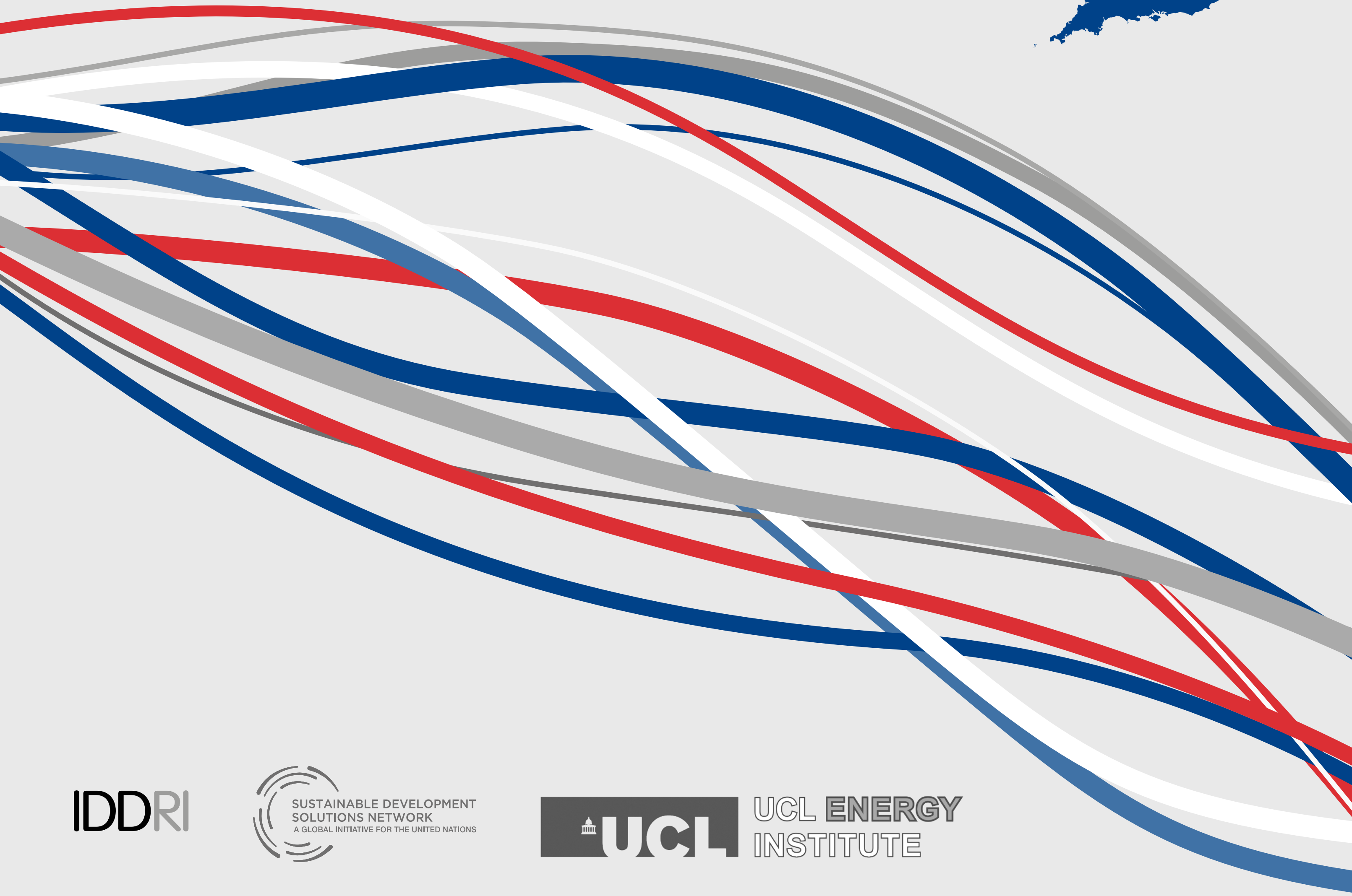
UK 2015 Report

pathways to
deep decarbonization
in the United Kingdom



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Deep Decarbonization Pathways Project

The Deep Decarbonization Pathways Project (DDPP), an initiative of the Sustainable Development Solutions Network (SDSN) and the Institute for Sustainable Development and International Relations (IDDRI), aims to demonstrate how countries can transform their energy systems by 2050 in order to achieve a low-carbon economy and significantly reduce the global risk of catastrophic climate change. Built upon a rigorous accounting of national circumstances, the DDPP defines transparent pathways supporting the decarbonization of energy systems while respecting the specifics of national political economy and the fulfillment of domestic development priorities. The project currently comprises 16 Country Research Teams, composed of leading research institutions from countries representing about 70% of global GHG emissions and at very different stages of development. These 16 countries are: Australia, Brazil, Canada, China, France, Germany, India, Indonesia, Italy, Japan, Mexico, Russia, South Africa, South Korea, the United Kingdom, and the United States.

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The Sustainable Development Solutions Network (SDSN) was commissioned by UN Secretary-General Ban Ki-moon to mobilize scientific and technical expertise from academia, civil society, and the private sector to support of practical problem solving for sustainable development at local, national, and global scales. The SDSN operates national and regional networks of knowledge institutions, solution-focused thematic groups, and is building SDSNedu, an online university for sustainable development.

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pathways to **deep decarbonization** in the United Kingdom

Executive summary

2015 is a critical year for making progress on international efforts to combat climate change, with the next major summit, COP21 in Paris, a key event for moving the agenda forward. The window of opportunity for ensuring we have any reasonable chance of limiting global temperature rise to no more than 2°C is rapidly closing. What is urgently needed is both near term political action to ensure that we get on a sustainable pathway, and a longer term outlook that provides a vision of how to transform energy systems to being low-carbon.

The Deep Decarbonization Pathways Project (DDPP) is an important initiative that seeks to demonstrate how major emitting countries can transform their energy systems, to deliver long term, sustainable emission reductions. Crucially, the pathways are for individual countries, operationalising the types of action required now, over the next 15 years, and in the long term, out to 2050.

This is the UK country report under DDPP, setting out some of the domestic opportunities and challenges in ensuring deep decarbonisation, and the role the UK can play in helping lead efforts to combat climate change internationally. The UK has been a leader in legislating long-term climate mitigation targets and crucially setting a binding institutional and reporting framework to ensure that a series of 5-year carbon budgets are adhered to. In summary, this report seeks to demonstrate, alongside other countries, that a 2°C target could be achievable, and still remains an important political goal to aim for at the coming climate talks in Paris.

Over the last 10 years a coordinated modelling effort for the UK Government has established that significant emissions reductions in the UK energy system are achievable, based on the mix of technologies that is available or that will soon be commercial, and that the costs of such a transition is manageable. Analysis also suggests that this transition affords the UK an opportunity to address some entrenched problems in the current system in a sustainable manner, such as capacity replacement in the power sector, greater use of indigenous renewable resources reducing reliance on fossil imports, and energy efficiency as a tool to alleviate fuel poverty experienced by many low income households.

However a robust discussion continues about what type of pathway the UK should choose. This debate has been sharpened by the recent financial recession which has highlighted the challenges in government funding of new technologies and infrastructures, and the lack of social acceptance of energy price increases without the benefits being clearly articulated. This debate also reflects key uncertainties around the role of specific technologies, and the effectiveness of policies to deliver such a major transformation. However, uncertainty must not be a basis for inaction; the role of Government must be to put in place the right policy framework now that drives technology development and deployment at scale, facilitates market uptake of new technologies, and engages society in what will be a re-orientation of the energy system.

The modelling and supporting analysis featured in this report provides some key insights into the low-carbon transition, from which we can draw some important conclusions for the policy process.

Reducing emissions from the power generation in 2030 by 85-90% relative to current levels is critical, to meet domestic climate objectives and to provide the platform for the expansion of electrification of end-use sectors thereafter. In addition to being the most cost-effective sector in which to target action, the power sector allows for more rapid GHG reduction potential within the tight timescales of the next 15 years, with the near term need to replace much of the current capacity affording an excellent opportunity for this transition.

However, the costs of mitigation in the power sector would be significantly higher without specific key low-carbon technologies. Delay in deployment and subsequent lower levels of nuclear and carbon capture and storage (CCS) leads to significantly higher costs of abatement. CCS is not only important for low-carbon expansion of the power sector, but also key to the provision of mitigation in the industry sector and low-carbon hydrogen supply.

While some important progress has been made through the Electricity Market Reform process, we have highlighted concerns around consistency of the current policy approach, notably the capacity mechanism to ensure system stability, and the lack of certainty for investors due to inadequacy of the policy timeframe. It is also important that all current low carbon technologies continue to be supported with the necessary incentives and policies, particularly those that are proven and cost-effective e.g. onshore wind. If these related issues are not addressed, there is a real risk of ‘slippage’ in the deployment at sufficient scale of low-carbon generation technologies.

The evidence base is now well established that demand side measures can reduce costs by decreasing energy service requirements, and this should also be a key focus for Government. A stronger policy approach is needed to deliver energy efficiency retrofits of existing buildings in the near term, and to increase the deployment of demand side reduction and modal shifting measures in the transport sector. More effective delivery of energy efficiency across end use sectors requires improved understanding of consumer’s response to energy price changes as well as desired levels of energy service demands. Furthermore, additional modeling is required on the interactions between institutions and society. Finally, if the potential of the residential buildings sector is to be achieved, affordable energy solutions need to be found for lowest income groups at most risk from fuel poverty.

Significant re-orientation of energy supply to end use sectors will be required in a low-carbon system. Electrification of these sectors by 2050 is between 30 – 40% (of final energy), a more than doubling of supply relative to current levels. An increased share of electricity would be challenging as firstly, it is very difficult for electricity to displace all gas used for heating buildings, due to the large peak demand in winter, and secondly our assumption that battery electric technology only applies to light duty vehicles. These barriers could of course be both overcome by development and deployment of cost-effective battery technology.

A significant role for fossil fuels in the energy system after 2040 is wholly contingent on CCS. Our analysis shows that the continued use of gas on the supply side is subject to its use in CCS, for electricity and hydrogen production. **It is imperative that energy policy first focuses on developing CCS technology, not in developing new fossil resources, which cannot be used otherwise**.

Bioenergy can play an important role in decarbonisation – including for providing negative emission savings – but this is limited by supply availability. We estimate that bioenergy can only account for around 15-20% of UK primary energy at best, and that there is significant uncertainty around resource availability and costs, particularly with all other countries accessing global supply for decarbonisation.

Our analysis also suggests that **further strengthening of the UK long-term mitigation target would be extremely challenging via a technology-focused approach alone**, owing to hard-to-mitigate residual emissions in specific sectors. Notably, non-CO_2 GHGs, and CO_2 from international aviation, account for 70% of residual emissions in 2050, meaning that UK territorial energy sector emissions must reduce by 90%, relative to 1990 levels, with very high mitigation costs at the margin. And we note that this situation could be further compounded if our technical modelling assumptions in other sectors (e.g., hydrogen in freight and international shipping) are found to be optimistic.

It is important to recognise the fragility of these challenging mitigation objectives. **Without a sustained and strong policy push that increases year on year in ambition, the delivery of low carbon technologies at sufficient scale will not be achieved**. This applies across the technology spectrum from low-carbon technologies for power generation through to deployment of heat pumps in the building sector and low emission vehicles in transport.

Policymakers have a significant challenge in facilitating the change required. Fundamentally this revolves around a clear and consistent policy framework in terms of pricing, innovation and removal of market barriers. What is crucial is a consistent package of measures, where short and long term decisions all move in a ‘low-carbon direction’. Examples of this are firstly, that longer term infrastructure policy needs to take account of GHG reduction targets, including airport expansion, other transport infrastructure (incl. urban design), and extractive industries. And secondly, that current and future policy must deliver certainty for investors, particularly given the lead in time and payback periods for longer lived energy system assets. It also needs to recognise that this transition will be to a more capital intensive, fixed cost system, requiring necessary incentives and access to capital.

Finally, it is important that Government keeps the 2050 target under review, and reflects whether it should be tightened based on the science. It is evident from the IPCC budgets that we will the need to move to a net zero emission situation soon after 2050. Further work is needed to develop our modelling capability to firstly provide improved representation of options in those hard-to-mitigate sectors, to explore stronger mitigation ambition, such as additional demand side and action and potentially lifestyle options. There is also a need to start considering the post-2050 system, to better understand whether our longer term investments to 2050 are adequate for the more ambitious reductions required thereafter.

The UK, like most other countries, will not be able to deliver the required transition to a deeply decarbonised system alone. Firstly, there will need to be strong international cooperation on key technologies, such as CCS, where learning has to be fairly rapid if indeed this technology can be scaled globally to the required levels. The UK can also look to develop technologies in areas where it has specific expertise, notably offshore wind and marine technologies. Secondly, the UK should looks for ways to share experiences of what policy mechanisms have worked, and approaches to setting up institutional capacity. The UK can also learn from effective action in other countries. Thirdly, the UK should at least maintain and look to increase its assistance to developing countries in the area of climate change and sustainable energy through various channels, including via DFID funding.

1 Introduction

1.1 The need for deep decarbonisation of the global energy system

The 5th Assessment Synthesis Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC 2014) states (with high confidence) that '*Without additional mitigation efforts beyond those in place today, and even with adaptation, warming by the end of the 21st century will lead to high to very high risk of severe, widespread, and irreversible impacts globally*.' Addressing the challenge of climate change is recognised by many Governments as an imperative. At the 20th session of UN Framework Convention on Climate Change (UNFCCC) Conference of Parties (COP20) in Lima, the UN Secretary General reiterated the need to ensure future global temperature rises do not exceed 2 °C, stating that '*There is still a chance to stay within the internationally agreed ceiling of less than 2 degrees Celsius global temperature rise. But the window of opportunity is fast closing. All countries must be part of the solution…it is a time for transformation.*'[1]

All countries need to act because the required GHG emissions reductions are large, timescales in which to act are short, given the finite carbon budget available. According to the IPCC (2014b), to ensure a better than evens chance of remaining below a 2 °C average surface temperature rise (relative to 19th century global temperatures) will require global reductions in GHG emissions (relative to 2010) of 42-57% by 2050, and 73-107% by 2100. For CO_2 alone, these emissions reductions correspond to a cumulative budget of 860-1180 $GtCO_2$ for the years 2011-2050. On average, this means limiting global CO_2 emissions to around 26 $GtCO_2$ every year; current emissions since the start of this budget period have been around 35 $GtCO_2$,[2] a 34% overshoot each year.

With CO_2 from fossil fuels and industrial processes accounting for 65% of total global GHG emissions in 2010, and 78% of the total GHG emission increase from 1970 to 2010 (IPCC 2014b), achieving the emissions reductions required to limit warming to 2 °C will require deep decarbonisation of the global energy system. This means a radical shift away from the use of fossil fuels in all sectors of the economy, through four 'pillars' of decarbonisation: improved energy efficiency, a switch to lower carbon fuels, decarbonisation of electricity and demand reduction. It will be imperative that action is taken across all countries, given the scale of the challenge and the need to cooperate internationally. A recent Nature paper (McGlade and Ekins 2015) reinforced the need for reducing the use of fossils fuels in the energy system, by suggesting that out to 2050 a third of oil reserves, half of gas reserves and over 80% of current coal reserves should remain in the ground to meet the 2 °C target.

2015 is a critical year for making progress on international efforts to combat climate change, with COP21 in Paris a key event for moving the agenda forward. Further delays in action to 2030 is estimated to substantially '*increase the difficulty of the transition to low longer-term emissions levels and narrow the range of options consistent with maintaining temperature change below 2 °C relative to pre-industrial levels*' (IPCC 2014b). The UK Government has recognised the need for global action on climate change, and has led the way in

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[1] Remarks by the Secretary General at COP20, Lima, 9th December 2014. http://unfccc.int/files/meetings/lima_dec_2014/statements/application/pdf/cop20cmp10_opening_speech_ban_ki_moon.pdf

[2] PBL/JRC (2014). Trends in global CO_2 emissions: 2014 Report, PBL, Netherlands Environmental Assessment Agency The Hague, 2014. ISBN: 978-94-91506-87-1.

establishing a legislative framework for reducing domestic emissions. As Ed Davey, the UK's former Secretary of State for Energy and Climate Change stated in 2014, *'We need a deal in Paris – there is no alternative that will protect our national security, our economy and the way of life we take for granted.'*[3] The new UK government has an important role in building momentum with international partners in the run up to COP21.

This report describes how the UK has started to re-orientate its energy systems towards a lower carbon model, and sets out how it might achieve the objective of deep decarbonisation by 2050. It highlights both the challenges and opportunities of such a transition, and the vital importance of global cooperation for technology R&D, resource management and financing.

1.2 The DDPP initiative

The Deep Decarbonization Pathways Project (DDPP) is an international initiative, aimed at understanding and demonstrating how major emitting countries can transition to low-carbon economies, and in doing so move towards the internationally agreed 2°C target. Led by the UN Sustainable Development Solutions Network (SDSN), and the Institute for Sustainable Development and International Relations (IDDRI), Paris, it comprises 16 countries that account for over 70% of current global greenhouse gas emissions. Participating countries include Australia, Brazil, Canada, China, France, Germany, India, Indonesia, Italy, Japan, Mexico, Russia, South Africa, South Korea, the United Kingdom, and the United States.

This is a unique collaborative assessment. For the first time, a comprehensive analysis is being undertaken from the national perspective, to explore radical emission reduction pathways. The key benefit is that the analyses under the DDPP take account of national circumstances. In turn, it is hoped that this establishes greater traction with national stakeholders, and shows how the type of pathways required to move us towards the 2 °C target can be operationalised at the country level. An important feature of DDPP is that it aims to ask how far all countries can decarbonise. Therefore, there is no explicit discussion of differentiating targets and resolving the equity dimension. The principle is that all countries need to act, and decarbonise strongly. However, it is recognised that further consideration of enabling mechanisms is required, including how developed countries can support action in developing countries through financing and technology transfer.

An interim DDPP analysis was published in September 2014 (SDSN & IDDRI, 2014), and presented to Ban Ki Moon at the World Leaders' Climate Summit. It presents a global pathway that shows a CO_2-energy emissions level of 12.3 Gt by 2050, down from 22.3 Gt in 2010, representing a 45% decrease over the period, and a 56% and 88% reduction in emissions per capita and the carbon intensity of GDP, respectively. While not sufficient to make staying below the 2 °C limit likely[4], this initial pathway provides the basis for further iterative analysis in 2015 to explore deeper decarbonisation pathways.

The interim report also highlighted a number of important findings, including the need for global cooperation on technology research and development, challenges to abatement action in specific sectors, and the need for Deep Decarbonisation Pathways (DDPs). The report concludes that DDPs are crucial '*to developing a long-term vision for deep decarbonization and shaping the expecta-*

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[3] Quotation reported in a Telegraph newspaper article, http://www.telegraph.co.uk/earth/environment/climatechange/11262835/One-year-to-save-the-planet-from-climate-change-disaster-Ed-Davey-warns.html

[4] The pathway is not sufficient for two reasons; firstly, emissions peak too late to stay within cumulative budgets, and secondly, the 2050 level does not leave sufficient emissions headroom for all the other countries not included in this analysis.

Box 1. Reasons for optimism that, with strong political will and immediate action, a 2°C target can be achieved

In addition to the economic and technical arguments set out in this report showing how we can realise significant GHG reductions in the future, current events suggest reasons to be cautiously optimistic that countries can start to work together to build a strong framework for delivering a global 2°C pathway.

1. **Action pledged by leading nations.** In November 2014, China and the USA released a Joint Announcement on Climate Change.[1] In this strongest political statement on climate change to date, the USA stated that it *intends to achieve an economy-wide target of reducing its emissions by 26%-28% below its 2005 level in 2025 while China intends to achieve the peaking of* CO_2 *emissions around 2030*. Such levels of ambition had not been stated previously and, while insufficient to achieve the 2°C objective, it at least reflects a more positive direction of travel.
2. **Emissions growth can be stabilised.** The International Energy Agency (IEA) stated in March 2015 that preliminary figures suggest that energy-related CO_2 emissions have not increased in 2014. This is the first time in 40 years where a halt or reduction in emissions was not tied to an economic downturn.[2] If such estimates are correct, it helps further demonstrate that continued growth can be achieved without increased emissions.
3. **Increasing focus on addressing supply of fossil fuels.** Strong attention continues to focus on the idea of constraining the supply of fossil fuels, gaining increased traction through scientific work on what reserves need to remain in the ground (McGlade and Ekins 2015), the fossil fuel divestment campaign[3], and consideration of energy sector liabilities, including the issue of a carbon bubble.[4]
4. **Strong global growth in renewable energy.** Renewable energy growth continues to be strong, with the United Nations Environmental Programme (UNEP) reporting that global investment in renewable technologies grew by 17% in 2014, reaching $270 bn. This year also saw the highest level of newly installed capacity of 103 GW (compared to 86 GW and 89 GW in 2013 and 2012 respectively).[5] The outlook is also positive; the IEA projects that *over the medium term, global renewable electricity generation is projected to grow by almost 45%, or 2245 TWh, to over 7310 TWh in 2020 (+5.4% per year)*.[6] Much of this growth will be driven by large emerging markets, such as India and China, which have very ambitious renewable energy programmes. In addition, a number of commentators have suggested that lower oil prices may not necessarily impact renewables growth as such technologies become increasingly cost-competitive.[7]

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[1] U.S.-China Joint Announcement on Climate Change
https://www.whitehouse.gov/the-press-office/2014/11/11/us-china-joint-announcement-climate-change

[2] IEA news release Global energy-related emissions of carbon dioxide stalled in 2014
http://www.iea.org/newsroomandevents/news/2015/march/global-energy-related-emissions-of-carbon-dioxide-stalled-in-2014.html

[3] For example, the Guardian's Keep it in the ground campaign
http://www.theguardian.com/environment/ng-interactive/2015/mar/16/keep-it-in-the-ground-guardian-climate-change-campaign

[4] In March 2015, the Bank of England stated that it has been carrying out analysis to better understand the risks associated with insurers investing in assets that could be left 'stranded' by policy changes which limit the use of fossil fuels.
http://www.bankofengland.co.uk/publications/Documents/speeches/2015/speech804.pdf

[5] Global Trends in Renewable Energy Investment 2014, UNEP.
http://fs-unep-centre.org/publications/gtr-2014

[6] Medium-Term Renewable Energy Market Report 2014, IEA.
https://www.iea.org/Textbase/npsum/MTrenew2014sum.pdf

[7] For example,
http://www.bloomberg.com/news/articles/2015-03-30/cheap-oil-unlikely-to-slow-growth-of-renewables-citigroup-says

tions of countries, businesses, and investors about future development opportunities. The DDPP and similar processes afford a unique opportunity for teams to work together across countries to map out how the global 2 °C limit can be operationalized and achieved at the country level.'

1.3 *The UK country analysis*

This UK country report under the DDPP is an independent analysis of UK transition pathways aimed at contributing to the national debate on climate change action, and will feed into the final DDPP report, scheduled to be published in September 2015. It outlines the possible pathways that the UK could take to decarbonise its energy system. It first provides the UK context in section 2, describing the established legislative framework and policy priorities for energy system decarbonisation. It also highlights other scenario analyses that have been undertaken to inform low-carbon transition pathways. Section 3 underlines the challenge for the UK, describing the historic and current emissions. Section 4 introduces the scenario modelling undertaken for the DDPP initiative, including the analytical framework, with sections 5-7 presenting the results. Section 8 sets out the key conclusions, and what the emerging insights mean for domestic policy and international co-operation and coordination.

