower the carbon footprint of their activities.

Data quality: The further the investigation along the supply chain, the less reliable the data can be. Default values are used when actual data is not available, which is likely to be the case for suppliers in developing countries. This could potentially represent a problem for firms that have several suppliers in developing countries (the default data could be much higher than the actual data).

Standardisation: While the protocols developed for carbon footprinting offer guidance on how to develop transparent lifecycle measures for products, they are not detailed enough to provide a standard sector-specific approach (e.g. boundary issues, sensitivity to changes in parameters, and difficulty in measuring land use change emissions). Businesses can also play a vital role by working with government to help make the 'rules' consistent and effective.

In summary, carbon footprinting can be effective in helping businesses to reduce emissions within their control and use their influence in the value chain. These activities should be encouraged by the Government as part of its sustainable consumption and production strategy. Footprinting can also help businesses to influence consumer behaviour by removing the worst-offending products from their shelves and by promoting lower-carbon options. We discuss these further below.

Demand-side options

Consumer engagement

Consumers can play an important role in cutting consumption emissions, through choosing lower-carbon alternatives where available and through cutting consumption more generally (e.g. by using products for longer). Extensive research by the Government and other groups on encouraging sustainable behaviour has identified that demand-side options are most effective when used as part of a package of complementary measures (Box 3.5). Potential measures include:

- **Carbon taxes.** Reflecting the carbon content of different products in prices would provide a strong signal about the full costs (resource and carbon) of consumer decisions. However, any additional consumer taxes are likely to be politically sensitive. Carbon taxes would also need to reflect overlap with emissions trading which similarly prices carbon.

- **Influencing choice.** Governments and/or businesses can influence the choices made by consumers by banning or voluntarily removing products that have high carbon intensities and by offering and/or incentivising those with lower carbon intensities (e.g. the EU has banned incandescent lightbulbs and B&Q decided in 2008 to stop selling patio heaters because of their high carbon emissions).
- **Communication.** Communicating low-carbon choices to influence behaviour is complex. Labelling is one option which has been successfully applied in the case of energy labels for appliances and cars. However, these work hand-in-hand with minimum standards, thus making an effective 'package' as described above. Businesses have also experimented with carbon labelling but there is limited evidence about its effectiveness and most labelling programmes have been scaled back (Box 3.6). However, while widespread carbon labelling is unlikely to be very efficient, there may be a benefit in labelling the carbon footprint of a targeted range of products where lower-carbon alternatives are available (e.g. timber instead of aluminium windows).

Box 3.5: Promoting sustainable behaviour – evidence on effective interventions

In 2011, the Department for Environment, Food and Rural Affairs produced a framework for sustainable lifestyles[6] which identified best practice to influence behaviour and provided key insights on why some people act. The findings include:

- An integrated package of measures, including both policy and communications tools, is most effective.
- Different approaches and packages are effective for different population groups.
- What others are doing is key.
- 'What's in it for me' is important.
- Understanding the science of climate change is less important to people than being given the skills and feeling capable of making a difference.

In 2013, the Scottish Government published results from its climate change behaviour research programme[7] which suggest that:

- Leading by example by key players remains a critical starting point for developing new social norms around sustainable lifestyles
- Any 'behaviour change' intervention is most likely to be successful when it works in an integrated way (i.e. programmes that bring together individual, social and material elements to create new and lasting social norms).
- There are genuine opportunities for influencing behaviour via 'moments of change' (i.e. major life events such as having a child). Engagement with these has to date been limited.
- There is a need to test out behavioural thinking in a systematic way in order to help drive more sustainable lifestyles.

In response, the Scottish Government's long-term strategy will work beyond the individual to look at broader social and infrastructural contexts, be based on leadership and values-based engagement, and make change as easy as it can be. It is also commissioning a series of projects to test out innovative ideas for influencing behaviours.

A House of Lords Science and Technology Sub-Committee's report on behaviour change[8] found that non-regulatory measures ('nudges') used in isolation are less likely to be effective and concluded that it is important to consider the whole range of possible interventions (regulatory and non-regulatory) when policy interventions are designed.

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[5] http://archive.defra.gov.uk/environment/economy/documents/sustainable-life-framework.pdf

[6] http://www.scotland.gov.uk/Resource/0041/00413385.pdf

[7] http://www.publications.parliament.uk/pa/ld201012/ldselect/ldsctech/179/179.pdf

Box 3.6: Experience with carbon labelling

Tesco committed in 2007 to labelling all its own-branded products but has since significantly scaled down the labelling programme, after finding labelling very complex, time-consuming and expensive. However, Tesco still has a target of finding ways to help their customers reduce their own carbon footprints by 50% by 2020. Marks and Spencer has switched from labelling to carbon footprinting focussing on supply chain 'hotspots'. Some of the issues encountered in the early labelling experience were:

- Limited consumer understanding relative to other labels such as nutritional Guideline Daily Amounts. Carbon footprint is a more abstract concept (e.g. 75 gCO_2 in a 35 g bag of crisps) and there is no 'allowance' to put it in context.
- Consumers have different sustainability concerns (e.g. ethical sourcing, climate change, excessive packaging) and their priorities will change in response to media stories, NGO campaigns and other factors such as the wider economy. Furthermore, price is still a strong driver of consumer choice
- Anecdotal evidence showing an increasing 'anti-label-feeling' and cynicism about 'greenwash'.