2 Decarbonisation in the UK: context and understanding

2.1 Moving from aspiration to legislation

The case for deep decarbonisation of the UK energy system was first made in a landmark report by the Royal Commission on Environmental Pollution in 2000 (RCEP 2000), which proposed a voluntary 60% reduction in CO_2 emissions by 2050, recognising the serious challenge of climate change. Over the decade that followed, the Government undertook a number of strategic analyses, notably in 2003 and 2007 (DTI 2003, DTI 2007), which further assessed the techno-economic implications of long term deep decarbonisation. These strategies, and supporting modelling (for example, Strachan et al. 2008), laid the foundation, in 2008, for the UK to be the first G20 economy to legislate a long-term emission reduction target. Under the Climate Change Act 2008,[5] a GHG reduction target of 80% is to be achieved by 2050 (relative to 1990 levels), with a set of 5-year carbon budgets independently proposed and monitored by the statutory Committee on Climate Change (CCC).

In their first report providing guidance on setting the 2050 target, the CCC (2008) proposed that the UK should adopt a target for a reduction of at least an 80% reduction in GHGs for 2050, stating that '*the Committee's opinion is that it is difficult to imagine a global climate deal which is either pragmatically achievable or fair which does not involve the UK and other developed countries reducing their emissions, over the long-term, to a per capita level which if applied across the world would be compatible with our climate objectives, that is just over 2 tonnes of CO_2-equivalent per capita.*'

The question is whether this is indeed deep decarbonisation, and whether the UK should go further? The latter point relates to the equity question, and is not one that we consider in this report, or the wider DDPP analysis (as mentioned earlier). Concerning our concept of deep decarbonisation by 2050, our scenarios achieve 1.5 tCO_2 / capita,[6] which is broadly consistent with what is needed globally to achieve the 2 °C target, acknowledging the large range of uncertainty in the IPCC AR5 budgets. Importantly, the CCC leaves the door open to more ambitious longer term action, stating that the 2050 reduction should be 'at least' an 80% reduction. Later in the report (section 8), we discuss the potential for further reductions in 2050, and what would be needed to achieve this.

Since 2008 the focus of Government (and advice from the CCC) has firstly been on what interim levels of GHG reduction there should be in order to meet the final 2050 decarbonisation target. These five-yearly targets have been termed the UK's 'carbon budgets'.[7] Secondly, the Government has developed a portfolio of measures to achieve these proposed emission reductions. Some of the key measures are described in Table 1.

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[5] Climate Change Act, 2008. Chapter 27. The Stationary Office. Available at: http://www.opsi.gov.uk/acts/acts2008/ukpga_20080027_en_1S

[6] For all GHGs, the figure is 2.1 t/CO_2e / capita.

[7] The overarching Government decarbonisation strategy is described in DECC (2011), and sets out how the UK will meet its first four carbon budgets, out to 2027. Advice to Government on meeting carbon budgets can be found in CCC (2013, 2010).

Table 1. Key low carbon energy policies in the UK, by sector

Power	Electricity Market Reform (EMR)	EMR focuses on delivering a low-carbon system that is both cost-effective and reliable. It has four key elements - 1. **Emissions Performance Standard (EPS)**, to prevent the construction of new coal-fired power stations (without carbon capture and storage (CCS)). 2. **Contracts-for-Difference (CfDs)**, to encourage investment in low-carbon electricity generation by providing companies with a guaranteed fixed price for the power they generate. 3. **Capacity Market mechanism**, to ensure reliable forms of power (both demand and supply side) are available during high demand periods. This is done via payments to generators for ensuring the availability of reliable sources of capacity. 4. **Carbon Price Floor (CPF)**, a carbon tax to make low-carbon generation more competitive with fossil fuel generation.
	CCS Commercialisation competition[1]	The Government is funding two demonstration projects - White Rose Project and the Peterhead Project. These projects, currently in the design phase, and their associated infrastructure are seen as crucial to ensuring that this technology can be established commercially by the late 2020s.
Buildings	Renewable Heat Incentive (RHI)[2]	The RHI, split into domestic and non-domestic schemes, aims to provide financial incentives to invest in renewable energy. The domestic scheme, implemented in 2014, pays participants per unit of heat generated for 7 years from a range of renewable technologies – heat pumps, biomass boilers & solar thermal. The non-domestic scheme (including industry) was introduced in 2011, and subsequently enhanced in 2013 to improve take-up.
	Green Deal	This is a scheme that provides home energy efficiency assessments and loans to implement improvements, focusing on cavity and loft insulation. The scheme has largely been disappointing based on a low uptake of loans, due to unattractive interest rates. Additional incentives introduced in 2014 hope to improve the impact of this scheme.
	Energy Company Obligation (ECO)	This measure puts obligations on energy companies to implement certain energy efficiency measures. Some elements are specifically targeted at low income households, focusing on lower cost improvements; this has proved relatively successful. However, other elements focused on harder-to-treat homes have been less successful, in part due to higher costs (CCC 2014).
Transport	EU targets on emissions from cars and vans	EU targets on emissions from new light duty vehicles will help to drive efficiency of ICEs and the promotion of low emissions vehicles (LEVs).
	Fiscal measures to encourage take-up of lower emission vehicles	A number of measures seek to promote vehicles with lower emissions including Vehicle Excise Duty and Company car tax graduated according to CO_2 emissions, and capital allowances for firms on low emissions vehicles (CCC 2014).
	Funding through Office of Low Emission Vehicles (OLEV)	£500 million is committed from 2015 until 2020 to continue to support the growing market for ultra-low emission vehicles (ULEVs), in addition to the £400 million committed to 2015. One key measure is the plug in car grant of 35% off the cost of a car, up to a maximum of £5,000. An industry-government funded Advanced Propulsion Centre will also help develop low-carbon power train industries to facilitate the move to ULEVs.[3]
Industry	EU Emissions Trading Scheme (ETS) / Climate Change Agreements (CCAs)	Industrial emissions are largely covered by EU ETS and Climate Change Agreements (CCAs). The effectiveness of the EU ETS has been limited, given the low price for traded carbon in recent years. The CCAs are energy efficiency agreements negotiated directly with Government.
	Industrial Sector 2050 Decarbonisation Roadmaps	UK Government has facilitated the development of a series of Industrial Sector 2050 Decarbonisation Roadmaps which have recently been published. These will identify mitigation potential and challenges to realizing the potential across the main industry sectors.

[1] CCS commercialisation competition, https://www.gov.uk/uk-carbon-capture-and-storage-government-funding-and-support

[2] RHI scheme, https://www.gov.uk/government/policies/increasing-the-use-of-low-carbon-technologies/supporting-pages/renewable-heat-incentive-rhi

[3] Advanced Propulsion Centre UK website, http://www.apcuk.co.uk/

European legislation is also an important driver of policy as reflected above. Another important cross-sectoral piece of legislation is the Renewable Energy Directive, which requires 15% renewable energy to be part of the UK final energy mix by 2020.[8] Current levels (for 2013) are at 5.2%, up from 4.2% in 2012.[9]

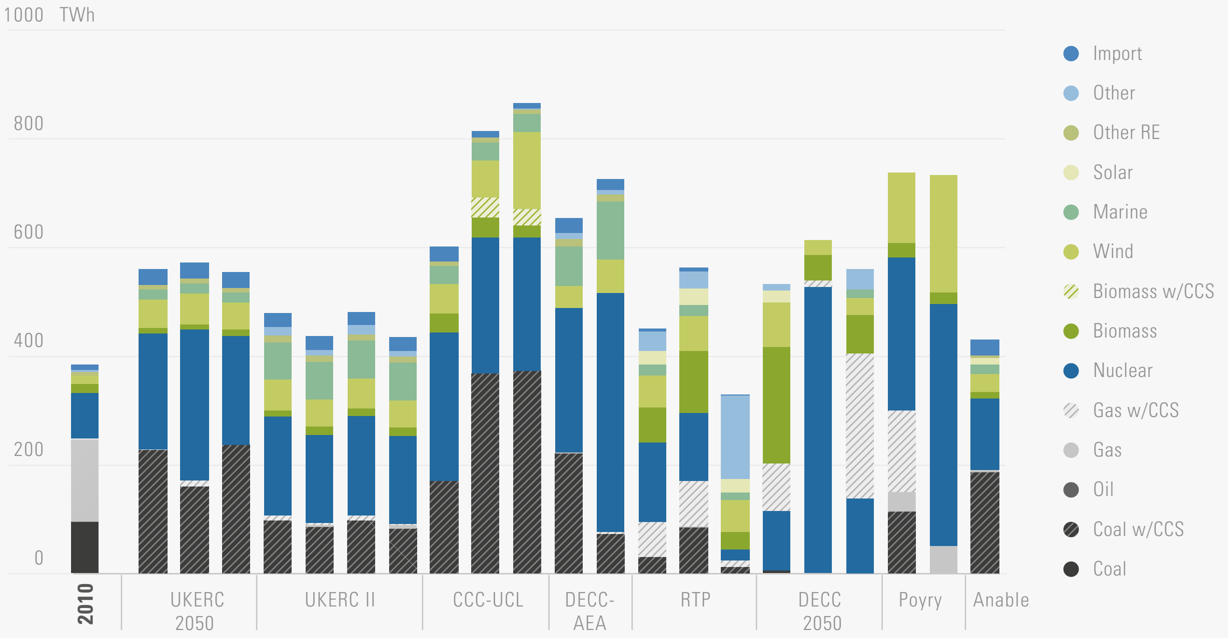
In later sections of this report, reference is made to some of the above policies, their effectiveness and recommendations for strengthening.

2.2 Multiple long term pathways to a low-carbon transition

Recent analysis suggest that the current policy package is very much focused on a 2020 timeframe, and that a 'policy gap' (or deficit to what current policy can deliver) of 60 $MtCO_2e$ is apparent in relation to the 4th carbon budget in 2025 (set at an average 390 $MtCO_2e$ / per annum, or 50% lower than 1990 levels) (CCC 2014). Therefore, the pathways to 2030 and beyond are subject to large uncertainties. While the types of technologies that will deliver a low-carbon system are evident, the specific role of these technologies in a future system is less clear.

Many modelling analyses have been undertaken that consider different systems under a range of assumptions (ETI, 2015; National Grid, 2014; Foxon, 2013; Ekins et al. 2013; CCC, 2013; DECC, 2011). These analyses show a diverse set of low-carbon transition pathways that could achieve the UK's stated climate policy goals. This is illustrated by the diversity of power generation scenarios in Figure 1, reflecting different technology focus, role of mitigation in the pow-

Figure 1. Power sector generation in 2050 from selected scenario studies



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[8] DIRECTIVE 2009/28/EC, requiring 15% of gross final energy consumption (GFEC) to be from renewable energy sources.

[9] Digest of UK Energy Statistics (DUKES) 2014, https://www.gov.uk/government/statistics/renewable-sources-of-energy-chapter-6-digest-of-united-kingdom-energy-statistics-dukes

er generation sector, demand drivers, and economic assumptions. It both highlights different supply-side choices and levels of electrification in demand sectors.

Despite differences, some emerging themes can be identified from recent scenario analyses, for both the power and other sectors. These include

- A strong role for electricity system decarbonisation, in particular carbon capture and storage (CCS), wind and nuclear technologies (with gas often used for peak back-up). Post 2030, strong electrification of end-use sectors is often observed.
- Bioenergy is prioritised for use with CCS in the power sector and other applications, where it provides much greater emission reductions per tonne of bioenergy than in non-CCS applications.
- Emissions remaining in 2050 are often associated with hard-to-mitigate freight and international transport sectors, and specific industry sub-sectors.
- A decline in gas use is apparent in most scenarios, although does not phase out completely. In specific scenarios, its use with CCS allows for higher consumption levels; however, the decline in direct use for heating is a strong trend.
- Depending on the assumptions, there are distinctive outlooks for different vehicle types, particularly in relation to passenger cars, with either hydrogen fuel cells (H_2FC) or electric vehicles dominating. Strong efficiency gains reduce final energy requirements.

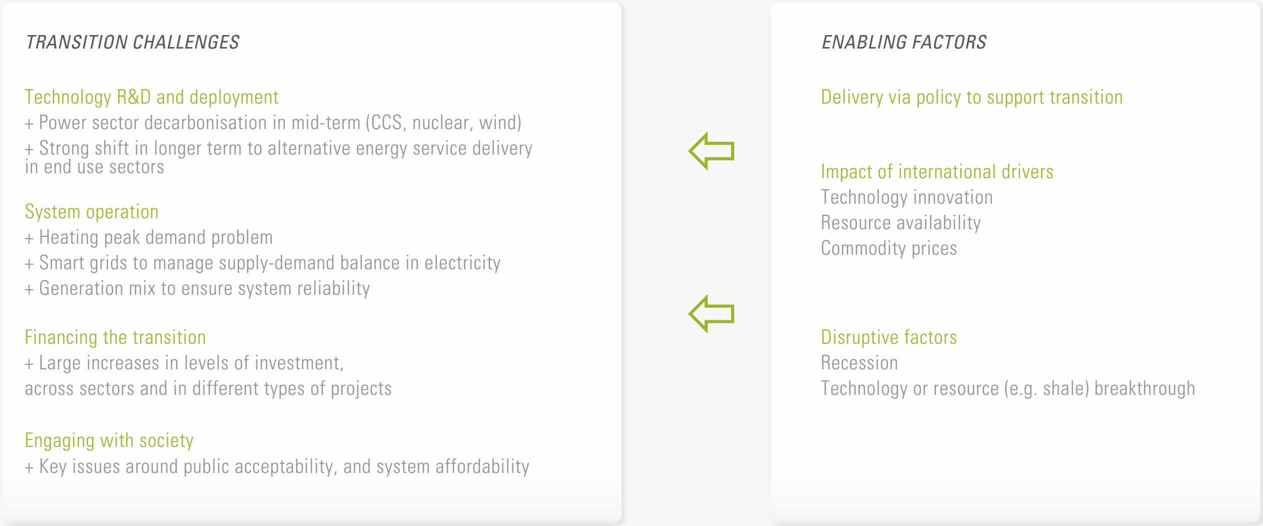
UK policymakers have the challenging role of developing policy that delivers low-carbon investment into the energy system (including necessary infrastructure) but which is not too prescriptive as to the ‘best’ option(s). There needs to be room for a portfolio of options to ensure the UK can implement a transition as affordably as possible, deliver energy services reliably and spread the risks associated with technology delay or failure. This can only be done through the use of long-term pathway analysis, allowing for the design of near-term action. Compounding the challenge is the need to act now, despite the given uncertainties, in order to bring about strong mitigation by 2030. Therefore, recognition of these uncertainties is needed to ensure they can be mitigated as far as possible.

2.3 The key emerging challenges

There are a number of key challenges to transitioning to a low-carbon energy system that are evident from the range of analyses undertaken, and are being recognised (to differing extents) by UK policy makers. These are summarised in Figure 2. Firstly, development and deployment of low-carbon technologies at scale is a significant challenge, not only because many are emerging technologies but also because of the timescales. Power sector decarbonisation is critical for meeting the carbon budgets out to 2030, and requires strong roles for wind, nuclear and CCS (CCC 2013). Starting to ramp up the deployment of other low-carbon technologies in end-use sectors through the 2020s will also be critical to ensure market-readiness and supply capacity. As highlighted recently by the ETI (2015), *over the course of the next decade, the UK must prepare for a comprehensive energy transition out to 2050*.

Secondly, there is the issue of system operation. An intermittent power-generation system with a high wind load will require increased levels of storage and back-up capacity to ensure system security and stability (Pöyry, 2011). Higher demand for electricity in the longer term is likely to increase this challenge. Thirdly, the incremental investment for low-carbon technologies will mean higher costs of energy, at least in the near term. Many lower-carbon technologies are also highly capital intensive, requiring increased levels of upfront capital (Blyth et al. 2014).

Figure 2. Key challenges facing the UK low carbon transition



TRANSITION CHALLENGES

Technology R&D and deployment
+ Power sector decarbonisation in mid-term (CCS, nuclear, wind)
+ Strong shift in longer term to alternative energy service delivery in end use sectors

System operation
+ Heating peak demand problem
+ Smart grids to manage supply-demand balance in electricity
+ Generation mix to ensure system reliability

Financing the transition
+ Large increases in levels of investment, across sectors and in different types of projects

Engaging with society
+ Key issues around public acceptability, and system affordability

ENABLING FACTORS

Delivery via policy to support transition

Impact of international drivers
Technology innovation
Resource availability
Commodity prices

Disruptive factors
Recession
Technology or resource (e.g. shale) breakthrough

Finally, significant changes in the system of energy delivery will require engagement and 'buy-in' from a range of stakeholders. Watson et al. (2014) state that *'engagement with people and communities is an essential component of the UK's low-carbon transition'* not just for individual technologies but for the whole system, and that a focus of engagement should be on how a transition is organised and paid for. This includes acceptance of citing specific technologies in local communities, and how energy services are provided in the future. There are also affordability concerns, with consumers paying for this transition through direct purchases of low-carbon technologies or through energy bills. There are also concerns that the fuel poor could be impacted unless adequate mitigation measures are put in place (JRF 2011). To 2030, support to low-carbon policies are estimated to account for 13.5% of a household bill (CCC, 2014b) but increases could be largely offset by energy efficiency measures.[10]

How these challenges are met will be dependent on what we call 'enabling factors'. These factors include the effectiveness of domestic policy, the impact of international drivers, including global cooperation on mitigation measures, and disruptive factors. Domestic policy makers have less control around the latter two factors, and therefore national policy also has a role in ensuring resilience against external factors. International drivers depend on how international communities cooperate and collectively act on climate change mitigation, which in turn impacts resource availability and commodity prices and drives innovation. Disruptive factors include recessionary effects, geopolitical events and technology / resource breakthroughs. A key technology breakthrough may, for example, enable stronger deployment of low-carbon technologies while the prospect of new fossil resources could divert investment away from such deployment.

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[10] The current support level is at about 9% of household bills (for those households using gas for heating).

3 GHG emissions: current levels and future reduction targets

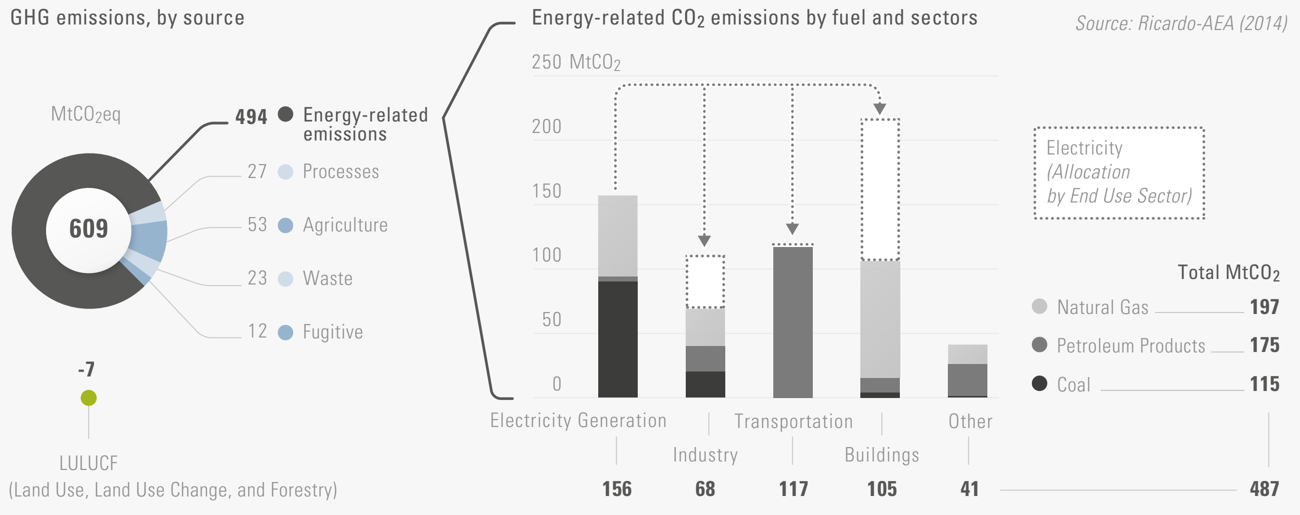
3.1 Current levels and past trends

The level of UK GHG emissions in 2010 was 602 $MtCO_2e$ (excluding international aviation and shipping), 82% of which were CO_2 emissions related to fuel combustion.[11] The three sectors that constitute the largest sources of emissions include power generation, transport, and buildings, accounting for 77% of total CO_2 emissions. Concerning emissions from energy use, gas consumption has the largest share (40%), based on its use for power generation and heating in buildings. This is followed by oil use (36%), primarily in transport, and coal (24%) for power generation and industrial processes.

International aviation and shipping (IA&S) in 2010 was estimated at just under 41 $MtCO_2$, increasing transport sector emissions to 157 $MtCO_2$ and making it the largest direct emitter of GHGs. Total GHG emissions including those from the IA&S sector were estimated at 643 $MtCO_2$ in 2010. It is important to examine this sector in this report as IA&S emissions are included within the UK's 2050 target. In per capita terms (including IA&S), the UK emitted GHG emissions in 2010 at a rate of 10.4 tCO_2e/capita, and 8.8 tCO_2/capita for CO_2 emissions only.

UK GHG emissions have been falling since 1990, and in 2010 were 22% below 1990 levels. Over half of this reduction (56%) can be attributed to CO_2 emissions, with the remainder from non-CO_2 emissions. A key driver of the reduction in CO_2 emissions has been the

Figure 3. 2010 UK GHG emissions, $MtCO_2eq$ and Energy-related CO_2 emissions by fuel and sector, excl. IAS



Source: Ricardo-AEA (2014)

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[11] The GWP factors for non-CO_2 GHGs are based on those in the IPCC's Second Assessment Report, and include 21 for CH4 and 310 for N2O. Recent guidance by IPCC suggests a factor of 25 for CH4 and 298 for N2O, based on the 4th Assessment Report, both of which have now been adopted for UK GHGI reporting. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/407432/20150203_2013_Final_Emissions_statistics.pdf

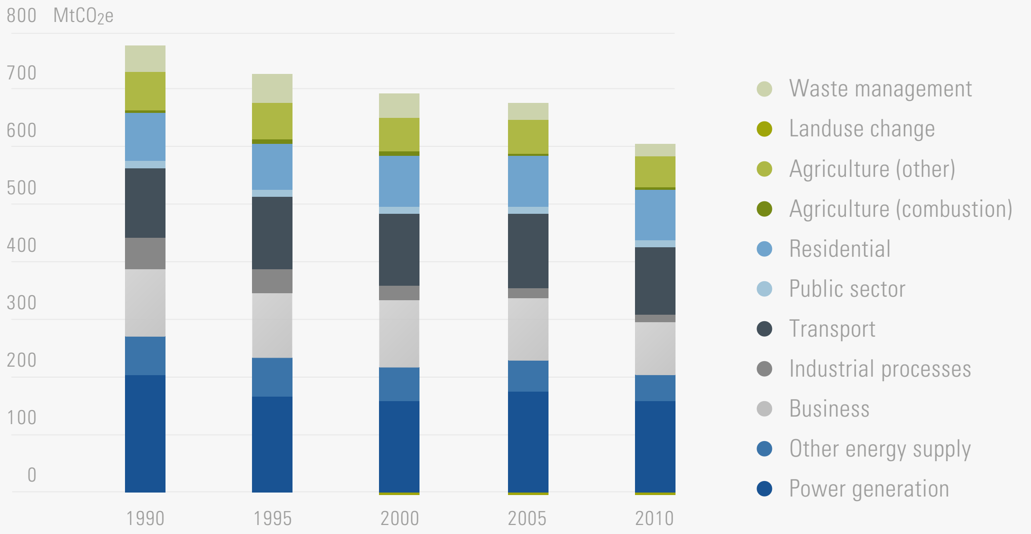
large-scale take-up of gas for power generation (the so-called 'dash for gas'), reducing the UK's historical reliance on coal (Figure 4). The other key driver has been economic restructuring, with large reductions in emissions from industrial energy use (including in the iron and steel sector) over the period and a general shift to a lower energy-intensive economy. Efficiency gains in end-use sectors (buildings, transport) have led to either no growth or small decreases in emissions, relative to 1990, despite rising incomes and population growth. For non-CO_2 gases, the main reductions have been from lower CH_4 emissions from the agriculture sector, and N_2O emissions from specific industrial processes.

3.2 Emission reduction targets

The projected emissions reduction trajectory assumed in this report is based on the legislated 2050 target, an 80% reduction in GHGs relative to 1990 levels, and the four agreed interim carbon budgets. These carbon budgets essentially put a limit on total emissions of GHGs the UK can emit over a 5-year period, and cover the period between 2008 and 2027 (Table 2). During the course of 2015, the UK's Department of Energy and Climate Change (DECC) will be determining the level at which to set the 5th carbon budget for the period 2028-2032.

The relatively undemanding first carbon budget has now been met through a combination of low-carbon measures and recessionary impacts

Figure 4. GHG emissions in the UK excl. IAS, 1990-2010



Source: Ricardo-AEA (2014)

Table 2. UK Carbon Budgets

Carbon Budget Period	1 (2008-2012)	2 (2013-2017)	3 (2018-2022)	4 (2023-2027)
Budget Limit, $MtCO_2e$	3018	2782	2544	1950
Annual average of budget	604	556	509	390
% reduction of annual average below 1990 level	22%*	28%	35%	50%

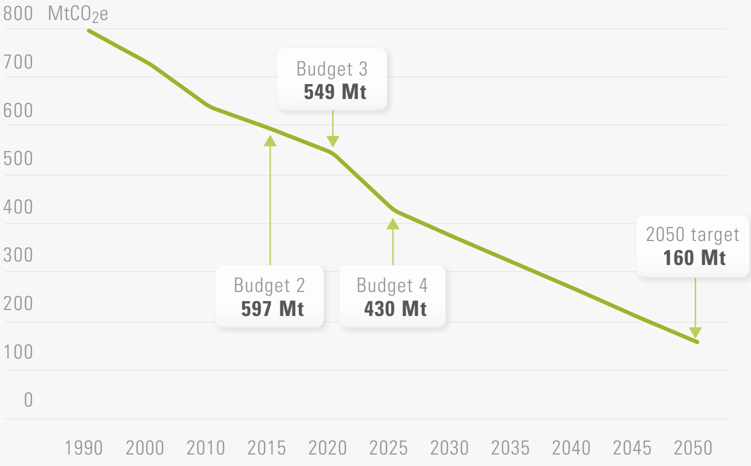
* Across the 1st Carbon Budget period, emissions averaged 597 $MtCO_2e$.

Source: DECC 2011

(CCC 2014). Future carbon budgets will be considerably more challenging: with any potential future economic downturns unlikely to deliver the necessary savings, much stronger efforts around the introduction of low-carbon measures will be required. The necessary average annual emission reduction rate is around 1.5% per annum between budgets 1 and 2, but increases to over 4% between budgets 3 and 4.

The reduction trajectory used in our analysis, based on the agreed carbon budgets and 2050 target, is shown in Figure 5. Note that the average annual budget levels shown have been adjusted to allow for emissions from the IA&S sector (not currently included in the actual UK budgets). The periods after 2025 are assumed to have carbon budgets in place, and are estimated based on a linear interpolation between the average 4th carbon budget level and the 2050 target. Based on this trajectory, we estimate that cumulative CO_2 emissions over 2011-2050 are around 12.5 $GtCO_2$. This is 1.2% of the median global budget (1020 $GtCO_2$) discussed earlier in this report.[12]

Figure 5. Historic GHG emissions (1990-2010) and adjusted target trajectory (2015-2050)



4 Modelling transitions to a low-carbon economy

The focus of this report is to present modelling of the energy system transition to 2050, to consider the key options that could help achieve deep decarbonisation. The analysis also highlights the key challenges facing the UK, and the package of policies that are required. In this section, we introduce the analytical framework used for the analysis, and the set of scenarios developed.

4.1 Modelling approach

To explore the transition, our modelling approach uses the new UK TIMES energy system model, UKTM.[13] UKTM has been developed at the UCL Energy Institute over the last two years as a successor to the UK MARKAL model (Kannan et al. 2007), which was a major underpinning analytical framework on long-term low-carbon technology pathways and decarbonisation costs for UK energy strategy development and legislation from 2003 to 2013 (DTI 2007, CCC 2008, DECC 2009, DECC 2011). It is based on the model generator TIMES (The Integrated MARKAL-EFOM System), which is developed and maintained by the Energy Technology Systems Analysis

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[12] For context, the UK estimated population in 2050 will be 77 million, or 0.9% of the global population (9 billion).

[13] Additional information on UKTM can be found at http://www.wholesem.ac.uk/documents/uktm-documentation.

Programme (ETSAP) of the International Energy Agency (IEA) (Loulou et al., 2005).

UKTM is a model that explicitly represents the technology and fuel choices across different sectors under decarbonisation objectives. These choices are made based on what is economically-optimal, subject to a range of constraints that ensure greater realism. Such constraints include balancing of supply-demand, limits on technology build rates, and representation of available resources e.g. wind, bioenergy etc. Energy service demand drivers are exogenous to the model, while the supply choices (including electricity generation) are endogenous.

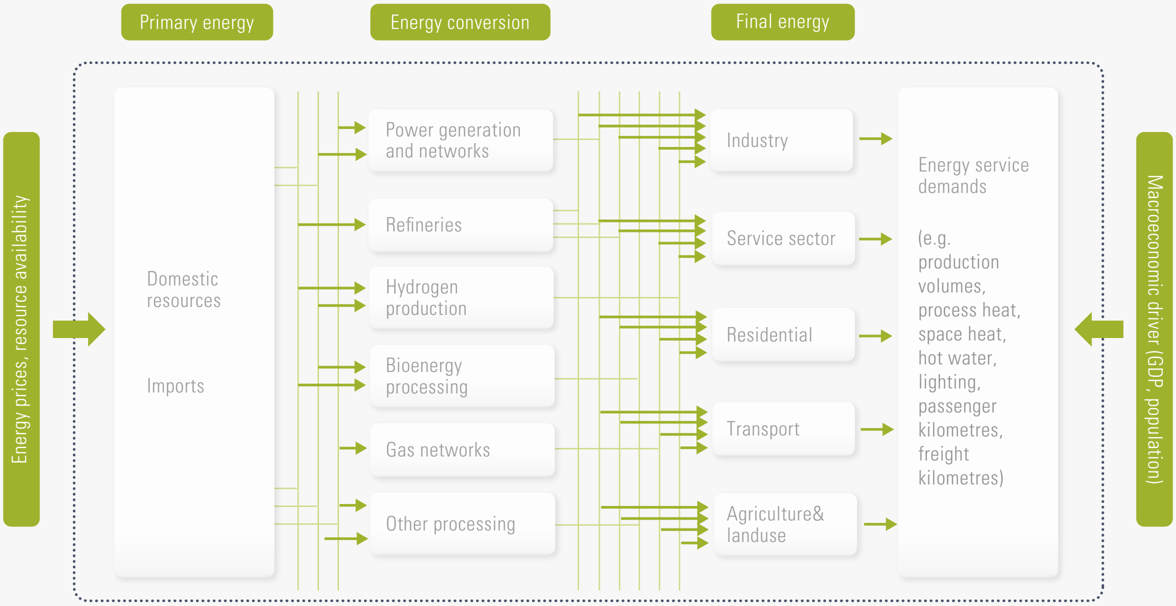
A key strength of UKTM is that it represents the whole UK energy system under a given decarbonisation objective, which means that trade-offs between mitigation efforts in one sector versus another can be explored. The system is represented as a network of processes (e.g. different types of power plants, heating systems of transport technologies etc.) linked by commodity flows (e.g. energy carriers, emissions, materials etc.); a simplified representation is shown in Figure 6. Further information on the model structure and key assumptions is provided in Appendix 1.

4.2 Scenarios

The purpose of the scenarios used in this report is to illustrate divergent pathways to achieving a decarbonised energy system by 2050. By using multiple pathways, we can illustrate the different challenges of deep decarbonisation, some of the critical uncertainties under such transitions, and identify the near term action that is needed. Scenarios were formulated based on the process steps shown in Figure 7.

As per step 1, modelling of scenarios should help to assess what the challenges are, and how they might be overcome (see section 2.3). Secondly, there are crucial 'determinants' of different pathways which need to be identified and considered. A third step is to tie different approaches to ad-

Figure 6. Simplified UK Reference Energy System in UKTM



dressing challenges and the role of determinants via scenario narratives. Based on this, scenarios were formulated and implemented in the model (as per steps 4 and 5). This process helps us to model consistent pathways that illustrate challenges, uncertainties and necessary action under different transitions.

Concerning step 1, the key challenges are shown in Figure 2, alongside the enabling factors that will determine how these challenges are addressed. Under the second step, key determinants of different pathways were identified that we wanted to feature in the scenarios (Figure 8), based on a review of previous scenario and sensitivity analyses. They also represent some key issues in the current climate policy debate. To ensure coherence, a set of scenario dimensions were used to tie the different assumptions relating to determinants together. These are listed to the right-hand side of Figure 8.

Three decarbonisation scenarios were chosen, based on the different roles of pathway determinants under distinct narratives.[14] They illustrate the role of key technologies, policy choices and other system wide factors that determine a given pathway. While not exhaustive, they also highlight the different choices to be made in

Figure 7. Steps in DDPP scenario formulation

1. Challenges to achieving a DDP
Solutions dependent on policy, international drivers and disruptive events

2. Determinants of transition pathway
Key factors determining the transition pathway

3. Shaping the scenario narrative
Different dimensions shape the narrative, and provide scenario coherence

4. Scenarios formulated
Scenarios developed based on steps 2 & 3

5. Model implementation
Scenarios modelled using standard & scenario-specific assumptions

Figure 8. DDPP scenario determinants and dimensions

Technology factors	*DDPP decarbonisation 'pillar'*	*Sector*
CCS R&D and commercialisation	Supply decarbonisation	Power generation
Deployment of other LCG techs	Supply decarbonisation	Power generation
Uptake of building retrofit measures	Energy efficiency (EE)	Buildings
Deployment level of LEVs / heat pumps	Fuel switching & EE	Transport, buildings & infrastructure
Industrial CCS and H2 penetration	Fuel switching & decarbonisation	Industry
Resource factors		
Bioenergy resource availability & use	Supply decarbonisation	Resource supply
Displacement of gas for heating in buildings	Fuel switching	Resource supply & buildings
Displacement of oil supply in transport	Fuel switching	Resource supply & transport
Demand–side factors		
Reduction in energy service growth	Demand reduction	All end use sectors
Behavioural response (price / non-price)	Demand reduction	All end use sectors

APPROACHES TO DELIVERY

STRENGTH OF POLICY FRAMEWORK

FOCUS AND TIMING OF SECTORAL ACTION

SOCIETAL PERSPECTIVES

KEY SOCIO-ECONOMIC DRIVERS

GLOBAL SYSTEM FACTORS

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[14] Counterfactual scenarios which show how the energy system evolves if not subject to deep decarbonisation have not been assessed. This is for two key reasons; i) the UK is committed to a low-carbon system, under current policy and ii) determining and using a counterfactual as a basis for comparison is fraught with difficulty due to the strong uncertainties associated with it.

achieving GHG emission reduction objectives and that such choices will lead to trade-offs between options. Finally, they provide a basis for exploring what near-term decisions need to be taken, and whether these are pervasive or distinctive under different pathways.

Scenario **D-EXP** (*decarbonise & expand*) puts a strong focus on near-term power sector decarbonisation based on a mix of low-carbon technologies including wind and nuclear, enabled by effective policy incentives. A stronger role for CCS emerges towards the end of the 2020s, with increasing build out across all of these generation technologies post-2030. This system expansion allows for increasing levels of end-use sector electrification, which becomes the core pillar for decarbonisation of end-use demand. Large-scale deployment of heat pumps in buildings is observed, resulting in electricity displacing gas as the primary supply of heat. In transport, electrification of LDVs increases in the 2030s with increasing market capacity, resulting in BEVs / PHEVs dominating in the 2040s.

Scenario **M-VEC** (*multi-vector transition*) foresees a system that is less reliant on electrification for decarbonisation, due to more limited deployment of key low-carbon generation technologies, namely nuclear and CCS. Wind generation capacity is greater than in D-EXP, resulting in more significant challenges for system operation. While electrification is lower, a generation system emerges that is actually larger in capacity terms. Other energy vectors, including hydrogen and bioenergy, play a much stronger role in decarbonisation of the energy supply in the longer term (post-2030).

Scenario **R-DEM** (*reduced demand*) illustrates how supply-side decarbonisation can be moderated by action to reduce demand. Stronger efforts are focused on building retrofit, motivated by government pushing to address affordability concerns and fuel poverty. Additional policy efforts also focus on reducing demand for passenger transport; government and local authorities encourage lower levels of personal car use through stronger car tax incentives and local based measures. In addition, future planning results in service provision that does not increase per capita demand for car-based travel demand (reinforcing current per capita trends showing saturation). Growth in international aviation slows due to higher costs associated with carbon-intensive transportation. Efforts to develop and deploy low-carbon technologies occur in parallel, although the ambition is scaled back due to the success of demand-side measures.

In Appendix 2, Table 5 provides additional detail on the scenario narratives, while Tables 6 and 7 outlines how the scenarios were implemented into our model framework, based on standard and scenario-specific assumptions.

5 Results: System transition

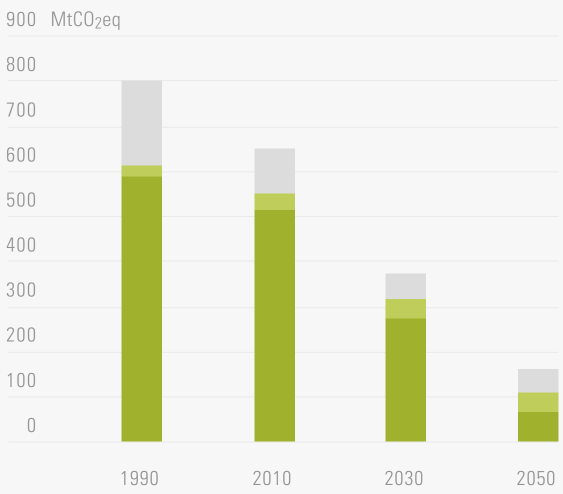
This section introduces the high level metrics that characterise the transition pathways, focusing on the timing and level of sectoral mitigation, the key types of mitigation undertaken, and the associated costs. Subsequent sections go into additional detail for each sector, and for system level energy resource supply.

5.1 Emission reductions are required across all sectors

The emission reduction trajectory is presented in Figure 9 showing the overall GHG emissions reduction of 80% by 2050, relative to 1990. For domestic CO_2 emissions, the reduction is almost 90%. This is due to an increase in emissions from international aviation and shipping, and a lower percentage reduction in non-CO_2 GHGs. In per capita terms, the GHG metric falls from a 2010 level of 10.4 to 2.1 tCO_2 in 2050, while for CO_2 (excl. IAS), the per capita level falls from 8.2 to 0.9 tCO_2.

Between 1990 and 2010, GHG emissions fell at a rate of approximately 1.0% per annum. The rate of reduction from 2010 to 2030 will need to increase to around 2.8%, and then to 4.1% between 2030 and 2050. These increasingly ambitious and large-scale reductions necessitate action across all sectors. However, the level and timing of action across sectors differs according to reduction potential, cost effectiveness of mitigation, availability of technology in addition to other factors. At the sector level, the carbon intensity of final energy consumption (FEC) indicates the level and timing of reductions (Figure 10). It is the power sector where the most significant reductions to

Figure 9. GHG emission reductions, D-EXP scenario

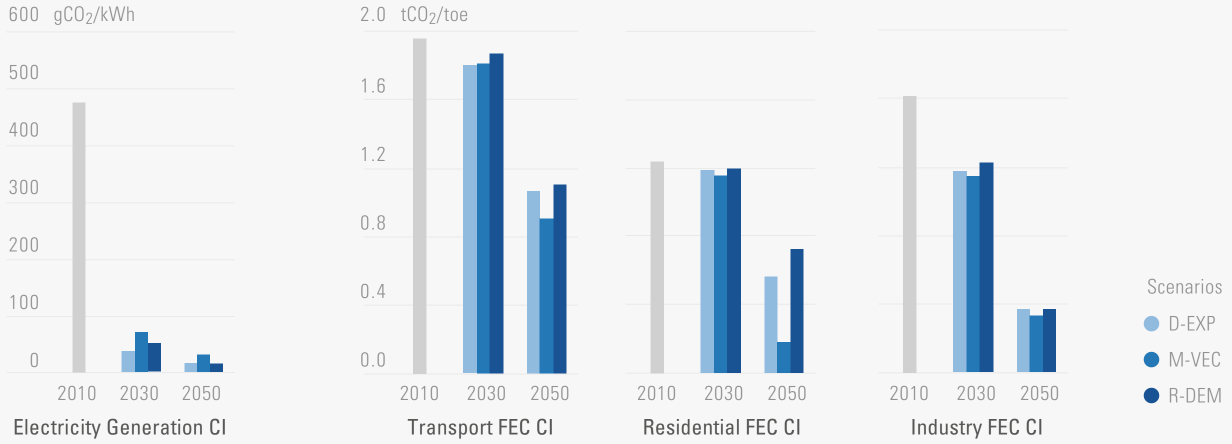


Reductions in 2050 relative to	1990	2010
Total	-80%	-75%
CO_2 (excl. IAS)	-89%	-87%
IAS CO_2	+77%	+8%
Non-CO_2 GHGs	-75%	-51%

Per capita CO_2eq	2010	2030	2050
CO_2 (excl. IAS)	8.2	3.9	0.9
CO_2 (incl. IAS)	8.8	4.5	1.5
GHGs	10.4	5.2	2.1

● Non-CO_2 GHGs
● IAS CO_2
● CO_2 (excl. IAS)

Figure 10. Carbon intensity by sector under DDPP scenarios



2030 are observed, with resulting carbon intensity in the range of 35 – 75 gCO_2/kWh, from a current level of just below 500 gCO_2/kWh. Of the end-use sectors, it is industry where the highest annual reduction is observed to 2030, at 1.5%/year; transport and residential sectors see annual average reductions of 0.3% and 0.2% respectively.

Post-2030, all end-use sectors see much stronger rates of reduction. However, none decarbonise to the same extent as the power sector, where carbon intensity drops to between 15 – 30 gCO_2/kWh.[15] In M-VEC, where the power sector carbon intensity is higher, a lower carbon intensity results in end-use sectors, most notably in the residential sector.

Our modelling suggests that given the stringency of the targets, action will be required across all sectors. While power sector decarbonisation is critical pre-2030, it does not preclude the need to start ramping up low-carbon policy actions across other sectors, to ensure the longer term transition. It is likely that stronger reductions will be needed prior to 2030 in transport and residential sectors than suggested by our modelling, which tends to back-load action. By 2050, the role of fossil fuels will be significantly reduced although will still play a role in specific sectors (international aviation) and in carbon capture-based technologies. Further discussion on the role of CCS, including with bioenergy fuels, is provided in section 7.2.

5.2 Energy efficiency combined with energy supply decarbonisation will be key drivers of transition

There are four key means of decarbonisation, all of which are critical for the transition to a low-carbon energy system. These include i) *increased efficiency* of energy use in end-use sectors, ii) *decarbonisation of electricity* and other fuels, iii) *fuel switching to lower carbon fuels*, including end-use sector electrification and iv) *demand-side reduction in energy-service consumption*, driven by societal change, or policy mechanisms. The importance of this fourth pillar, characterised under the R-DEM scenario, is discussed in subsequent sections of the report. Metrics for these different 'pillars' of decarbonisation are shown in Figure 11 across the three scenarios.

The energy intensity of GDP reduces by almost 70% in 2050, due to a 22% reduction in final energy consumption and a more than doubling of GDP. This reflects a strong push on improving efficiency across all end-use sectors, and some continuing re-structuring of energy-intensive industries (see section 6.3). The strong push on efficiency gains in the near term reflects the cost-effective nature of such mitigation action. The carbon intensity of the energy system also reduces radically, down by 75% in 2050, with much of the pre-2030 gains resulting from action to decarbonise the power generation sector (as illustrated above).

The post-2030 fuel decarbonisation reflects the expansion (doubling) of the supply of decarbonised electricity to end-use sectors, as shown in the third metric, and the increased use of low-carbon fuels such as bioenergy and hydrogen. A significant increase in electrification is not observed before 2030, with the focus on decarbonisation of the sector through replacement of existing capacity. This result also reflects the time it is likely to take end-use sectors to scale up a switch to increased electricity use in homes and transport.

A more detailed picture of final energy consumption is shown in Figure 12. It highlights first the reduction in final energy despite the growth in energy service demands, due to improve efficiency of use, and the shift to lower carbon fuels. A fossil dominated system based on oil and gas shifts to the increased use of electricity, and bioenergy use, and a growing contribution from district heating and hydrogen.