Even where consumers switch to lower carbon products, the impact on emissions may be limited:

- 32 years' worth of daily purchases of 'lower carbon' Tesco orange juice corresponds to avoiding one return flight from the UK to Spain
- Rebound effects: the purchase of low-carbon products could give people a sense of licence to increase carbon emissions through other activities.
- The use phase can be extremely significant; therefore there is a need for more than just a carbon footprint label to reduce effectively consumption emissions.
- Nevertheless, there is still some evidence that carbon labelling could influence consumer decisions. A Carbon Trust survey from 2011 suggested that more than a fifth (21%) of consumers would pay more for brands that label their products with the carbon impact and 47% are more likely to choose low-carbon labelled goods over non-labelled.
- A study for the EU Commission[9] indicated that a label similar to the energy label with a letter scale and a traffic light system (i.e. A/green is best) works best with consumers. It also found that consumers have different expectations for different product groups (e.g. for some products like electronics they understood issues around energy use and cost, whereas for others like cleaning products, concerns around toxicity were better understood), which suggests that carbon labels are best focused on carbon-intensive products.

Consumer engagement clearly has a role to play in reducing consumption and lifecycle emissions but there are no easy ways to achieve significant behaviour change. As discussed, packages of measures are likely to be needed and Governments, businesses and other stakeholders need to work together to find the most effective interventions.

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[8] European Commission – DG Environment (2012) Study on different options for communicating environmental information for products. http://ec.europa.eu/environment/eussd/pdf/footprint/ProductsCommunication_Final%20Report.pdf

Glossary

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

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

Border carbon adjustment
Policy to create a level playing field for trade by putting a price on imported emissions and/or refunding carbon costs to exporters.

Carbon accounting
The process undertaken to measure and make an inventory of the amount of greenhouse gases emitted.

Carbon budget
The Climate Change Act established a system of five-yearly carbon budgets, currently stretching to 2023-27. They restrict the amount of carbon that can be emitted in the UK during these five year periods.

Carbon capture and storage (CCS)
Set of technologies to capture the carbon dioxide emitted from industrial processes or from burning fossil fuels or biomass, transport it, and store it in secure spaces such as geological formations, including old oil and gas fields and aquifers under the seabed.

Carbon dioxide equivalent (CO_2e) emission
The mass 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 mixture of greenhouse gas emissions.

Carbon footprint
Total amount of greenhouse gas emissions caused directly and indirectly by a nation (equivalent to consumption emissions), a business, a product (equivalent to lifecycle emissions) or a person.

Carbon-intense
Activities or goods that have a high emissions intensity (see below).

Carbon intensity
See 'emissions intensity'.

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.

Climate Change Levy (CCL)
CCL is a tax on the supply of specified energy products (e.g. electricity and gas) for use as fuels that is for lighting, heating and power by business consumers.

Climate objective
To keep central estimates of global mean temperatures as close to 2°C as possible, and to limit the likelihood of temperature change above 4°C to very low levels.

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.

Competitiveness
The ability of firms to sell and increase market share and profitability in international markets.

Consumption emissions
Production emissions minus emissions embedded in export of goods and services, plus emissions embedded in imports of goods and services.

Contracts for Difference (CfD)
Form of hedging on the future price of a commodity in which a strike price is pre-specified. Payments are made between counterparties depending on the difference between the strike price and the market price at the time.

Conventional gas
Natural gas from conventional reserves.

Direct emissions
Emissions from sources that are owned or controlled by the installation.

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.

Electro-intensive
In this report, taken to be a sector or firm where electricity costs are around 10% or more of gross value added.

Emissions intensity
A measure of total emissions generated per unit of activity. In consumption emissions accounting, typically defined as total emissions per unit of monetary output.

Energy-intensive
In this report, taken to be a sector or firm where energy costs are around 10% or more of gross value added.

European Commission
Executive arm of the European Union.

European Union Allowances (EUAs)
Emissions credits traded within the EU ETS.

European Union Emissions Trading System (EU ETS)
Cap and trade system within the EU covering the power sector, energy intensive industry, and from the start of 2012 all domestic and international aviation.

Feed in Tariff
A type of support scheme for electricity generators, whereby generators obtain a long-term guaranteed price for the output they generate.

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
Emissions of gases from pressurised equipment due to leaks, e.g. from gas wells or gas pipelines.