The continued role for gas and oil in 2050 in end-use sectors is evident, albeit at much lower levels than in 2030. Concerning oil, much of the remaining use is in the international aviation sector where supply side options are deemed limited, and in hard-to-mitigate subsectors in road transport and industry. Gas is primarily used for heating in buildings, with central heating an

Figure 11. ‘Pillars’ of decarbonisation (variations shown are scenario averages)

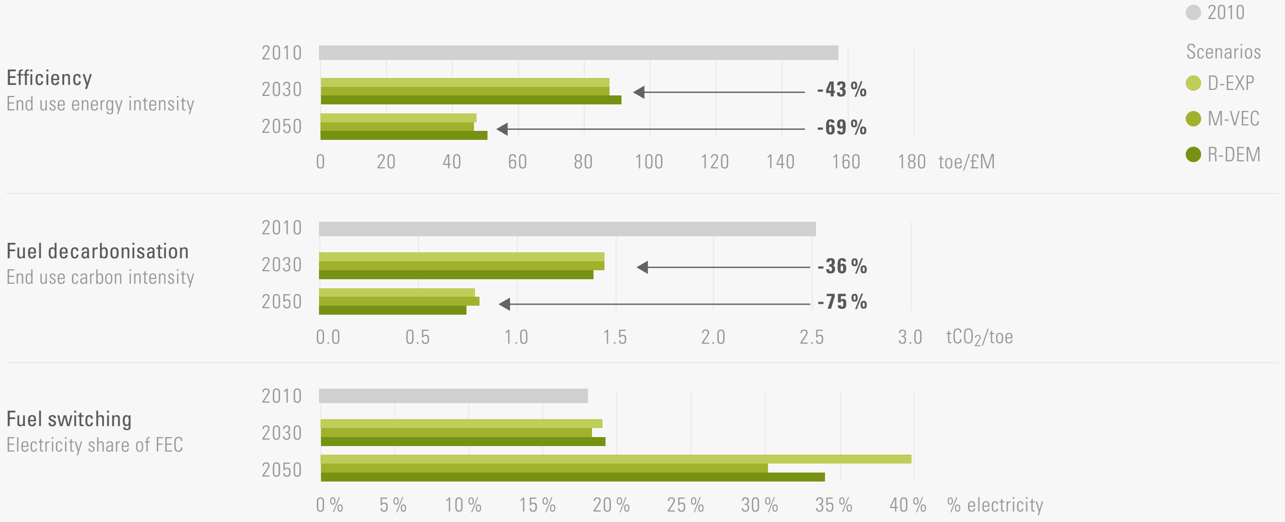
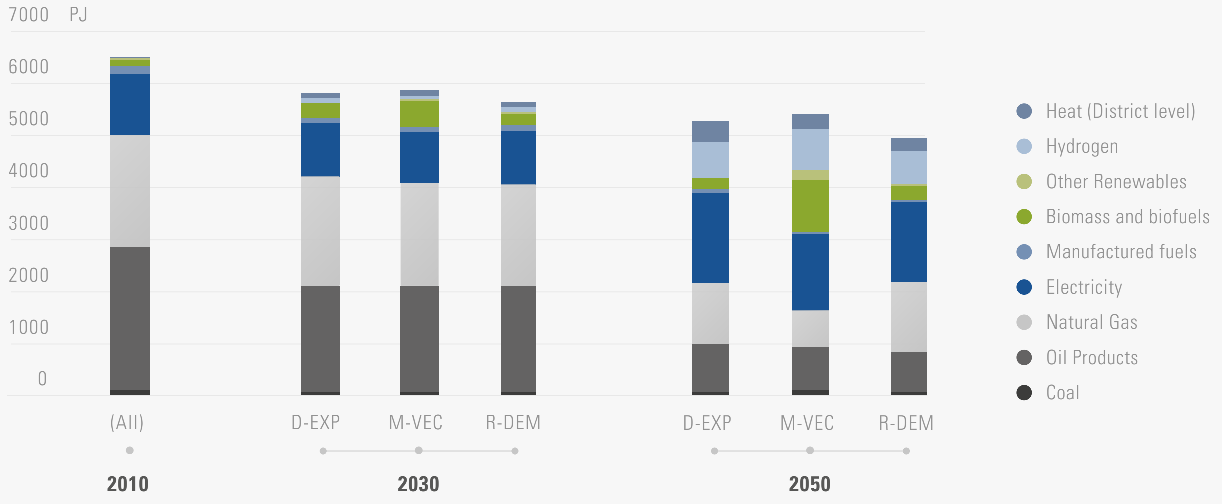


Figure 12. Final energy trajectory, 2010 - 2050



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15 Note that the bioenergy use in CCS in this metric has been allocated zero emissions, not negative emissions, for two reasons. This provides a more transparent view of the role of different technologies, and secondly, bioenergy in CCS could just as easily be used in non-power sectors using CCS given the marginal differences in costs. Although not included in this metric, emission accounting in the model does take account of so-called negative emissions.

extremely effective means of heating and difficult to displace with electric-based systems (as discussed in section 6.2).

Under R-DEM, final energy use is lower due to efficiency gains and lower demand, while under M-VEC there is more direct use of biomass, and other renewables (in 2050) as a means of end-use sector decarbonisation, with lower levels of electrification.

5.3 Increasing investment will be required across the system

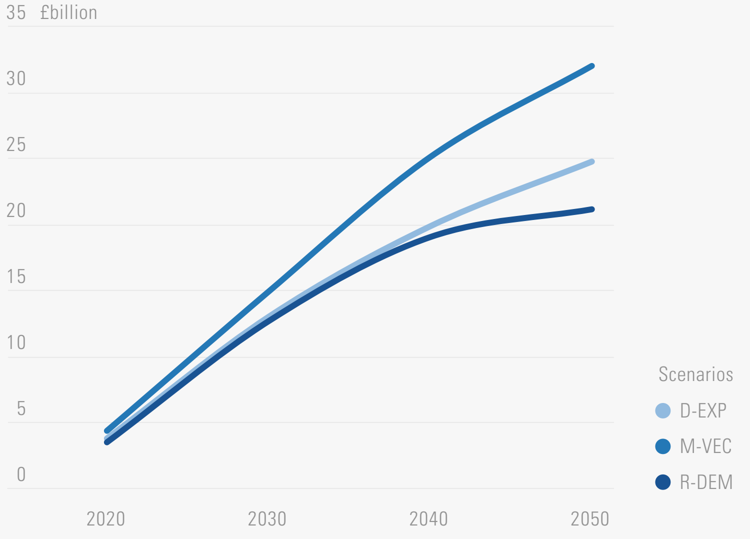
The transitions as fundamental as those presented in this report will require significant levels of capital investment, and at rates much higher than observed historically. This is not only indicative of the system infrastructure needing renewing but a shift towards more capital intensive technologies, essentially a move to a 'fixed' rather than 'variable' cost-heavy system. Increased investment is of course offset by savings across other parts of the system, including fuel expenditure. Given these savings and the need to invest to replace energy system capacity (under any future pathway), many modelling analyses estimate that the additional system costs (compared to a counterfactual) of the low-carbon transition to be in the region of 1-2% of GDP in 2050 (CCC 2008; ETI 2015).

Concerning increasing investment levels, the power sector is a useful example. During the 2000s, annual investment levels were around £1.1 billion, but have increased in recent years (2009-2012) to £4.6 billion. Based on a review of multiple analyses, this increases to annual investment requirements of 6.1, 8.0 and 12.3 £M in 2020, 2025 and 2030 respectively (Watson et. al., 2014). Our modelling estimates also suggest a ramping up of investment levels to 2030, as the power sector decarbonises, and then strong growth post-2030, as electrification of the energy system increases (Figure 13).

The M-VEC scenario has the highest investment levels, due to the focus on wind generation (and the additional back-up capacity required on such a system). The lower investment levels under R-DEM are indicative of the gains that can arise from a system with lower demand levels.

Other analyses have considered the affordability concerns for households of increased investment levels in higher cost technologies. According to an analysis by the CCC (2014b), household bills (both gas and electricity) are estimated to be 14% higher in 2030, relative to 2014, with 9% of the increase attributable to low-carbon policies. However, this rise could more than be offset by energy efficiency measures. Post 2030, reducing costs of low-carbon technologies would reduce the additional support required, ensuring bills do not increase to the same extent. Government will have a key role to play in ensuring households experiencing or vulnerable to fuel poverty are protected from increases, through assessment of distributional impacts of policy (DECC 2013) and a robust fuel poverty strategy (DECC 2014),

Figure 13. Annual investment levels in power generation sector, 2020 – 2050



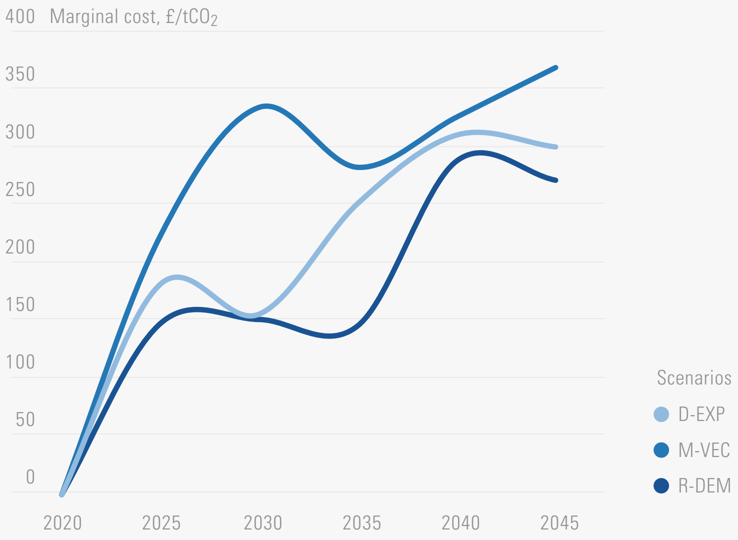
which promotes energy efficiency measures for such households.[16]

5.4 Strong and stable carbon price signals will be needed to drive the transition to a lower-carbon economy

Our modelling suggests that as decarbonisation objectives become more stringent, the incentives (as reflected by a carbon price proxy[17]) necessary to ensure the requisite investment in mitigation will need to increase over time. Going forward, incentives could be an explicit market price for carbon (as under the EU ETS), or policies that ensure investments in low-carbon policies are economically viable (e.g. Contract for Difference (CfDs)). As demonstrated by the recent history of the EU ETS, the market price needs to be both set at an adequate level and stable to provide investor confidence, and this requires effective policy design.[18]

The modelled estimates of carbon prices required under the scenarios highlight the increasing challenge of the 4th carbon budget, shown by the increase between 2020 and 2025 (Figure 14). The continued increase under M-VEC to 2030 indicates delayed and lower uptake of key mitigation technologies in the power sector, namely nuclear and CCS. R-DEM is consistently lower than D-EXP due to the higher efficiency gains, and lower demand observed under this scenario. By 2045, estimates are between £270-370/tCO_2, up from £150 – 250/tCO_2 observed in 2025. The results for 2050 are not plotted but indicate an extremely challenging situation (>£1000/tCO_2), driven by residual emissions that are difficult to mitigate. Potentially indicative of the limitations of our modelling, this also highlights the need for policy makers to address all emission sources by 2050, due to the required reductions to meet the target. Policy makers have also got to contend with large uncertainties in the future, which also relates to the level of incentive needed to deliver the necessary reductions. Pye et al. (2015) highlight that carbon prices need to take account of future uncertainties, which may or may not be sufficient depending on the evolution of technology costs. Key uncertainties identified which could render a lower carbon price ineffective in the longer term include biomass availability (where used in conjunction with CCS) and gas prices, again based on the use of gas with CCS technologies.

Figure 14. Carbon price estimates from modelling, 2020 – 2045



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[16] Many analyses in the UK suggest that tackling fuel poverty and reducing emissions can be delivered through appropriate targeting of energy efficiency measures, as articulated in this response by the CCC. http://www.theccc.org.uk/news-stories/addressing-fuel-poverty-and-meeting-carbon-budgets-go-hand-in-hand-7-october-2014/

[17] The shadow price of CO_2 from the model represents the marginal cost of mitigating the last tonne of CO_2 under the emissions cap.

[18] For example, see latest Sandbag review of the EU Emissions Trading Scheme, http://www.sandbag.org.uk/site_media/pdfs/reports/Sandbag-ETS2014-SlayingTheDragon.pdf

6 Results: Energy demand by sector

The type of low-carbon transitions we are exploring will require significant changes to the way energy is supplied and used across all end-use sectors. This includes changes to fuels, technologies and their utilisation. In this section, we illustrate the changes emerging from the scenarios, focusing on the transport, residential and industry sectors.

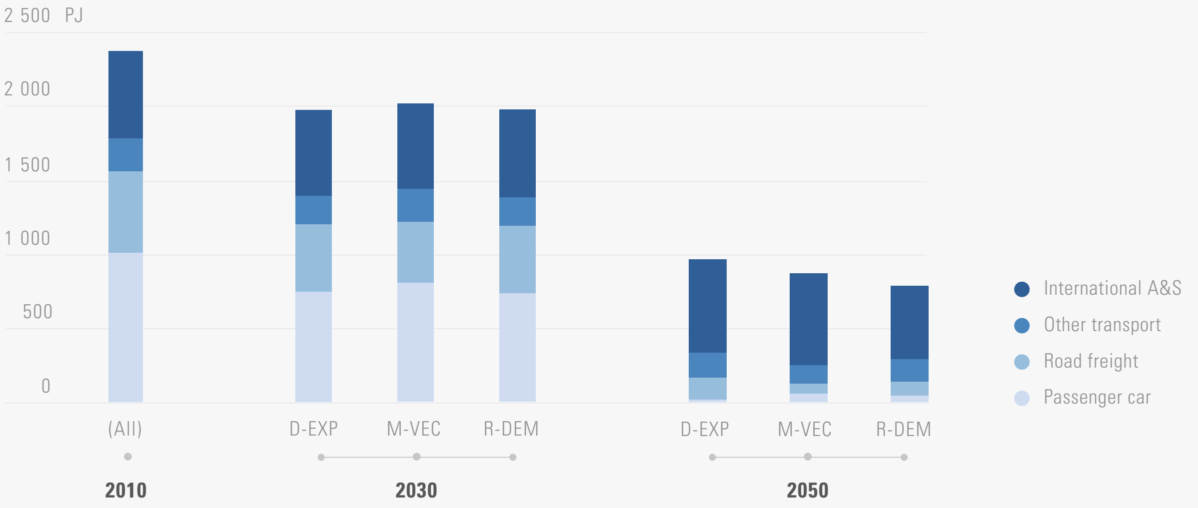
6.1 Transport: a strong decline in oil use, and radical shift in technologies

The transport sector currently accounts for approximately 25% of UK GHG emissions, including emissions from international aviation and shipping (IA&S). Emission reductions in this sector are therefore vital to achieving mitigation objectives, and essentially require a shift away from oil consumption, as illustrated in Figure 15. Total consumption is almost 20% lower by 2030, and 70% lower by 2050. The striking feature is the oil consumption in the international transport sector, which remains at a similar level out to 2050,[19] by which time it is estimated to account for 25% of total UK GHGs. This results in the transport sector maintaining its overall share of emissions (as seen in 2010). The exception is under R-DEM, where slower growth in aviation demand is assumed.

Passenger car demand

This sector accounted for around 43% of transport emissions in 2010. We estimate that across the stock, cars emitted on average 168 gCO_2/km in 2010. Across the scenarios, this carbon intensity will need to reduce significantly by 2050, to less than 10 gCO_2/km as illustrated in Figure 16.[20] Reaching this level of ambition will

Figure 15. Transport sector oil consumption, DDPP scenarios, 2010 – 2050



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[19] Due to demand growth, emissions would be significantly higher in 2050 in this sector were it not for a transition to hydrogen fuel use in international shipping, and strong fleet efficiency gains in international aviation.

[20] The emission intensities reflect direct vehicle emissions. Any emissions from upstream energy production is accounted for in those production sectors, and not reflected in these intensity values.

be helped by European legislation, which obligates manufacturers to ensure that new car sales meet a fleet average of 95 gCO_2/km by 2021.[21] Our modelling suggests that the carbon intensity levels can be achieved by a strong roll-out of more efficient vehicles (based on hybrid technology), and an increasing penetration of electric vehicles in the fleet by 2030, ramping up significantly prior to 2050. This roll-out is based on the 'natural' vehicle stock turnover, not an enforced, more rapid turnover. Across the scenarios there is also a role for hydrogen in the later periods. In our modelling, 40% of new sales of PHEVs and BEVs is achieved under the D-EXP scenario by 2030, increasing to above 90% by 2040. These rates are broadly in line with the necessary market penetration discussed in recent CCC analysis for the 4th Carbon Budget review (CCC 2013). Slightly slower market growth is achieved under R-DEM, due to lower car transport demand, and under M-VEC, due to stronger growth in H_2FC vehicles.

Figure 17 illustrates the transition across the scenarios. The graphic compares the emission level that would occur in 2050 based on the 2010 carbon intensity, fixed in future

Figure 16. 'On-road' carbon intensity of passenger car travel, 2010 – 2050

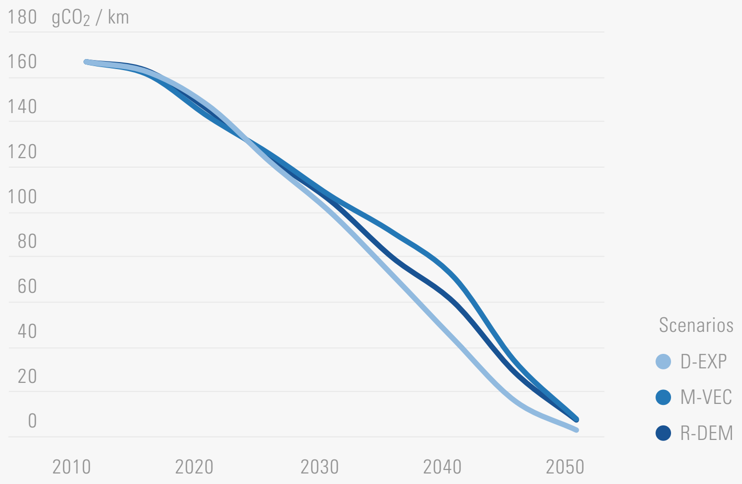
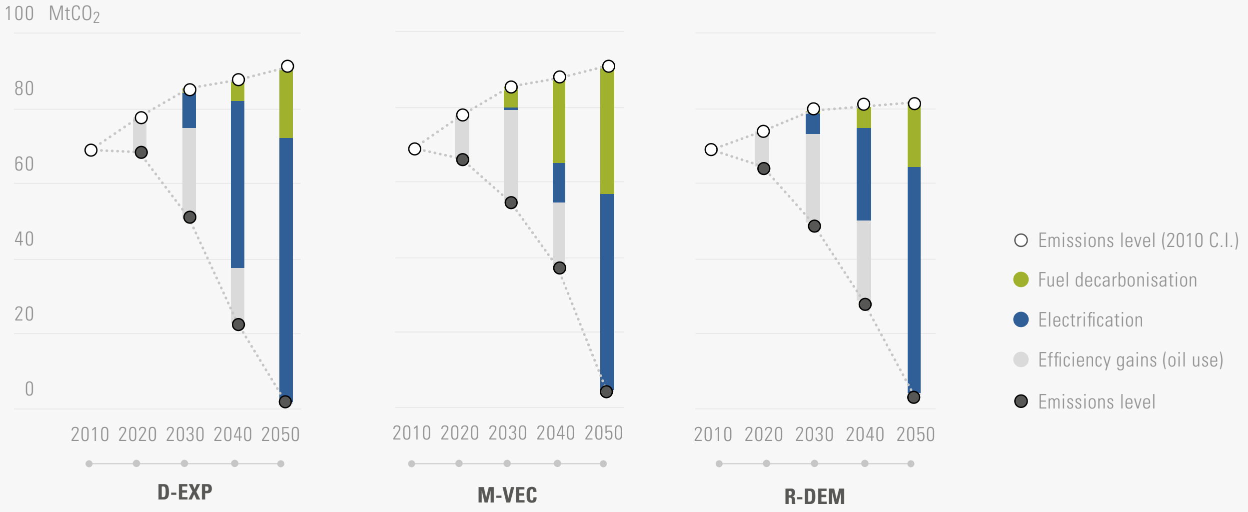


Figure 17. Decarbonisation of passenger car demand, 2020 – 2050



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[21] Details of the legislation can be found at http://ec.europa.eu/clima/policies/transport/vehicles/cars/index_en.htm. Based on the latest data, the current UK average for new sales is 125 gCO_2/km, down from 173 gCO_2/km in 2003, https://www.gov.uk/government/publications/new-car-carbon-dioxide-emissions. This is below the 2015 target of 130 gCO_2/km.

years, versus the modelled emissions level. The contribution by different abatement options is illustrated. Out to 2030, efficiency gains in cars using fossil fuels are shown as grey bars; starting in 2030, low emission vehicles start to pick up, with electric vehicles (BEVs / PHEVs) and H_2FC vehicles (represented as 'fuel decarbonisation').

Lower and later mitigation efforts are seen in the R-DEM case compared to the other scenarios, due to lower demand levels allowing for emissions 'headroom' and lower levels of diffusion, while in M-VEC, earlier uptake of hydrogen and late expansion of electric vehicles market is observed, primarily due to expansion limits of the electricity system and higher costs of electricity.

The role of demand reduction, as illustrated under R-DEM, should not be overlooked, as it is an important mitigation option for this sector. Goodwin (2007) states there is evidence that reductions in car demand of up to 20% could be achieved based on such measures, and that particularly in the longer term, larger reductions are possible based on higher long-run price elasticities. A recent paper by Pye et al. (2014) estimated, based on best available information, that price-induced demand response could see a mean reduction of 6% in car travel demand, but could be as high as 9%. Despite associated welfare losses, this was seen as a particularly cost-effective means of further reducing emissions.[22] Other analysis around the use of behaviour-orientated measures to reduce demand have also shown that up to 10% reduction could be achieved (Cairns et al. 2008, Gross et al. 2009).

Road freight demand

Accounting for 24% of total transport emissions, road freight emissions are made up of heavy (HGV) and light (LGV) goods vehicles (61% and 39% respectively).[23] The average emission intensity of freight transport is around 1400 gCO_2/vkm; to meet emission reduction objectives, this has to fall to between 100-300 gCO_2/vkm by 2050. As illustrated in Figure 18a, the decarbonisation of HGVs is based on a shift to hydrogen-fuelled vehicles in the long term, with compressed natural gas (CNG) vehicles playing an important transitioning role.

By 2050, the whole fleet is using hydrogen in the M-VEC case; in part this reflects the stronger role for hydrogen systems in this scenario. Under R-DEM, lower demand (and emissions) means CNG remains part of the mix. It is important to note a key uncertainty concerning the use of hydrogen in HGVs, with industry questioning the feasibility of such a technology. Without the use of hydrogen, the key alternative pathway is one dominated by CNG. The LGV transition, in Figure 18b, is more characteristic of that seen for passenger cars. Again, a stronger role for hydrogen is observed under M-VEC, with lower levels of low emission vehicles in R-DEM due to the role of demand reduction.

Policy challenges for decarbonising road transport

There are clearly significant policy challenges in delivering the decarbonisation of the road transport sector, through deployment of new vehicle technologies, and ensuring adequate associated infrastructure. For cars and LGVs, our scenarios

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[22] It is important to note the other benefits that could arise from lower traffic levels, for improved air quality, less congestion and noise, and improved public transport provision. In addition, welfare losses calculated could be offset by welfare gains through non-energy expenditure.

[23] HGVs are heavy goods vehicles constructed for transporting goods, with a gross weight of more than 3.5 tonnes while LGVs are light goods vehicles, also constructed for transporting goods, with a gross weight of 3.5 tonnes or less.

point to a particularly important role for electric vehicles. An analysis by Element Energy (2013) suggests that high penetration of electric vehicles could be possible by the second half of the 2020s but that a number of issues need to be addressed. These include financial support to overcome EV price premiums for buyers, sufficient rapid charging infrastructure[24], a range of EV models on the market to cover consumer preferences, and strong consumer awareness of the technology, and associated infrastructure. The cost barrier is viewed as particularly important to

Figure 18a. HGV, Transition in vehicle type for transport freight sector, 2010 – 2050

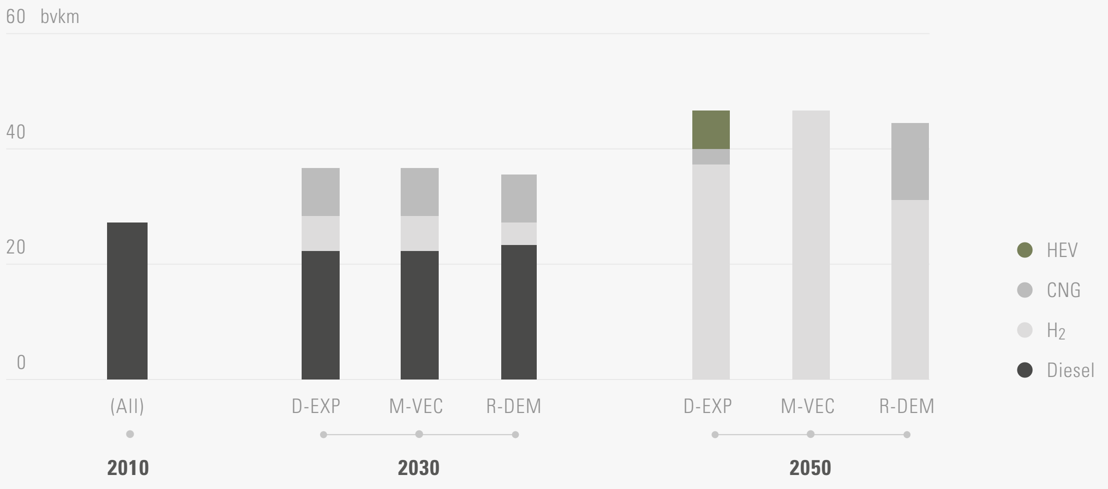
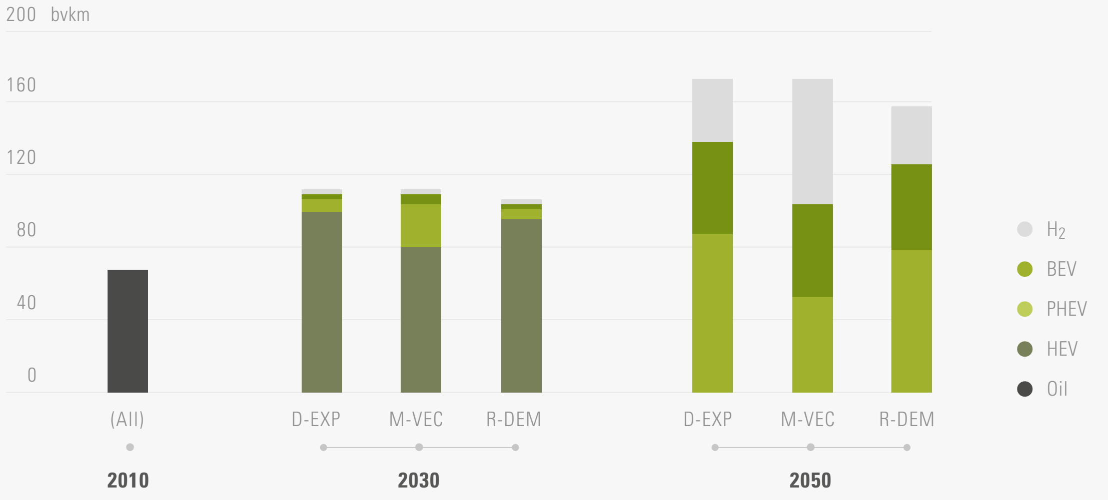


Figure 18b. LGV, Transition in vehicle type for transport freight sector, 2010 – 2050



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[24] The report suggests infrastructure of 20,000 units over 2,100 sites by 2030, compared to around 8,600 liquid fuel stations in the UK currently.

higher uptake; new models of vehicle ownership and finance could reduce the necessary financial support, for example via a battery leasing scheme that spreads the capital cost premium of EVs over a 10+ year period.[25]

In their latest progress report, the CCC (2014) highlight some important developments to ensure increasing uptake of LEVs, particularly EVs. This includes a strong government funding commitment, continued growth in the charging infrastructure, increasing models on the market to meet consumer needs and the important EU legislation on passenger CO_2 emissions. It is key that these measures are sustained and strengthening in future years to ensure the necessary level of transition by 2030 shown in our scenarios, and beyond. One such type of measure identified by a recent UKERC analysis is to ensure that consumers are confident of ongoing support to reduce costs of ownership for low-carbon vehicles that are currently expensive e.g. continued exemption of BEVs from vehicle excise duty (Watson et al. 2014).

In addition to the carbon benefits of decarbonising the transport sector, there could be important economic benefits. Cambridge Econometrics (2015) estimate that on average low-carbon vehicles will be £600 cheaper to fuel, could contribute to a net £7 billion saving for the UK by 2030, and lead to strong air quality benefits, estimated to be worth around £1 billion. There are also potentially wider economic benefits in jobs growth from developing these technologies, and opportunities to help manage electricity supply-demand through helping provide reserve capacity and reducing curtailment[26] from intermittent renewables.

While much focus has been on electric vehicles, it is important that other types of LEVs are not 'ruled out' of the future energy mix. Our scenarios suggest a role for H_2FCs in the longer term, and it is important that measures specific to such technologies are also explored. There do appear to be greater challenges to widespread deployment, particularly due to the higher infrastructure cost and challenging business model to provide an extensive re-fuelling system, and the assumed higher costs of the vehicles. However, a number of car manufacturers are actively pursuing the development of such fuel cell technologies (e.g. Honda and Toyota), but strong uncertainties remain around how fuel cell technology costs will evolve in the future.

The role of biofuels is limited under all scenarios, reflecting the limited bioenergy resource for use across the system. Biofuels are only domestically produced, with no imports permitted, and the use of bioenergy is focused in other parts of the energy system. As a result, the share of biofuel liquids in the transport sector only ever reaches a share of between 5-10%. However, increased biofuel use could be foreseen if imports were permitted, and domestic production technologies were more cost-effective, particularly given the need to displace fossil liquids in the IA&S sector.

While our scenarios show a strong reduction in emissions from freight vehicles by 2050, through the use of natural gas and then hydrogen, it is important to note the even larger challenges to ensuring such a transition. Firstly, there is a lack of overarching policy framework to drive HGV efficiency gains, in the same way that the European legislation does for passenger cars, primarily due to the problems of establishing methods for assessing whole truck efficiency. Secondly, the move to CNG and then hydrogen trucks is

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[25] Further information on innovative financing mechanisms is provided in CCC (2014).

[26] Curtailment effectively means that generators have to reduce their output as it is not needed by the grid operator to meet demand.

going to require large scale investment in vehicle technology development and associated infrastructure. Finally, as mentioned earlier, there is a question about the viability of H_2 use in larger goods vehicles.

Non-road transport

Non-road transport emissions are dominated by international aviation and shipping. They accounted for 6% of total GHG emissions in 2010, with this share projected to rise to 25% in 2050, highlighting the entrenched oil use in the aviation sector. Our modelling assumes the energy demand for international transport grows by approximately 40%, despite efficiency gains, largely driven by international aviation. By 2050, the shipping sector does not contribute to any emissions in the sector as it is assumed to have switched entirely to hydrogen.

As with hydrogen use in HGVs, there is considerable uncertainty as to whether the global infrastructure could be put in place to support hydrogen supply to ships. Without this mitigation measure in shipping, international transport emissions would likely to be 15-20% higher. Limited fuel switching potential in the aviation sector means emissions cannot be reduced significantly; the obvious switch to biofuels is not observed as available bioenergy is used in other sectors, and imports of biofuels are limited (see section 7.4).

It is important that alternative options are explored in future modelling, to better understand what additional options could be considered. Other systems analyses (e.g. Pye et al. 2014) point to an important role for demand reduction measures in the aviation sector, where increasing carbon prices (assumed to be passed through to fares) result in a strong price induced demand response based on own-price elasticity assumptions, thereby lowering demand. A slower growth in international aviation under the R-DEM scenario, resulting in 20% less energy demand by 2050, helps contribute to mitigation costs that are almost 20% lower than seen under D-EXP.

The Government has a strong role to play in managing the growth of the aviation sector, by ensuring that any additional airport capacity expansion takes account of the sector's role in meeting the longer term emission reduction targets. The independent advisory body, the CCC (2013b), noted recently in a letter to the Airports Commission that emissions levels in 2050 should be no higher than in 2005, and given reasonable assumptions on efficiency improvements and biofuel availability it should plan to limit growth to 60% of 2005 demand levels. As our modelling indicates, higher emissions from international transport put pressure on other sectors to mitigate. CO_2 emissions excluding international transport need to reduce by almost 90% by 2050, which as the marginal abatement costs indicates (section 5.4), is stretching feasibility given our current understanding of mitigation options.

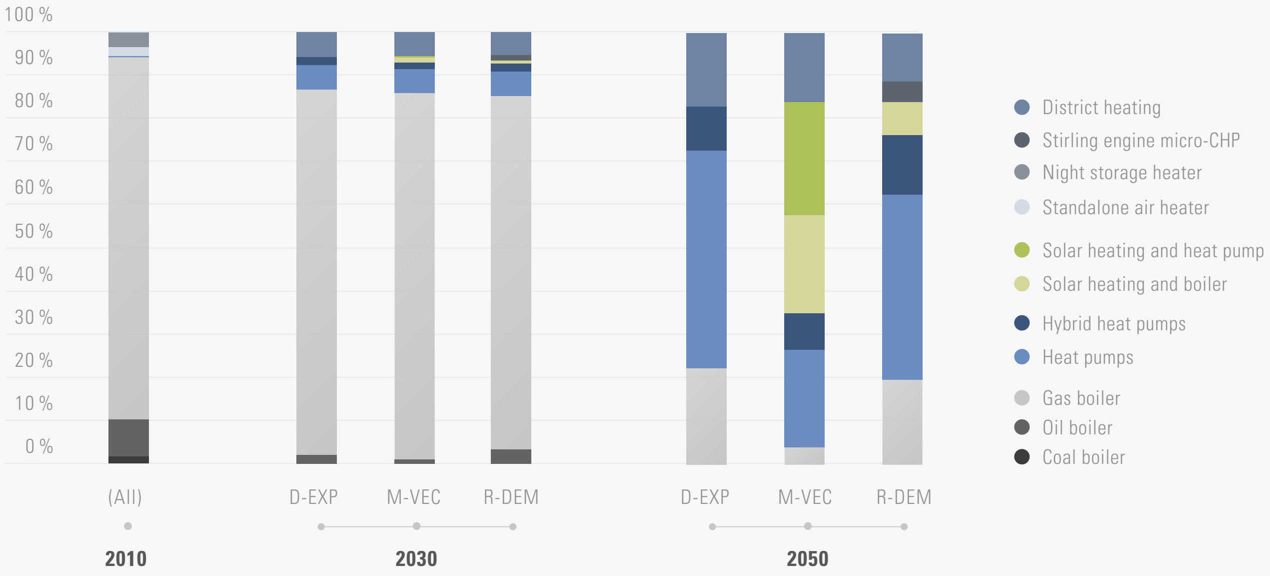
6.2 Residential buildings: a transition requiring a strong re-orientation of energy service provision

Direct emissions from the energy used in buildings accounted for 19% of total CO_2 emissions (including IA&S), or 16% of total GHGs. 80% of building sector emissions are from the residential sector, the vast majority of which come from gas use for heating (Figure 3). Therefore, this section of the report focuses on decarbonising residential space and water heating.

From a system wide perspective, the modelling suggest that carbon intensity of energy used in the residential sector will need to halve by 2050. This reduction in intensity, alongside energy efficiency measures, could lead to emissions from this sector falling to between 10 and 38 $MtCO_2$, from the 2010 level of 83 $MtCO_2$. Figure 19 illustrates how the residential heating sector could transform. In 2030, it remains dominated by gas-based central heating systems but with increasing penetration by heat pumps and district heating. By 2050, a radical shift has occurred, away from gas-based systems to heat pumps and hybrid heat-pump / gas systems.

Across all scenarios, the radical shift away from gas use is striking, with implications for gas distribution systems and how they might be operated in the future. However, gas use is difficult to fully shift; this is because it still plays an important role in meeting the heating demand peak in the winter. This peak is very high, with heating needs between 2-4 times higher during a winter evening than during the day. The major problem is lack of storage for electricity; to build a generation system that can cope with a winter peak demand is going to be extremely costly, as much of the capacity would be catering for this short but critical period. Hence the role of gas, providing 'top-up' heating during such periods, and working in conjunction with other technologies e.g. hybrid heat pumps, solar thermal systems. In 2050, the M-VEC scenario is quite distinctive; firstly, it has a much stronger use of solar and a lower use of gas, underlining a higher contribution to mitigation from this sector; it also has lower levels of electrification. Under R-DEM and D-EXP, heat pumps using electricity provide larger shares of heating provision. The role of district heating is also shown as increasingly important, although its growth is constrained by the challenges of building new infrastructure, and the limited options for providing carbon-free

Figure 19. Share of heating demand by technology in the residential sector, 2030 / 2050



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27 This is a potential mitigation option that is not adequately represented in the modelling; for example it is an important source of heating in other analyses e.g. ETI (2015). Further work is required to understand the potential for waste heat use and other heat from renewable sources (geothermal, marine heat pumps) in district heating systems, particularly the spatial constraints.

heat into the system, with most bioenergy more cost-effectively used in other sectors and limited potential in the model for using waste heat.[27] The R-DEM scenario also highlights the importance of a stronger push on energy efficiency measures, reducing final energy demand. This contributes to lower marginal costs of mitigation (Figure 14), and reduced costs of energy in this sector.

Challenges and policy needs

Depending on the assumptions of the analysis, a range of different residential sector heating supply systems could be envisaged, as shown in Eyre & Baruah (2015). Our modelling does however suggest a strong role for heat pumps across all of the scenarios (and to some extent district heating), and large reductions in gas, although its use does persist.

In addition to the necessary investment, a major challenge of delivering this change in energy service provision will be offering householders the necessary technology solutions and incentives to switch away from what is a very well-understood and convenient heating system, gas central heating. Infrastructure issues include ensuring distribution networks are adequately reinforced to provide for widespread heat pump use, ensuring continued gas supply through the existing infrastructure at low flow rates, and developing district heat networks.

Acceptability of new investments and associated affordability concerns by householders are also important issues that policymakers will need to grapple with. This is evident from the political sensitivity to fuel price rises, and the ongoing challenge of tackling fuel poverty (DECC 2014). However, there is an opportunity to increase affordability and address the fuel poverty challenge through targeted implementation of energy efficiency programmes.

The UK still retains significant potential in its existing building stock to make energy efficiency gains. However, the difficulties in incentivising householders to take-up such options are well known, and therefore it is critical that Government put the right mix of policies in place. There have been concerns that the current ECO and Green Deal package of measures are not achieving the rates and type of retrofit that is required to realise the necessary efficiency gains. This reflects a focus by ECO on more expensive options in harder-to-treat buildings, and inadequate financing incentives via the Green Deal. The CCC (2014) recommend a number of ways of strengthening the package going forward, which would not be subject to change that would increase industry uncertainty. A range of other commentators have suggested important changes necessary to improve the effectiveness of energy efficiency policy (for example, Rosenow and Eyre 2014), and how it can be more effectively targeted on those in fuel poverty (for example, Platt et al. 2013).

The dramatic shift away from gas observed by 2050 means the need for the current policy to start pushing low-carbon heat technologies. The RHI offers incentives for technologies such as heat pumps and solar thermal, and is therefore the main existing mechanism. The CCC (2014) note the need to increase the limited take-up to date by addressing non-financial and financial barriers associated with the RHI, and extending the policy timeframe to reduce investor uncertainty. They also point to additional measures to really scale technology uptake, potentially through a carbon price on heat and mandating installation through building regulations.

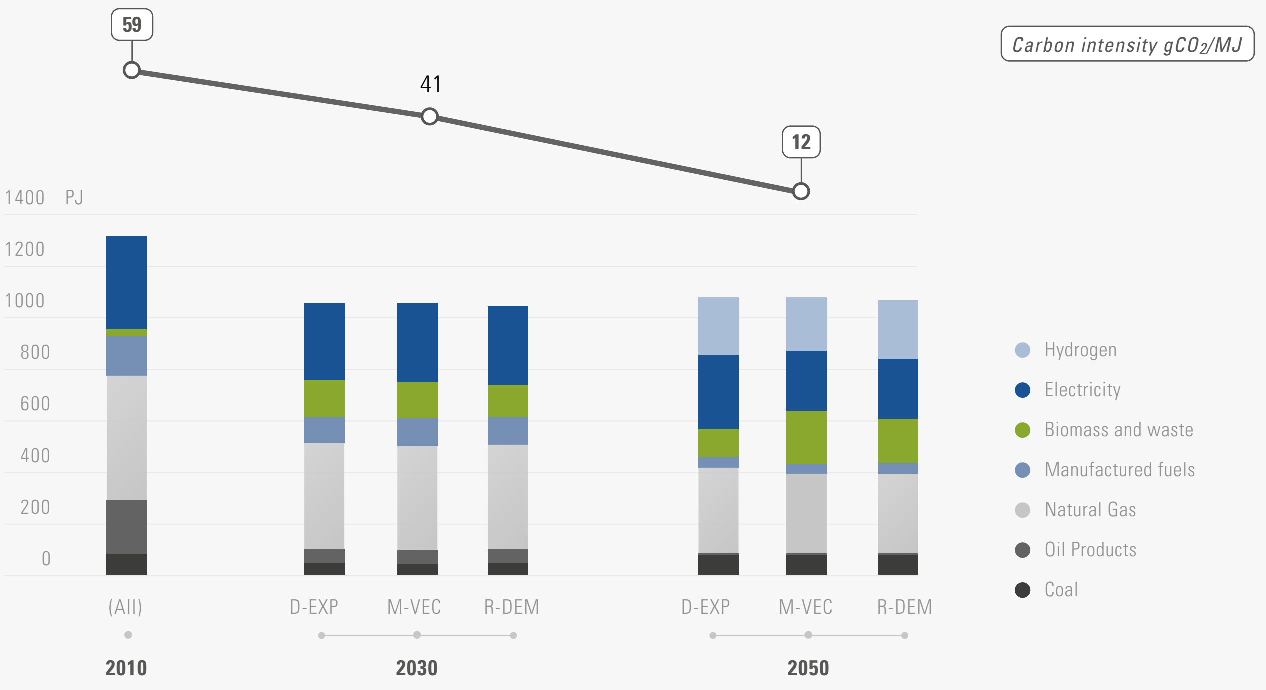
6.3 *Industry: a major innovation challenge to remain competitive and decarbonise*

In 2010, emissions from the industrial sector in the UK accounted for approximately 11% of total greenhouse gas emissions, at 72 $MtCO_2$, while the sector was responsible for just over 20% of final energy consumption. In terms of fuels, demand is currently dominated by natural gas and electricity which each account for a third of final consumption. In addition to emissions from fuel combustion, emissions from industrial processes, like cement or sinter production, which amounted to 12 $MtCO_2e$ in 2010, need to be taken into account. The UK industry sector has already in the past experienced a shift to high-value, less energy intensive subsectors, and this is expected to continue. In the future, the sector will face the dual challenge of implementing low energy and low-carbon technologies while at the same time maintaining international competitiveness. Before outlining the various mechanisms which lead to sector decarbonisation, an overview of the development of industrial energy consumption and carbon intensity is provided in Figure 20.

In all three scenarios, GHG emissions drop by more than 80% until 2050 compared to 2010 (over 90% compared to 2010). This represents the highest emission reduction of all end-use sectors; only in the scenario M-VEC a similar cut in GHG emissions is realized in the residential sector.

Final energy demand sees strong reductions of up to 20% between 2010 and 2030, through a combination of falling output levels and energy efficiency efforts. After 2030, with limited efficiency potential remaining, the sector moves towards increasing decarbonisation of energy use, particularly through the use of CCS technologies and radical process changes in some energy-intensive subsectors (as discussed later in this section). In terms of the fuel mix, the use of bioenergy for low temperature heat increases until 2030, followed by increasing deployment of hydrogen boilers,

Figure 20. Development of final energy consumption, Carbon intensity in the industry sector



mainly at the expense of gas and oil products. Contrary to other end-use sectors, no shift to electrification occurs in any of the scenarios, highlighting limits on the role of electricity for process heating. Limited differences are observed between scenarios due to few variations in scenario definition for this sector.

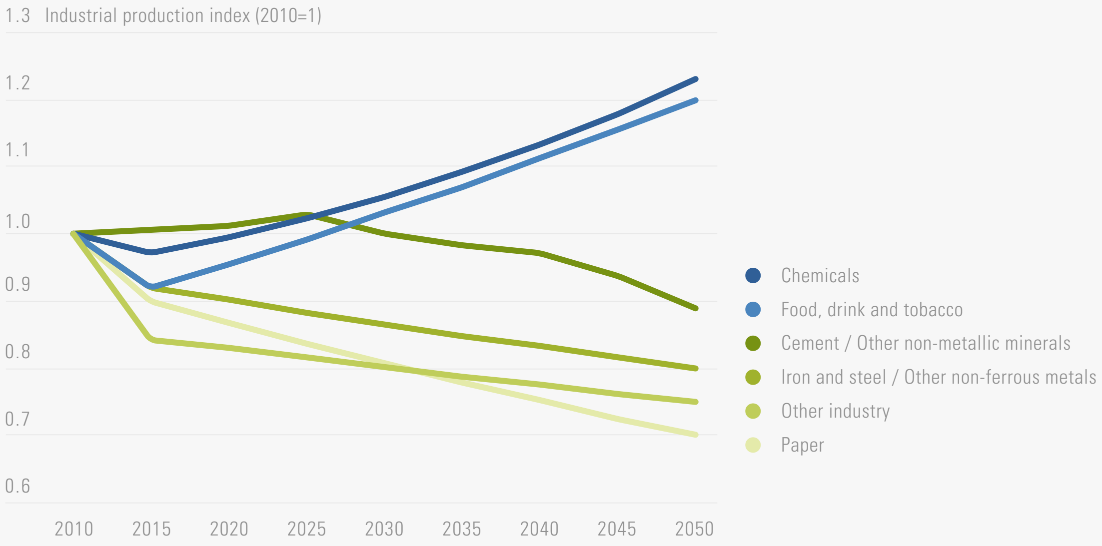
Reduction in industrial production levels

One of the factors leading to falling energy consumption and emissions in the industry sector is the continued shift to less energy-intensive subsectors. The production trajectories shown in Figure 21, and used in the modelling, are based on the econometric-based DECC Energy and Emissions Projections model (EEP), and reflect changes due to domestic demand and international market competitiveness effects. The projections show that apart from the chemicals sector, falling productions levels are expected in all energy intensive industry sectors. Due to the continuous trend to digitalisation, the paper industry exhibits the strongest reductions with a reduction of 30% in 2050 compared to 2010. The decline in the broad category of non-energy intensive "other industries" can be explained by the previously mentioned shift to high-value, less energy consuming subsectors.