Heat pumps
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. Both air source and ground source heat pumps can provide heating for buildings.

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 e.g. Toyota Prius.

Gross Domestic Product (GDP)
Key indicator of the output of the whole UK economy including taxes and subsidies, such that: GDP = GVA + taxes on products – subsidies on products.

Gross Value Added (GVA)
Measure of the contribution to the economy of each individual producer, industry or sector.

Indirect emissions
Emissions that are a consequence of the activities of the installation or firm but occur at sources owned or controlled by another entity.

Input-output analysis
An economic technique that records the flows of goods and services using the transaction values between industrial sectors and nations. Methodological basis for estimating consumption-based emissions.

Joule
The standard international unit of energy. Related units are: Kilojoule (kJ) = 1000 Joules, Megajoule (MJ) = 1 million Joules, and Gigajoule (GJ) = 1 billion Joules.

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 Terawatt-hour (TWh) = 1,000 GWh. The kilowatt-hour is equal to 3.6 million Joules.

Lifecycle analysis
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).

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

Liquefied natural gas (LNG)
Natural gas cooled to a low temperature so it becomes a liquid occupying a much smaller volume (1/600), which can then be transported over long distances without the need for fixed infrastructure.

LULUCF emissions
Emissions occurring in the land use, land use change and forestry sector with croplands the single largest source of emissions. Emissions in this sector are offset by carbon sequestered by forestry and grasslands.

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 (1 tonne of methane emission 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.

Mitigation
Action to reduce the sources (or enhance the sinks) of factors causing climate change, such as greenhouse gases.

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

Nitrous oxide (N_2O)
Greenhouse gas with a global warming potential of 310 (1 tonne of nitrous oxide emission 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).

Offshoring
The relocation of a firm's business or processes to a foreign country.

Pass-through rate
The extent to which a rise in firms' costs are passed on to higher product prices.

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).

Production emissions
Territorial emissions plus emissions from international aviation and shipping on the basis of bunker fuels.

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.

Shale gas
A type of unconventional gas, extracted using hydraulic fracturing ('fracking') i.e. the pumping of fracturing fluids (water, chemicals and proppants) at high pressure to crack open the rock and release the gas trapped inside.

Standard Industrial Classification (SIC)
System for categorising economic activities in the UK by type of activity. At the highest level there are 21 classifications (A-U), for example Manufacturing (C). These sections are further broken down into divisions, groups, classes and subclasses which are represented in a two-five digit hierarchy.

Territorial emissions
Greenhouse gas emissions occurring within a country's borders e.g. from burning fossil fuels for electricity generation, in transport and industrial production, direct emissions from heating in households and businesses, as well as emissions related to a number of other activities such as agricultural, forestry, and waste management activities.

Trade intensity
(Imports+exports)/(output+imports).

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.

2DS scenario
Global emissions trajectories developed by the International Energy Agency in its 2012 Energy Technology Perspectives to meet a global 2°C climate objective (see 'Climate objective').

4DS scenario
Global emissions trajectories to 2050 developed by the International Energy Agency it its 2012 Energy Technology Perspectives reflecting a world where international actions would not go beyond the pledges made at the United Nations Climate Change Conference at Copenhagen in 2009. This scenario is projected by the International Energy Agency (IEA) to lead to a long-term temperature rise of 4°C.

Abbreviations

AD	Anaerobic Digestion
ASHP	Air source heat pumps
BEV	Battery electric vehicle
CCC	Committee on Climate Change
CCGT	Combined cycle gas turbine
CCL	Climate Change Levy
CCS	Carbon capture and storage
CH_4	Methane
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
DECC	Department for Energy and Climate Change
Defra	Department for Environment, Food and Rural Affairs
EC	European Commission
EPR	Environmental Permitting Regulations
EU	European Union
EU ETS	European Union Emissions Trading System
EUA	European Union Allowance
EV	Electrical vehicle
GDP	Gross Domestic Product
GHG	Greenhouse gas
GSHP	Ground source heat pumps
Gt	Giga tonnes
GVA	Gross value added
GWP	Global warming potential
HFC	Hydrochlorofluorocarbons
HGV	Heavy goods vehicle

ICE	Internal combustion engine
IEA	International Energy Agency
kWh	Kilowatt hour
LNG	Liquefied natural gas
LULUCF	Land use, land use change and forestry
MACC	Marginal abatement cost curve
MJ	Million Joules
MRIO	Multi-region input-output
Mt	Million tonnes
N_2O	Nitrous oxide
NAEI	National Atmospheric Emissions Inventory
OECD	Organisation for Economic Cooperation and Development
ONS	Office for National Statistics
PHEV	Plug-in hybrid electric vehicle
PV	Photovoltaic
ROW	Rest of the world
2DS	Two degrees scenario
4DS	Four degrees scenario

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