Energy efficiency gains

Saygin (2012) has identified significant unexploited potential for energy efficiency improvements in the industry sector as a major decarbonisation strategy. In our scenario analysis, a persistent trend towards reduced energy intensity can be mainly observed in the non-energy intensive industry sectors (Figure22a), especially through the use of more efficient boiler technologies and hydrogen technologies. In the energy intensive sectors (Figure22b), a continued increase in energy efficiency is only realized

Figure 21. Development of industrial production (2010=1) *



** It should be noted that in case of the energy intensive sectors (iron and steel, cement, paper and part of the chemicals industry), the demand projections describe changes in aggregate output (in tonnes), while in the case of the remaining sectors, both changes in output and energy intensity are taken into account and demand is expressed in terms of PJ of useful energy.*

in the paper industry through the improvement of existing production routes (e.g. online moisture management, several improvements to the press section and a switch to impulse drying) and a limited uptake of the alternative production process of dry sheet forming after 2035. In all other energy intensive branches, initial energy efficiency gains are counteracted by the deployment of CCS technologies after 2030. The efficiency penalty of using CCS varies strongly between industrial technologies, with an increase in energy input compared to the respective technology without CCS of between 10 and 30%. Considerable increases in energy intensity due to the higher energy consumption of production plants with CCS

Figure 22a. Development of energy intensity in the non-energy intensive industry subsectors (scenario average)

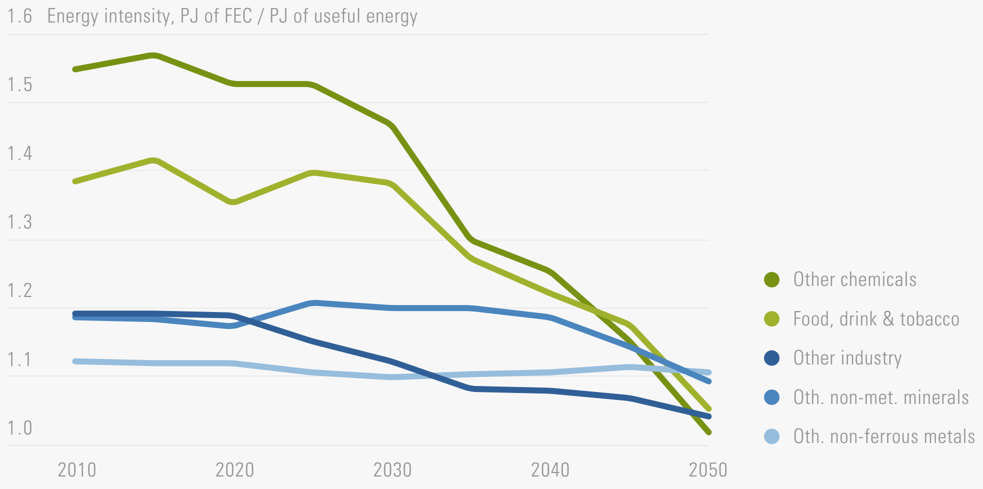
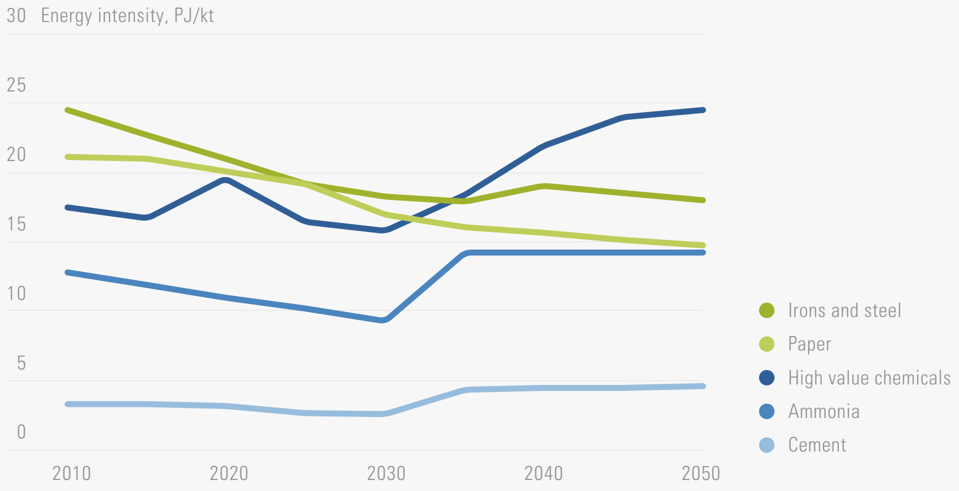


Figure 22b. Development of energy intensity in the energy intensive industry subsectors (scenario average)



occur particularly in the chemicals industries.

Decarbonisation of the fuel mix

In addition to reducing energy intensity in the production of manufactured goods, the decarbonisation of input fuels represents an essential abatement strategy for the sector, particularly after 2030 (as shown previously in Figure 10). Until 2030, limited progress is made through an increased use of bioenergy technologies for low-temperature heat and a slightly higher share of electricity in the fuel mix, mainly at the expense of oil products (Figure 20). In the long-term, biomass plays the most significant role in the scenario M-VEC with a share of 19% in total industrial energy demand in 2050 compared to 10% in the scenario D-EXP.

At the same time, the relative and absolute importance of electricity decreases in all three scenarios, with the strongest reduction of 38% between 2010 and 2050 in the scenario M-VEC. A decline in electricity use can particularly be observed for technologies providing high-temperature heat in the non-metallic minerals and the non-ferrous metals industry (mostly replaced by hydrogen) and for low-temperature heat boilers in the food & drink and other industries (mostly replaced by biomass).

Due to the possibility to produce hydrogen in centralized plants with carbon capture, the use of hydrogen becomes a significant low-carbon fuel option from 2040 onwards with a share of up to 21% in final energy consumption in 2050. Its primary use is in industrial boiler technologies for the provision of high and low temperature heat, and for drying and separation services.

Carbon capture and storage is identified as a key means of decarbonisation in a variety of recent reports (Saygin 2012, DECC 2012b, IEA 2013), in particular for the abatement of process-related emissions. In the model analysis, CCS is represented in the iron & steel, cement and chemicals industry. In all three scenarios, industrial CCS technologies are deployed from 2035 onwards and there is less variation between the scenarios compared to the use of CCS in electricity and hydrogen generation. The chemicals sector (both ammonia and high value chemicals production) has the highest level of CO_2 captured by 2050 (Table 3).

Radical process changes in energy intensive subsectors

Decarbonisation can also be achieved by implementing some radical technological changes in the energy intensive industry branches. In the cement industry, the main changes consist of the deployment of more energy efficient fluidised bed kilns as well as kilns with higher waste utilization from 2025 onwards and the option to reduce the amount of clinker required per unit of cement by substituting for other materials. In the scenario M-VEC, a limited shift to a 'low-

Table 3. Carbon captured in the industry sector by technology (scenario D-EXP)

Sector	Technology	CO_2 captured, Mt (cumulative, 2033 - 2050)
Iron & Steel	HISarna steelworks with CCS	53.1
	Top-gas recovery blast furnace with CCS	47.7
Cement	BAT kiln with Partial Oxy-combustion CCS	2.9
	BAT kiln with MEA Post-combustion CCS	80.2
Ammonia production	Steam reformer with CCS	43.7
High Value Chemicals	Steam cracking with post-combustion CCS	90.4
Total		**318.0**

CO_2' cement production process representing technologies like Novacem, E-Crete, Celitement or Aether (Net Balance Foundation 2007, Stemmermann et al. 2010, Velandia et al. 2011, Walenta 2011) can also be observed.

Due to the high uncertainty of these technologies, relatively high cost assumptions are assumed and their share in total cement production is limited to 20% in 2050. In combination with the use of CCS technologies, the carbon intensity of cement production in the UK decreases by 75% from about 640 $kgCO_2e/t$ of cement in 2010 to 160 $kgCO_2e/t$ in 2050 in all three scenarios (excluding emissions from electricity and hydrogen generation). Compared to the intensity estimates of 240 - 390 $kgCO_2e/t$ of cement in 2050 provided in the IPCC's 5th Assessment Report (Fischedick et al., 2014), these reduction levels are more radical.

About three quarters of the steel production in the UK is currently produced through the coke oven - blast furnace route (integrated steel production), while the remaining share relies on the substantially less energy and emission intensive electric arc furnace route. The expansion of the latter option is, however, constrained to 40% in the model due to the limited availability of metal scrap. Because of the comparatively long technology lifetimes and the current overcapacities in the UK steel industry, radical changes only occur after 2030. A shift to more efficient blast furnaces (top-gas recovery and HIsarna steelmaking processes) is realized, mostly in combination with carbon capture.

With respect to the electric arc furnace route, a shift to Comelt furnaces occurs in all scenarios. Other new production technologies, like the ULCORED or MIDREX direct reduced iron route, do not become competitive. The combined use of innovative production technologies, CCS and a limited shift to hydrogen boilers result in a reduction of the sector's carbon intensity from about 2 tCO_2e per ton of steel in 2010 to 0.2 tCO_2e/t in 2050 (including emissions from blast furnaces, but not from coke ovens and excluding emissions from electricity and hydrogen generation), compared to the IPCC's estimates of 0.47 to 0.84 tCO_2e/t of steel in 2050 (including the emissions of coke ovens) (Fischedick et al., 2014).

For the paper industry, no radical process changes are expected in the future. Through the application of various energy efficiency options to existing production routes and a slightly increased share of electricity, the carbon intensity of paper production in the UK declines from 315 $kgCO_2e/t$ of paper products in 2010 to 160 $kgCO_2e/t$ in 2050 (excluding emissions from electricity and hydrogen generation); IPCC's estimates are 160 to 200 $kgCO_2e/t$ of paper in 2050 (Fischedick et al., 2014). Emission mitigation in the production of ammonia and high value chemicals is strongly focused on CCS technologies from 2035 onwards. In the mid-term, a switch to the highly efficient autothermal steam reforming can be observed in ammonia production. The uptake of Fischer-Tropsch technologies in steam cracking remains limited, due to the assumed high costs.

Challenges and policy needs

Decarbonisation in the UK's industry sector relies on a combination of several mitigation strategies, including a shift to high-value, less energy-intensive subsectors, progress in energy efficiency, the decarbonisation of the fuel mix and some radical process changes in the most energy-intensive subsectors. Some significant challenges and uncertainties can be identified with respect to this transition. In some energy-intensive sectors, especially those with high levels of process-related emissions, abatement is strongly focused on the deployment of CCS technologies. However, the implementation of CCS in industry depends strongly on the availability of the associated CCS infrastructure which, in turn, is contingent on the successful deployment in electricity (and possibly hydrogen) generation.

Moreover, major innovative efforts are required to ensure that the expected radical technological changes in some of the emission-intensive sectors are actually realized. Significant uncertainty also exists around the long-term production levels of the UK's manufacturing industry and its international competitiveness. Such considerations around competitiveness to some extent limit the scope for high cost decarbonisation in the near term.

From a policy perspective, the high level of heterogeneity in the sector makes the design and implementation of effective policy instruments particularly challenging. Various research efforts have been undertaken in recent years to evaluate the energy and emission reduction potential of various industrial sectors.[28] To incentivise industrial decarbonisation, establishing strong and predictable carbon price signals will be essential. The energy-intensive industries are covered by the European Emissions Trading Scheme which, assuming that the price will recover, could induce the required mitigation efforts. In addition, strengthening the research and innovative capacity of the UK industry sector will help to realize the low-carbon transition at reasonable costs. In this context, special policy support will probably be required for the CCS industry. Finally, policy can play a role as information provider and to encourage energy management systems, especially in less energy-intensive branches.

7 Results: Energy supply

7.1 Decarbonisation and expansion of the electricity system

The carbon intensity of electricity generation has to fall significantly by 2030, to less than 75 gCO_2/kWh (as per the scenario results) to ensure mid-term mitigation objectives, and subsequent longer term targets can be met (Figure 10). The near term focus on this sector reflects both the cost effectiveness of mitigation efforts in this sector, including the ability to tackle large point sources of emissions over a shorter time period. From an investment perspective, the UK is at a point in time when it needs to replace much of its current nuclear and coal capacity over the next 15-20 years; therefore, there is also an opportunity to transition to a much lower carbon system at limited additional cost.

However, it is likely to be a challenging transition to 2030. The capacity of the system in 2010 was predominantly fossil-based (Figure 23). Shifting towards a low-carbon system will require large increases in investment (Figure 13), changes in system operation through smarter systems and an effective package of policy measures to incentivise such changes. Some progress is being made in the sector; since 2010, wind capacity has more than doubled (from 5 to 10 GW), support-

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[28] See for example the UKERC project "Industrial Energy Use from a Bottom-up Perspective" (*http://www.ukerc.ac.uk/programmes/energy-demand/industrial-energy-use-from-a-bottom-up-perspective.html*) and DECC's Industrial 2050 Carbon Reduction and Energy Efficiency Roadmaps Project (*https://www.gov.uk/government/publications/industrial-decarbonisation-and-energy-efficiency-roadmaps-to-2050*)

[29] Energy Trends 2015 (DECC publication), *https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/415976/ET_Mar_15.PDF*

[30] UK CCS commercialisation project, *https://www.gov.uk/uk-carbon-capture-and-storage-government-funding-and-support*

ed by the Renewable Obligation mechanism, while solar capacity, supported by a feed-in tariff mechanism, has grown from less than 100 MW to over 5000 MW.[29] Other lower carbon generation types are also being developed; Hinckley C represents the start of a potentially larger new nuclear build programme, while the Government's CCS demonstration programme has gained some much needed momentum in the last 2 years.[30]

Routes to decarbonisation

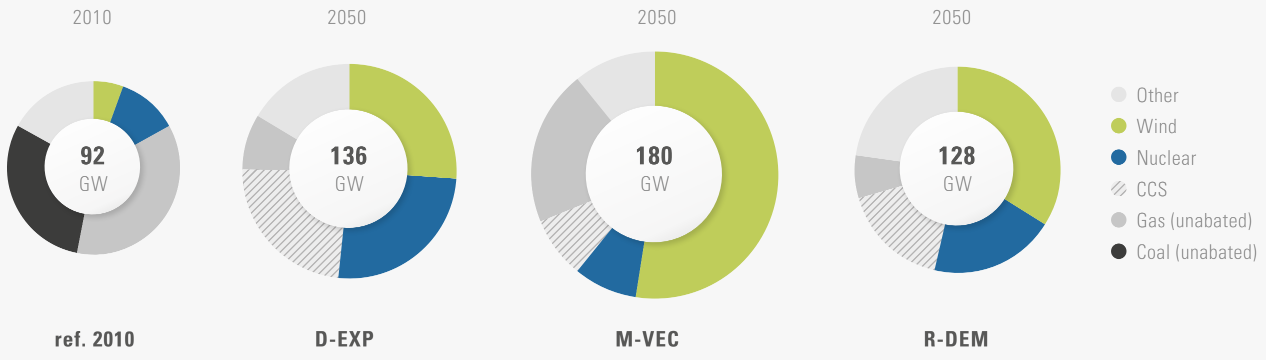
Our modelling suggests that generation system decarbonisation to 2030 will largely be achieved by three key technologies – wind, nuclear, CCS - with different mixes depending on the assumptions made. The D-EXP scenario, for example, highlights a strong role for both nuclear and wind generation to 2030, and the transition towards CCS technologies using gas underway. M-VEC shows a pathway strongly reliant on wind generation (Figure 24).

Post-2030, the expansion of the system can be observed, due to increasing electrification of end-use sectors. Under D-EXP, the system is approximately 50% larger in 2050 compared to 2010, and with similar but slightly lower growth under R-DEM due to lower demand levels. Under M-VEC, despite lower levels of end-use sector electrification, growth is closer to 100%, reaching a system size of 180 GW, due to the strong contribution from wind generation, and the need for low utilisation back-up capacity (as shown by the share of gas plant capacity in Figure 23).

In all scenarios, coal generation is no longer in the system by 2025, and unabated gas generation has decreased to very low levels by 2030, effectively providing generation during peak periods only. Under D-EXP, generation levels increase most rapidly post-2030, accounting for 40% of final energy consumption. This higher electrification is due to a more cost-effective mix of technologies being deployed, lower infrastructure investment requirements and lesser challenges to system operation, due to a higher thermal generation contribution. The growth is primarily driven by increased demand from residential heating and car passenger and light freight transport sectors (Figure 24).

D-EXP assumes expansion of CCS is contingent on 10 GW deployment by 2030. ETI (2015b) recently published a study that shows that such a deployment is possible, and will lead to cost reductions compared to a situation where CCS deployment is delayed. This will of course require significant investment (£21-31 billion), and the necessary

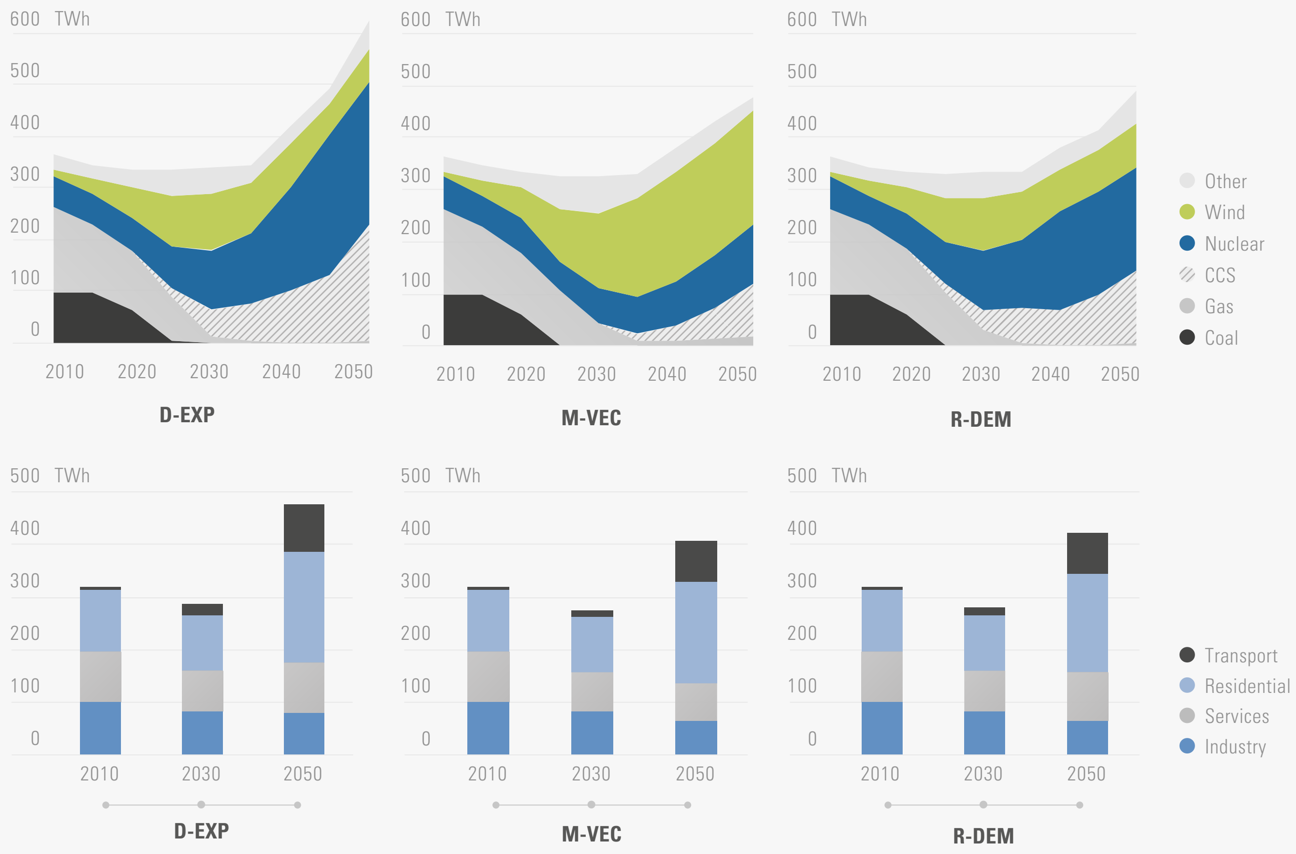
Figure 23. Capacity levels in power generation sector, 2010/2050



support to allow profitability in the wholesale market. The scenario also assumes a strong roll out of new nuclear capacity, with reduced public acceptability concerns and continued investment support by Government, as provided for Hinckley C under the CfD mechanism. It is important to note that both technologies are subject to strong uncertainties; for nuclear, this is whether rapid roll-out can be achieved cost-effectively given delays across other 3rd Generation plant builds, while for CCS, the concerns are around Government support in the UK and elsewhere to effectively demonstrate the technology at scale and its integration across all system elements (capture, transport and storage).

The other two scenarios also provide credible pathways, both of which result in lower levels of end-use sector electrification to those under D-EXP. In the case of M-VEC, a system emerges that is wind dominated, with limited deployment of nuclear and gas CCS technologies. By 2050, wind capacity is over 90 GW, mainly driven by offshore wind deployment. Key system operation challenges emerge under such a high renewable-based system; in their Renewable Energy review, based on studies such as Poyry (2011), the CCC (2011b) state that the costs of dealing with intermittent generation at levels higher than those shown in M-VEC are likely to be low relative to generation costs (~1 p/kWh), through

Figure 24. Power generation by type (top) and sectoral electricity consumption (FEC) (bottom), 2010-2050



options such as demand-side response, interconnection, and balancing generation.

There are however important economic considerations; investment levels (and capacity levels) are significantly higher than under this portfolio (see Figure 13), and the costs of generation can be significantly affected if the system cannot be adequately managed e.g. curtailment can occur where wind is available, but the grid operator does not require the power on the grid, or shedding where higher wind generation means other low-carbon sources do not generate. Key to this are the different options for managing such situations, including electricity storage, using electricity to generate other energy forms e.g. hydrogen via 'gas-to-grid' and interconnectors. There are also issues around market design to ensure the necessary incentives are in place to ensure for a secure and cost-effective generation system.[31]

While the generation supply mix is similar to D-EXP, the R-DEM pathway has lower generation levels due to a stronger focus on demand side action. In the longer term, this leads to a smaller system that does not require the same levels of investment across nuclear and CCS technologies. In summary, all scenarios show the need for decarbonisation by 2030 for cost-effective pathways and that end use sector electrification is critical in the long term. This finding is well understood, both in the UK (Ekins et al. 2013) and in other countries (SDSN & IDDRI 2014; Williams et al. 2012). The key challenge is now delivering the transition through effective policies, balancing the role of different technologies.

Challenges and policy needs

There are a number of key challenges; to 2030, the systems has to move away from mature to less well understood technologies, and to new modes of systems operation. Timing is also critical; investment levels need to be scaled, and CCS, nuclear and offshore wind programmes need to be well developed. Post 2030, system build out needs to be scaled significantly to deal with increasing end-use electrification.

Therefore, policy needs to address this challenge, ensuring that a framework is in place that will allow the market to orientate towards low-carbon forms of generation. The Electricity Market Reforms (EMR) provide an important platform, by providing additional support to low-carbon sources (via CfDs), setting a carbon floor price and limiting new coal plant. As discussed, Government also has a strong role to help 'back' certain technologies, recognising market limits, as it is doing via its CCS commercialisation programme and financial guarantees for Hinckley C. A recent report by a UK Government parliamentary committee (ECCC 2015), while welcoming progress on EMR implementation, noted concerns that elements of EMR risked *pursuing competing aims rather than complementing each other*. Focusing on the capacity mechanism, they highlighted that 80% of the successful agreements were going to existing generating capacity, including coal-fired power stations, and that this risks *locking us into a higher carbon and more expensive trajectory than needed.*

The key challenge noted by the CCC (2014) for Government is that it needs to provide greater certainty about how the EMR policy will evolve in the 2020s, to ensure investor confidence in low-carbon technologies. The difference in current policy outlook versus the lead time for key technologies is illustrated in Figure 25, highlighting that the policy timeframe needs to be much longer to ensure certainty for project investments with long lead times. The CCC state that *the best way to do this is to announce strategies for the*

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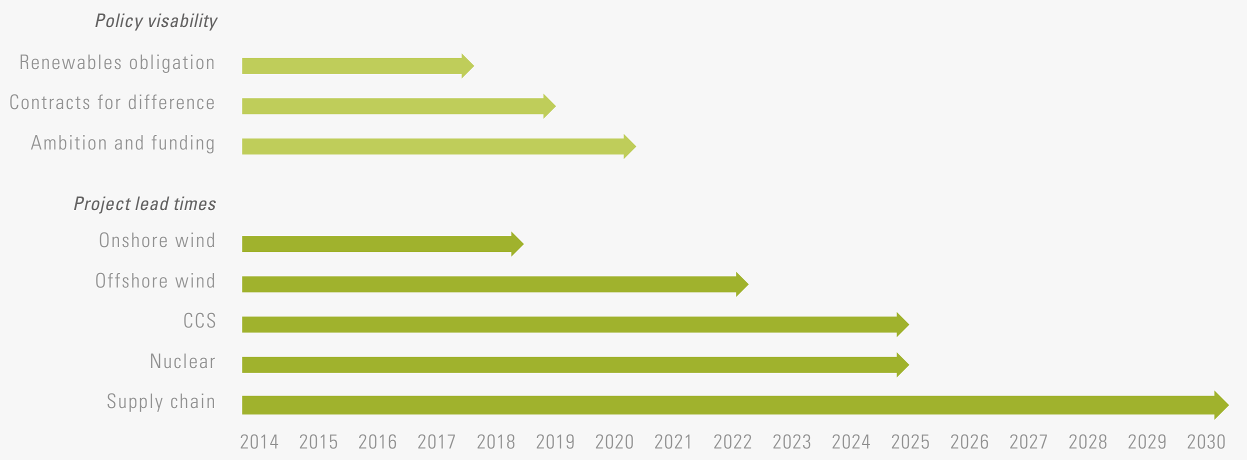
[31] For example, a useful overview is provided in INSIGHT_E briefing paper Electricity market design options for promoting low carbon technologies, found at *http://www.insightenergy.org/ckeditor_assets/attachments/71/rreb3.pdf*

commercialisation of emerging technologies along with the overall ambition for decarbonisation and the limit for funding of low-carbon generation in the 2020s. This will provide the visibility necessary to encourage investment, while retaining flexibility to respond to cost information and safeguard consumers against excessive costs. This last point is key for addressing affordability concerns, another challenge flagged at the beginning of this report.

7.2 The role of carbon capture and storage

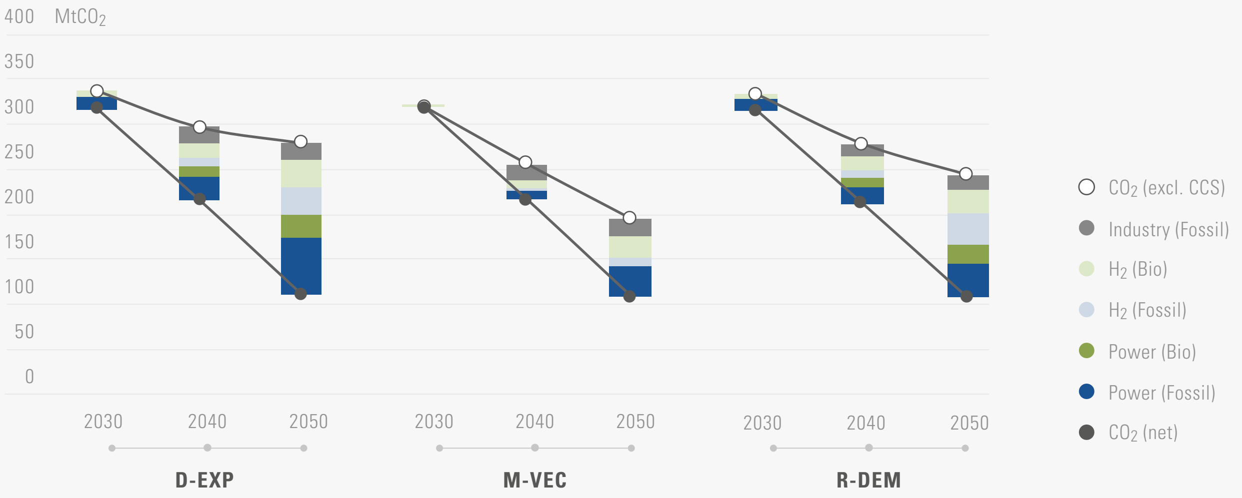
It is important to highlight the potential role of

Figure 25. Project lead times compared to policy visibility



Source: CCC (2014)

Figure 26. The contribution of CCS to CO_2 mitigation under DDPP scenarios, 2030-2050

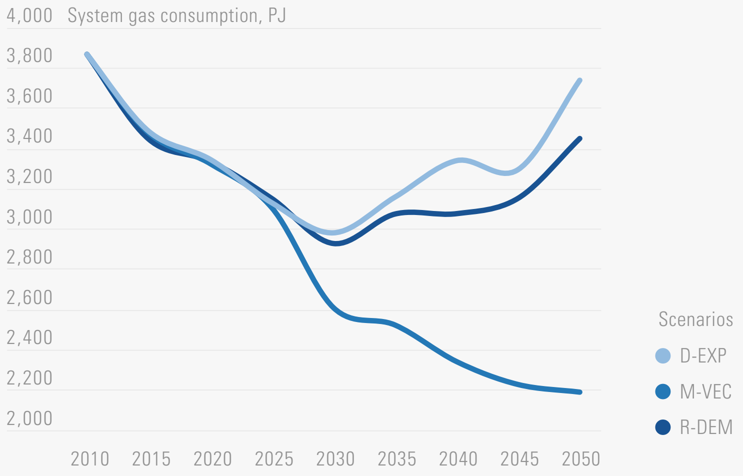


CCS in the energy system, for the power sector, hydrogen production and industry. Our results on the contribution of total system CCS to mitigation are shown in Figure 26. By 2050, D-EXP has a *CCS-reliance ratio* of 0.51, meaning that over half of all GHG emissions (emitted and captured) have been mitigated by CCS technologies; under M-VEC, it is 0.34. This level of reliance highlights that the cost-effectiveness of the system is highly dependent on CCS technologies delivering.

Bioenergy combined with CCS is also an important combination. Modelling by the ESME model suggests that missing out on one of these technologies doubles the costs of delivering climate change targets, increasing costs from 1% to 2% of GDP.[32] The sensitivity of the system costs to uncertainties across these technology options is confirmed in Pye et al. (2015). The level of CCS value to a future energy system is high due to the headroom it provides for other sectors to make lesser reductions. This high value (and system sensitivity) could be lessened if indeed effective mitigation action could be provided in those sectors for which emissions remain high in later periods (e.g. international aviation).

As already discussed, progress on CCS in the UK is being made, despite earlier delays. It is critical that the UK continues its efforts relating to these technologies, and ensures learning from the different initiatives being undertaken across Europe and elsewhere.[33] International learning and co-operation is going to be vital to enable the UK to scale its use of these technologies more rapidly. Developing infrastructure to transport and store CO_2 is going to be critical to the success of the technology, and the UK is fortunate to have significant storage capacity, primarily in the North Sea, and offshore expertise to exploit this storage. In our modelling, we also assume that transport infrastructure for H_2 production and industry will develop off the back of power sector-initiated investments. It is therefore critical that the power sector plays such a role to allow for the use of this technology in industrial areas.

Figure 27. Total gas consumption in the UK, 2010-2050



7.3 The changing role of gas: a transition from direct end-use to energy production with CCS

The UK is highly dependent on gas across all non-transport sectors, a dependency that has grown since the 1960s, following the discovery of large reserves in the North Sea. A key question is how the role of gas will change as the UK moves towards deep decarbonization.

Total gas consumption under our three scenarios is shown in Figure 27. A number of features are apparent: gas consumption in all scenarios reduces out to 2030, by around 20% in D-EXP and R-DEM and by over 30% in M-VEC. Thereafter, however, while gas consumption continues to fall in M-VEC, there is an upturn in D-EXP and R-DEM scenarios

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[32] ETI (2015). Targets, technologies, infrastructures and investments – preparing the UK for the energy transition. http://www.eti.co.uk/wp-content/uploads/2015/02/Targets-technologies-infrastructure-and-investments-preparing-the-UK-for-the-energy-transition.pdf

[33] For an overview of projects, see http://www.globalccsinstitute.com/projects/large-scale-ccs-projects

such that consumption returns to levels similarly observed in 2010. Based on our analysis, gas reduces by between 5-45%, highlighting a large uncertainty over its future role (as noted in Pye et al. 2015) but also showing that it continues to remain an important part of UK primary energy consumption. However, underpinning this level of consumption are multiple fundamental and wholesale shifts in how this gas is used.

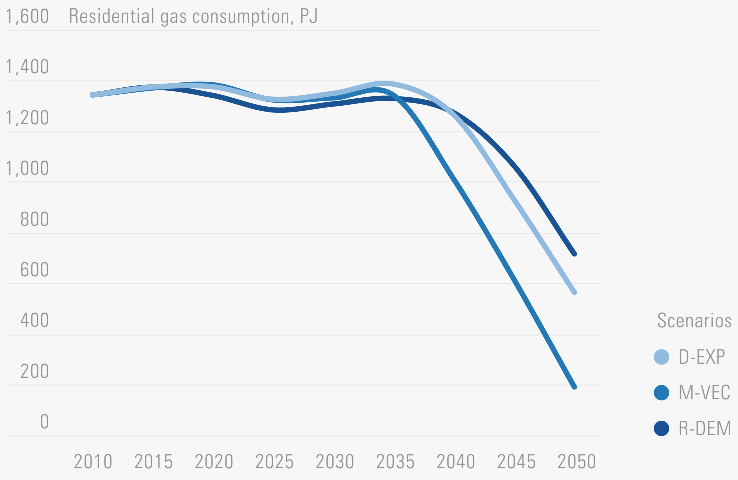
The first shift is the almost total removal of electricity generation from unabated gas. By 2030, gas accounts for around 10% of total electricity production, down from close to 45% in 2010. This electricity sector decarbonisation is the main driver of reduction in consumption prior to 2030, with a limited shift away from gas observed in other end-use sectors.

As discussed in Section 7.1, there is unabated gas capacity, but after 2030, it is used at very low load factors. Indeed in M-VEC, given the much higher level of intermittent renewables in the system, there remains over 20 GW unabated gas available as back-up capacity but this is still only utilised at around 5% of total potential load. The capacity mechanism within the Energy Act is designed to ensure that such capacity is built in a timely manner. However, it will be crucial that such unabated gas generation is used only with very low load factors, otherwise the electricity sector will not reach the necessary levels of decarbonisation. Although there is a large drop in the use of unabated gas, there is a significant increase in the use of gas with Carbon Capture and Storage (CCS) in all three scenarios, primarily after 2030. At least 15 GW gas with CCS is in operation by 2050, and in D-EXP there is nearly 30 GW. Coal CCS is not utilised in any of the scenarios; at the 90% capture rates assumed, it can only achieve a minimum of 90 gCO_2/kWh compared with 40 gCO_2/kWh for gas.[34]

This roll out of gas CCS results in rising gas consumption in the power sector, having previously fallen out to 2035. In the highest gas CCS case (D-EXP), levels of consumption by 2050 are close to those observed in 2010. It is clear, however, that this level of gas utilisation is only possible if CCS is effective and deployable on a widespread basis; without it gas would need to be almost entirely removed from the electricity system. CCS is important not only for gas in the electricity sector but also for the production of hydrogen (Section 7.5) using Steam Methane Reformer (SMR) technology. In 2050, under D-EXP and R-DEM, gas use for H_2 production accounts for around 25% of total gas consumption, or 24 billion cubic metres (Bcm)/year, which is nearly double current industrial gas consumption. In M-VEC H_2 production in 2050 is both slightly lower with a lower proportion from SMR (as discussed in Section 7.6 below), but still accounts for 10% of total gas consumption.

While increases are observed for power generation and H_2 production with CCS, gas consumption in end-use sectors declines significantly (Figure 12). In industry, gas consumption falls steadily by

Figure 28. The use of gas in the residential sector, 2010-2050



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[34] It is possible that higher capture rates could be achieved using coal CCS, for two reasons. Firstly, the concentration of CO_2 in the flue gas is higher for coal, and secondly, ensuring the economic viability of a coal CCS plant under a given carbon price is likely to mean plant design would ensure a higher capture rate is achieved.

around 1%/year as it is displaced initially (up to 2035) by biomass and biofuels and thereafter by hydrogen (Figure 20). The largest gas consumer is the residential sector, which currently accounts for around 40% of total UK gas consumption at just over 1300 PJ/year (around 35 Bcm/year). In spite of the decarbonisation efforts in all other sectors of the energy system, the residential sector continues its reliance on gas over the medium term, remaining broadly constant prior to 2035 (Figure 28). The existing extensive gas transmission and distribution network in the UK (measuring nearly 250,000 km in total) means that the continued use of natural gas boilers in the residential sector is the most cost-effective way to supply heating to buildings.

Shifting to an alternative energy source in the residential sector requires a massive investment in new infrastructure, new technologies, and the development of new markets. These alternatives, as discussed above in Section 6.2, are cost effective only at higher CO_2 prices and so only start to be adopted at a significant scale after 2035 (particularly in an optimisation modelling framework). It is important to note that the shift observed above is very ambitious, and would require significant development of infrastructure and market capacity beforehand to achieve. In reality, it is likely that the transition in supply will need to be underway in the mid-2020s. Given the scale of ambition, it is therefore unlikely that gas will be removed, and hence emissions reduced, from the residential sector by market factors alone. A combination of regulatory mechanisms in combination with market incentives will be required if policy makers want to decarbonise the residential sector over the medium term.

Key uncertainties concerning the role of gas

It is clear from the above that as long as key technologies are available, deployable on a wide scale, and cost effective, gas can continue to remain part of the UK energy system. However, it remains on open question how this consumption will be supplied. The UK became a net importer of gas in 2004 following a peak in North Sea production in 2001 and has to date relied predominantly on gas from Norway, and Liquefied Natural Gas (LNG) from Qatar (Bradshaw et al. 2014). The UK is also well connected with the continental European gas market through two interconnectors to Belgium and the Netherlands. Global modelling of the natural gas markets has suggested that there is sufficient gas available from these sources (McGlade 2014). However, from a diversification and security of supply perspective, and following the marked upturn in gas production in the United States, there is increased interest in developing new potential shale gas resources in the UK.

At present there is little accurate knowledge of the technically and economically recoverable resources of shale gas in the UK (McGlade 2013). Combined with the substantial and ongoing delays to which the industry has been subject as a result of political and regulatory processes and local opposition, a shale gas industry satisfying even a marginal level of UK gas consumption currently remains something of a distant prospect. From the perspective of reducing greenhouse gas emissions, a fundamental factor for shale gas is the level of methane that is leaked during production (so called 'fugitive emissions'). This is a contentious issue with much uncertainty over the extent to which they are significant. Suffice to say that given the difficulty in reaching the 80% reduction in emissions, if fugitive emissions are non-negligible, then it cannot be argued that shale gas is beneficial from an emissions perspective. If fugitive emissions are negligible or are easily controlled, then as discussed by MacKay & Stone (2013), shale gas is likely to have lower life cycle emissions than importing the gas from elsewhere such as LNG or gas imported by pipeline from, for example, Russia.

The final area to examine is the delivery system for gas. The importance of maintaining the existing gas transmission and distribution system over the medium term can be seen from the continued use of gas in the residential sector out to 2035. Gas use in the distribution system however then drops by at least 50% and by over 85% in M-VEC over the following 15 years. A key question therefore remains on how the distribution system will be maintained during the transition to a low-carbon energy system, particularly since any new investments in maintaining the grid will likely be used for a maximum of around 20 years compared with the usual technical lifetime of such pipelines of around 80 years.

7.4 Bioenergy: an important energy source but with large resource supply uncertainties

Bioenergy currently accounts for around 3% of total primary energy supply, the majority of which is used for electricity generation. Our modelling suggests that it will have an increasingly significant role to play, as sectors switch to lower carbon fuels, and bioenergy is used in electricity and hydrogen production (Figure 29). In primary energy terms, the share could be almost 20% by 2050 (under M-VEC).

Consumption increases markedly in 2025, as this is when the carbon budgets become particularly binding, requiring significant fuel switching. Under M-VEC, the system uses comparatively higher levels of bioenergy post-2030 due to the more limited role of electricity, highlighting

Figure 29. Bioenergy use in the UK energy system, 2010-2050

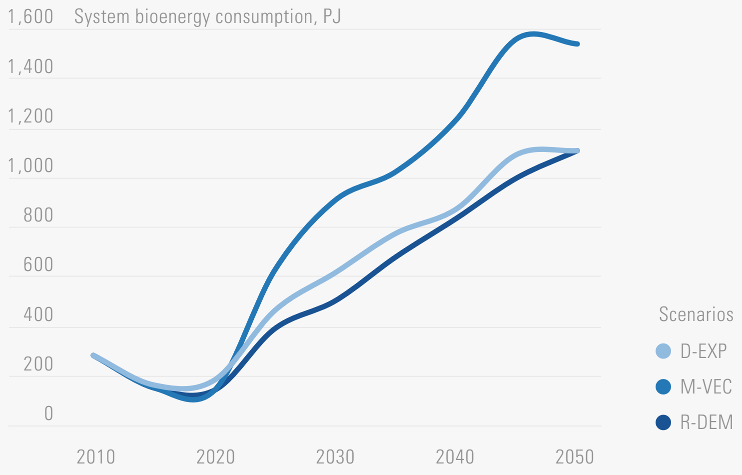
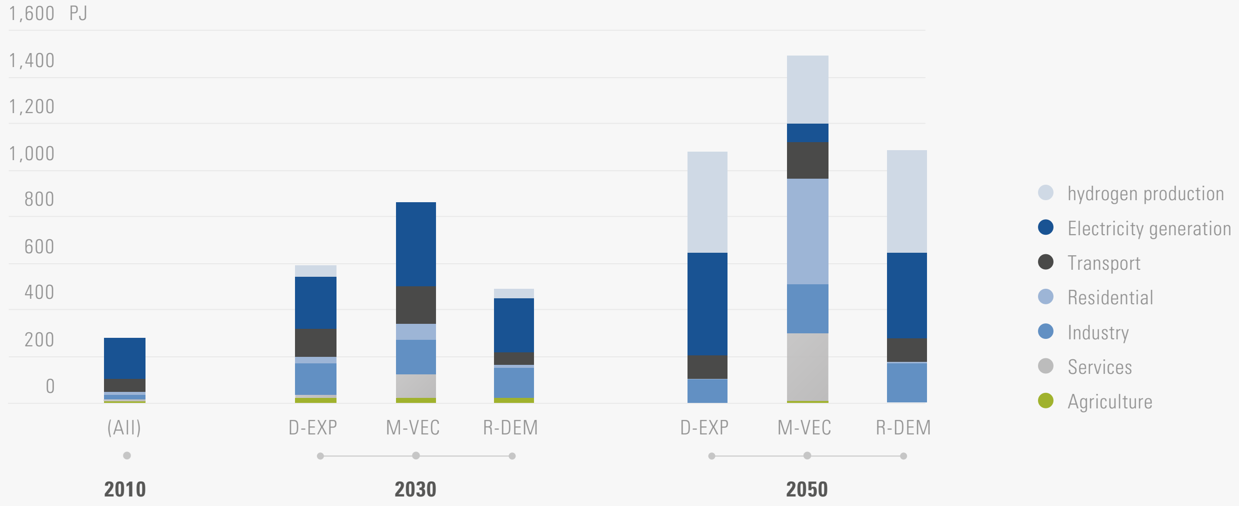


Figure 30. Bioenergy use in the UK energy system, by sector, 2010-2050



an important alternative decarbonisation pathway. This is shown in the 'use by sector' graphic (Figure 30), where more bioenergy is used directly in end-use sectors.

If permitted, bioenergy will be used to generate so-called negative emissions in electricity and hydrogen production using CCS technologies. In 2050, when this option is applicable, most of the allocation to hydrogen production and electricity generation sectors is used in CCS technologies. This provides emissions 'headroom', enabling other sectors to undertake lower levels of mitigation action. In Figure 26, under the D-EXP scenario, bio-energy use with CCS (BECCS) provides around a 50 $MtCO_2$ saving through its use in electricity and hydrogen production. Under M-VEC, the contribution is much lower (~20 $MtCO_2$), due to the later deployment of CCS technologies.

It is however important to recognise two of key uncertainties regarding the use of bioenergy. First, its carbon intensity. The carbon intensity of bioenergy is the ratio of CO_2 released upon combustion of the bioenergy to the amount of CO_2 sequestered during its growing. An important related point is the time delay associated with this. While the lifecycle emission from different sources of bioenergy is still debated (Matthews et al. 2014), it is clear that if it is not carbon neutral or very close to being carbon neutral, its importance in a DDP would be vastly reduced.

The second uncertainty regards the volumes of bioenergy that are available to the UK at different prices. This is particular important as the UK has relatively limited potential for growing bio-resources domestically. A CCC (2011) report suggested that the UK could produce between 390 PJ and 750 PJ in 2050 varying under different scenarios i.e. 25% to 50% of the consumption in M-VEC in 2050.

With a global effort working towards keeping the increase in average global surface temperatures below 2 °C it can be anticipated that bioenergy and bio-resources will be extremely valuable. The volumes that are available to the UK under such a scenario could therefore be much lower and the price at which it can import bioenergy higher. To understand how much may be available, global modelling of the energy system is required. Indeed, previous analysis using the global integrated assessment model TIAM-UCL suggested that the UK may not be able to import any bioenergy in 2050 in a globally cost-optimal 2 °C scenario although this did vary depending on other technological assumptions (Anandarajah & McGlade 2012). Nevertheless, given the demand from other regions (particularly China) under such a scenario, it was found that biomass prices were over four times higher than in a scenario with limited global action on emission mitigation.

Challenges and policy needs

Bioenergy supply is a critical fuel for decarbonisation. However, its availability is subject to large uncertainties, particularly in terms of imports, where under our assumptions all countries will be focused on decarbonising their energy systems. For a cost-effective transition, its availability has been estimated to have the strongest impact of any supply option, givens its potential role for use with CCS (Pye et al. 2015).

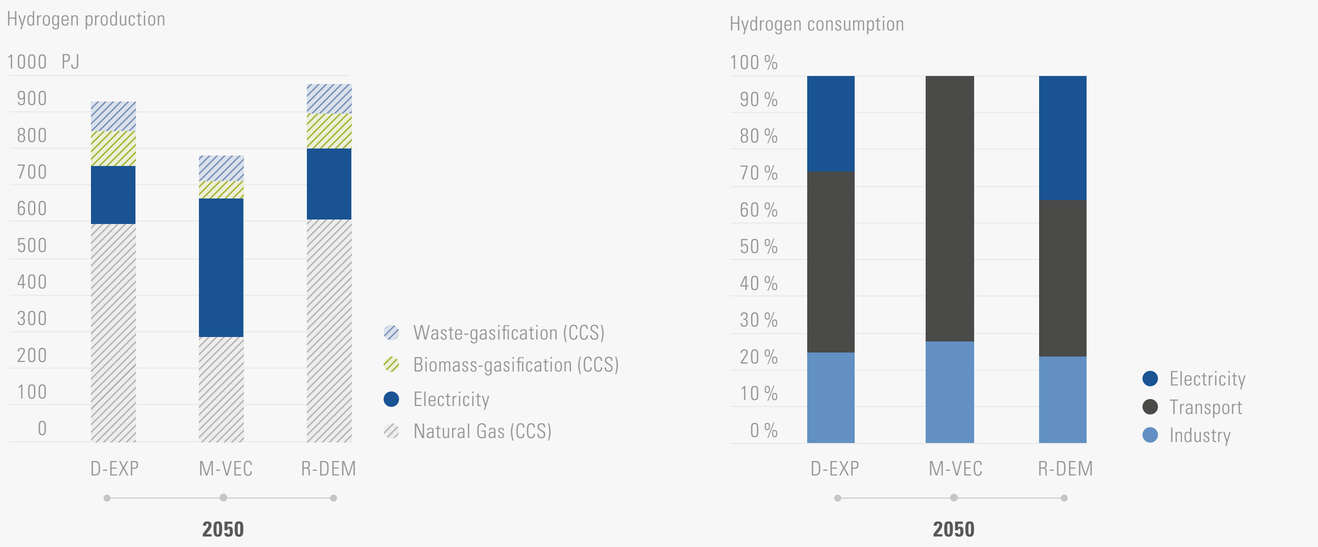
Our scenarios suggest that in 2050 between 25-75% of available bioenergy would optimally be used in combination with CCS technology, reflecting the opportunity to generate negative emissions. For this mitigation option, in addition to the need for CCS deployment, accounting rules will need to be established to allow for such mitigation benefits, and there will need to be broad acceptability about the use of such an option. Policies will need to be orientated to ensure that bioenergy that is used is both sustainable (to ensure carbon neutrality), and that it is used in way that reflects that this is a high value resource for emissions mitigation. The numerous uncertainties also need to be considered, concerning supply availability in a decarbonising world, the acceptable use of bioenergy in CCS, and the need for sustainable supply.

7.5 Hydrogen: large-scale deployment contingent on significant cost reductions

Under the DDPP scenarios, hydrogen starts to play an important role in the energy system from 2040, particularly in the transport, industry and electricity sectors. Despite the high costs of hydrogen supply in the model, its use in both freight transport and industry reflect the difficulty in cost-effectively reducing emissions in these sectors. In our modelling, due to infrastructure constraints and high costs, the use of hydrogen in the buildings sectors is not considered. However, it is important to recognise that a range of research does find application for hydrogen systems in these sectors (Dodds and Hawkes 2014). As noted in the previous section, production through SMR (with CCS), which relies upon natural gas as a feedstock, dominates hydrogen production, except in M-VEC, where electrolysis is the main means of production, using much of the surplus wind generation (and reducing curtailment), as shown on the left of Figure 31. This proves an especially effective means of using intermittent electricity for production of hydrogen, which can then be stored. Biomass use with CCS technology is also an important means of production, and for achieving significant mitigation benefits.

Enabling hydrogen systems will require significant development and investment in hydrogen production and fuel cell technology, and associated infrastructure. We assume limited use of hydrogen in existing gas networks, meaning that new transmission and distribution infrastructure is required. While expensive, costs can be reduced if infrastucture is built in the right place. For example, there is no need for hydrogen distirbution grids for transport since it is assumed that the transmission grid will be built along motorways to link up with re-fueling stations. This type of investment clearly requires some strategic planning, with central and / or

Figure 31. Hydrogen production by type (PJ), and sectoral consumption by share (%), 2050



regional government playing a crucial role in the decision to deploy such infrastructure. At some stage in the next 10-15 years, there will need to be a decision about whether infrastructure (at some scale) is required to support technology deployment, which will in turn be dependent on technology performance and cost. Prior to such decisions being made, it is important that hydrogen technology development is supported both at the national level and globally.

8 Conclusions

Modelling studies have long established that it is both technically feasible and economically viable to meet the decarbonisation objectives of the UK. However, there remains a live discussion about what type of pathway the UK should choose, to an extent articulated in the scenarios presented in this report. This reflects key uncertainties around the role of specific technologies, and the effectiveness of policies to deliver such a major transformation. However, uncertainty must not be a basis for inaction; the role of Government must be to put in place the right policy framework now that drives technology R&D forward, facilitates market uptake of new technologies, and engages society in what will be a re-orientation of the energy system. In their recent report, ETI (2015) made a strong case that the UK needs to scale up efforts now to allow for a large scale transition in the necessary timeframe.

The modelling featured in this report provides some key insights, from which we can draw some important conclusions for the policy process.

A reduction in power sector carbon intensity to 35-75 gCO_2/KWh (from current levels of just under 500 gCO_2/KWh) is critical by 2030, to meet domestic climate objectives and to provide the platform for expansion of electrification of end-use sectors after 2030. In addition to being the most cost-effective sector in which to target action, the power sector allows for more rapid emissions reduction within the tight timescales of the next 15 years. The need to replace much of the current capacity affords an excellent opportunity for this transition.

Given the tight timescales and the required scale of transition, policy needs to be strong and effective. While some important progress has been made through the Electricity Market Reform process, we have highlighted concerns around consistency of the current approach, for example the capacity mechanism allowing for coal plant to play a role, and inadequacy of the policy timeframe, meaning a lack of certainty for investors across key technologies. It is also important that all current low carbon technologies continue to be supported, particularly those that are proven and cost-effective e.g. onshore wind. Taken together, and if not addressed, there is potential for a real risk of 'slippage' in the deployment of low-carbon generation technologies.

The costs of mitigation would be significantly higher without specific key low-carbon technologies. The scenario analysis shows that delay in deployment and subsequent lower levels of nuclear and CCS (under M-VEC) will increase necessary investment levels, and lead to significantly higher costs of abatement. CCS is not only critical for low-carbon expansion of the power sector, but also key to the provision of mitigation action in the industry sector and low-carbon hydrogen supply. If this technology is to succeed, the Government must work with international partners on CCS technology, and have in place a successful UK demonstration programme and first-of-a-kind build out to 10 GW by 2030.

Crucially, demand side measures can reduce the costs by reducing energy use and energy service requirements, and this should be a key focus for Government. Such measures partly mitigate against the risks of slippage in deployment of supply side measures, and reduce the costs of mitigation. A stronger policy approach is needed to deliver energy efficiency retrofits of existing buildings in the near term, and to increase the deployment of demand side measures in the transport sector. We know what is need to achieve energy efficiency in the residential sector, and the resulting CO_2 reduction, economic and social benefits, particularly in tackling fuel poverty.

Electrification of end-use sectors appears to be critical, even accounting for the role of other low-carbon energy supply options. By 2050, electrification of end-use sectors is between 30 – 40% (of final energy) under all scenarios, a more than doubling of supply relative to current levels. An increased role could be envisaged if we foresaw a less optimistic outlook for hydrogen in industry and transport sectors.

However, there do appear limits to the share of electrification, based on our current understanding of the potential system pathways in our modelling. Firstly, it is very difficult for electricity to displace all gas used for heating buildings, due to the large peak demand in winter. This could of course be overcome by development and deployment of cost-effective on-grid or in-building battery storage systems. Secondly, our assumptions that battery electric technology only applies to light duty vehicles could be altered by future developments in battery technology.

Hard-to-mitigate residual emissions in the longer term make it extremely challenging to increase ambition levels via a technology-focused approach alone. Non-CO_2 GHGs and CO_2 from international aviation account for 70% of residual emissions in 2050. In our analysis, this results in energy sector emissions (excluding international transport) reducing by 90%, relative to 1990 levels, with very high mitigation costs at the margin. This situation could be further compounded by a strongly reduced role for hydrogen in freight and international shipping, which could be deemed optimistic in our scenarios.

For policy makers, attention needs to be focused on these hard-to-mitigate sectors. This means focusing additional research and development in this area, as has been done for industry recently through the *Industrial Decarbonisation and Energy Efficiency Roadmaps*,[35] shifting greater focus to demand side solutions, and ensuring policy does not make the problem worse. For example, it is not credible that the UK can have ever growing airport capacity whilst expecting to achieve its long term climate objectives.

A significant role for fossil fuels in the energy system after 2040 is wholly contingent on CCS. Our analysis shows that the continued use of gas on the supply side is subject to its use in CCS, for electricity and hydrogen production. It is imperative that energy policy first focuses on developing CCS technology, not in developing new fossil resources, which cannot be used otherwise. Fossil fuel use in end-use sectors is at around 35% of the 2010 level by 2050, reflecting the intractable situation whereby gas continues to be used to some extent for heating in buildings and few options emerge for dealing with oil use in international transport. In part, this reflects further important work necessary to determine more effective mitigation options for these sectors.

Bioenergy can play a role in decarbonisation but this is limited by supply availability. Our analysis shows a critical role for bioenergy, in-

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[35] For further information, see https://www.gov.uk/government/publications/industrial-decarbonisation-and-energy-efficiency-roadmaps-to-2050

cluding for providing negative emission savings. However, we estimate that it can only account for around 15%-20% of primary energy at best, meaning that it is limited in terms of displacement of other fuels. It is also worth highlighting that there is significant uncertainty around bioenergy resource availability and costs, particularly with all other countries accessing global supply for decarbonisation.

8.1 How much further could the UK go?

A question remains whether an 80% reduction in GHG emissions by 2050 is ambitious enough, and whether the rate of reduction needs to be stronger by 2030. It may be that the UK, under a future agreement, will need to increase its own rate of emissions decrease, and aim for a more challenging reduction level in the long term. Certainly, a range of commentators suggest that an 80% reduction is not adequate, if indeed we want to ensure that there is a much greater chance e.g. 80% chance of staying below a 2 °C temperature rise, as opposed to the less constrained global budget numbers quoted in this report.

We believe that it is important that the CCC keeps this longer term target under review, and reflects whether it should be tightened based on the science. We also consider that modelling analyses should start considering the even longer term, as the IPCC budgets imply the need to move to a net zero emission situation soon after 2050. For example, the CO_2 budget to 2050 (starting from 2011) as described in this report is 860 – 1180 $GtCO_2$; to 2100, the budget (on the same basis) is 960 – 1430. If we take the middle of each range, a difference of 175 $GtCO_2$ is estimated, allowing for only 3.5 $GtCO_2$ per year (assuming the budget up to 2050 was used). This means that there are important implications for the choices and types of infrastructure that we invest in before 2050 if indeed our ultimate aim is to have a net zero emissions system.

This analysis provides some insights into the challenges of more ambitious reductions, and what might be needed for deeper decarbonisation. Firstly, it is likely that stronger demand side reductions would be required, and much more ambitious than those under the R-DEM scenario. This is particularly pertinent to international aviation, which accounts for 0.5 tCO_2e per capita out of a total of 2.1 t in 2050. With strong efficiency gains for this sector included in the analysis, few technical options remain with the exception of increasing use of biofuels.

Secondly, further analysis of options to reduce non-CO_2 GHG is needed. However, again it is evident that most of the remaining non-CO_2 GHGs are associated with food production processes, and account for 0.6 tCO_2e per capita in 2050 (or 29% of remaining emissions). A radical change in dietary requirements, such as less meat in the diet, and improved efficiency of consumption may be needed to significantly reduce these emissions.

Our scenarios already assume the availability of two key mitigation options which are not yet commercially available; CCS for decarbonised electricity, and hydrogen for transport and industry sectors, most of which is produced with CCS technologies. A further associated option is the use of bioenergy with CCS, for gaining so called ‘negative emissions’. With our 2050 solution premised on such options, further reductions would appear very challenging.

Of course, it is important to note that our outlook on possible solutions is somewhat limited by our modelling approach. More work is needed to consider the role of storage and other aspects of smart systems for enabling higher levels of electrification, how district heating can play a more extensive role using renewable and waste heat sources, and what additional measures could be taken on the demand side. This further exploration of further reductions is certainly necessary, as we start analysing the post-2050 system and the need to move to a net zero emissions system. Some researchers have already been thinking about a net zero emissions future, for example the Centre for Alternative Technology (CAT). In their most recent report (CAT 2013), they map out a potential pathway to achieve this by 2030. This extremely ambitious pathway, dictated by CAT's view of the UK fair budget, provides some insights into the necessary options including changing diet (reduced meat intake), reducing food waste, strong push on energy efficiency and renewable generation (based on existing technologies). Whether timescales could allow for such a transition or not, this analysis highlights that greater ambition needs to move beyond technological supply-side focused solutions.

Further work is needed to develop our modelling capability to firstly provide improved representation of options in those hard-to-mitigate sectors. This includes a stronger focus on demand side and potentially lifestyle options if indeed a net zero emission system is to be achieved. As stated earlier, we also need to start considering the post-2050 system, to better understand whether our longer term investments to 2050 are adequate for the more ambitious reductions required thereafter.

8.2 Emerging policy and research needs

Based on our report, there are a number of key recommendations for policy, in ensuring that deep decarbonisation can be achieved in the UK, and some critical further research needs.

On policy –

- Longer term infrastructure policy needs to take account of GHG reduction targets, including airport expansion, other transport infrastructure (incl. urban design), and extractive industries. This will ensure that we are not `locked-in' to any new higher carbon infrastructure, which will remain in the system for many years. What is crucial is a consistent package of measures, where short and long term decisions all move in a low-carbon direction.
- Current and future policy must deliver certainty for investors, particularly given the lead in time and payback periods for longer lived energy system assets. It also needs to recognise that this transition will be to a more capital intensive, fixed cost system, requiring necessary incentives and access to capital.
- A greater focus must be made on delivering energy efficiency potential in the buildings sector, taking the opportunity to deliver affordable energy for those groups suffering from fuel poverty.
- In addition to scaling up deployment of low-carbon technologies for power generation now, a real focus is needed in preparing for strong deployment of heat pumps in the building sector, and low emission vehicles in transport. This means acting now to build supply and skills capacity, developing the necessary infrastructure, and embarking on some roll-out programmes to identify challenges.

On research -

- Further work is needed to better understand and aid policy makers in dealing with multiple uncertainties concerning technology, so that such uncertainties can be effectively mitigated under robust policy. This means improvement to modelling tools and analytical approaches.
- Greater focus is needed on options for hard-to-mitigate sectors, particularly demand side measures. As the analysis suggests, a lack of understanding here and poor representation of demand side options restricts our ability to increase our ambition level for long term mitigation.
- More research is needed on the role of different actors in the transition. This includes issues concerning market design and how this will affect consumers, and who will deliver the

investment required.

- Public acceptability concerns also need to be better understood. Given the significant transition that is envisaged, it is imperative that public acceptability concerns are given an appropriate level of attention. In their *Energy Strategies under Uncertainty,* Watson et al. (2014) stated that 'engagement with people and communities is an essential component of the UK's low-carbon transition' not just for individual technologies but for the whole system, and that a focus of engagement should be on how a transition was organized and paid for.

8.3 International cooperation and coordination

The UK, like most other countries, will not be able to deliver the required transition to a deeply decarbonised system alone. Firstly, there will need to be strong cooperation on key technologies, such as CCS, where learning has to be fairly rapid if indeed this technology can be scaled globally to the required levels. The UK can also look to develop technologies in areas where it has specific expertise, notably offshore wind and marine technologies. Secondly, the UK should looks for ways to share experiences of what policy mechanisms have worked, and approaches to setting up institutional capacity. Some of these experiences are listed below. The UK can also learn from effective action in other countries. Thirdly, the UK should at least maintain and look to increase its assistance to developing countries in the area of climate change and sustainable energy through various channels, including via DFID funding.

Concerning the second point, the experience of developing climate legislation and policy in the UK can provide some useful lessons to other countries embarking on the development and implementation of decarbonisation strategies. The positives in the UK experience relate to both establishing climate policy priorities and institutional capacity in legislation, and starting to tackle the implementation of policies to get the UK on its own low-carbon pathway. Firstly, by legislating for a long term target and setting up an independent advisory body under the Climate Change Act 2008, the UK Government has gone some way to de-politicising the objectives of transitioning to a low-carbon economy. There is now a general cross-party consensus on the objectives enshrined in the Climate Change Act 2008, as recently demonstrated by a cross-party pledge.[36] Critically, the climate legislation has remained intact across the last political cycle, and should do so for the next five years.

The CCC, as government advisors, not only provide independent advice on carbon budgets, largely accepted by Government to date, ensuring the UK remains on course to meet its long term objective, but also holds the Government record to account. This is done through the publication of an annual report (CCC 2014), where progress is measured against a set of indicators. Such an approach could usefully be adopted elsewhere following development of a strategy. This advisory and accountability role is enabled by the CCC having a strong analytical capability, in turn providing stakeholder confidence in the implementation of policy and monitoring of progress.

Finally, the Government, based on such advice, has embarked on a strategic and analytically robust approach to decarbonisation over the long term. Near to mid-term carbon budgets ensure the longer term pathway, and point to important areas for policy strengthening e.g. strong power sector decarbonisation, CCS commercialisation

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[36] Joint party pledge on climate change action - http://www.green-alliance.org.uk/resources/Leaders_Joint_Climate_Change_Agreement.pdf

etc. This has also helped to provide additional certainty to investors although it is evident that strong policy measures are also needed alongside this strategic framework.

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Appendix

Appendix 1. Additional information on UKTM

The UKTM model is divided into three supply side (resources & trade, processing & infrastructure and electricity generation) and five demand sectors (residential, services, industry, transport and agriculture). These are briefly described in Table 4. All sectors are calibrated to the UK energy balances (DECC 2011b) in the base year, 2010, for which the existing stock of energy technologies and their characteristics are taken into account. The large variety of future supply and demand technologies are represented by techno-economic parameters such as the capacity factor, energy efficiency, lifetime, capital costs, O&M costs etc. For most technologies or technology groups, growth constraints between 5 to 15% per year are fixed to ensure realistic future technology deployment rates.

While UKTM has flexible time periods, and can be run for any time horizon up to 2100, our analysis uses two single-year time periods representing 2011 and 2012 and there-after five year periods from 2015 up to 2050. To represent changes in demand across seasons and hours of the day, it features a time resolution of 16 time-slices (four seasons and four intra-day times-slices). This allows for some representation of peak demand, system security via a peak reserve margin, and therefore key requirements for power system operation. In addition to representing energy flows, UKTM models both energy and non-energy related CO_2, CH_4, N_2O and HFC emissions. In 2010, all emissions are calibrated to the UK Greenhouse Gas Inventory (Ricardo-AEA 2014), including

Table 4. UKTM sector descriptions

Resources and trade	Includes potentials and cost parameters for domestic resources and traded energy products. For fossil fuels, assumptions are mainly based on results from the global energy system model TIAM-UCL (Anandarajah et al. 2011), while the assumptions on bioenegy potentials are aligned with the CCC's Bioenergy Review (CCC 2011, Extended land use scenario).
Energy processing	Covers all energy conversion processes apart from electricity generation, including oil refineries, coal processing, gas networks, hydrogen production, bioenergy processing as well as CCS infrastructure.
Power generation	Represents a large variety of current and future electricity generation technologies as well as storage technologies, the transmission grid and interconnectors to Continental Europe and Ireland. The technology assumptions are mostly aligned with DECC's Dynamic Dispatch Model (DDM, DECC 2012).
Residential	Domestic housing is divided into existing and new houses. In addition to a large portfolio of heating technologies for the two main energy service demands of space heating and hot water, other services like lighting, cooking and different electric appliances are represented. The technology data is based on various UK-focused building studies, including Carbon Trust (2009), Bergman and Jardine (2009), Davies and Woods (2009), Radov et al. (2009), Element Energy & Energy Saving Trust (2013).
Services	As per residential structure, but stock divided into low- and high-consumption non-domestic buildings. The technology data is based mostly on the same UK-focused building studies mentioned for the residential sector.
Industry	Divided into 8 subsectors of which the most energy-intensive ones (iron & steel, cement, paper and parts of the chemicals industry) are modelled in a detailed process-oriented manner (based on Griffin et al. 2013), while the remaining ones are represented by generic processes delivering the different energy services demands. The demand projections are aligned with the DECC Energy and Emissions Projections model (EEP).
Transport	Nine distinct transport modes are included (cars, buses, 2-wheelers, light goods vehicles, heavy goods vehicles, passenger rail, freight rail, aviation and shipping). For road transport, the demand projections are based on the road transport forecasts 2013 (DfT 2013) and the technology parameters are mainly sourced from Ricardo-AEA (2012).
Agricultural and land use	Represents, in addition to processes for the comparatively small fuel consumption for energy services, land use and agricultural emissions as well as several mitigation options for these emissions (Moran et al., 2008).

Table 5. Characteristics of DDPP scenario narratives

Approaches to delivery	**D-EXP**	Strong central coordination to deliver large scale infrastructure. Delivery of end-use sector transition also requires strong incentives but uses a range of delivery mechanisms.
	M-VEC	Weaker central coordination results in more limited delivery of specific power sector technologies. Delivery of end-use sector transition also requires strong incentives but uses a range of delivery mechanisms.
	R-DEM	Delivery of measures in transport and buildings are community and local authority led, with Government providing the broader policy and strategic framework. This means stronger devolvement of energy and planning policy to regions.
Strength of policy framework	**D-EXP**	Policy strongly focused on delivery of power sector decarbonisation by 2030. This means effective long term incentives to investors, and a strong push on demonstration programmes for CCS.
	M-VEC	Policy does not achieve the deployment of nuclear and CCS but rather focuses on strengthening current incentives for offshore wind deployment.
	R-DEM	Policy is focused on both the delivery of demand side measures in parallel to key low-carbon supply-side technologies. A more devolved framework sees lower requirement for large scale deployment.
Focus and timing of sectoral action	**D-EXP**	Strong push on early power sector decarbonisation, while scale up of electrification in buildings and transport post-2030.
	M-VEC	Due to more moderate decarbonisation of the power sector prior to 2030, other sectors need to do more. Bioenergy resource requirements increase, as does the role of hydrogen in the longer term.
	R-DEM	Earlier demand side action on buildings and in transport, in parallel to deployment of key low-carbon technologies, realises lower system costs in the long run.
Societal perspectives	**D-EXP**	Public acceptance of key low-carbon generation technologies is evident. End-use technology transitions gain acceptability to ensure no radical shift in energy using behaviour.
	M-VEC	Public acceptance of nuclear and CCS is low, in part due to delay and insufficient policy delivery. End-use technology transitions gain acceptability to ensure no radical shift in energy using behaviour.
	R-DEM	Society pushes for the more devolved approach to the transition, embracing measures for building retrofit via community based approaches, and to reducing car usage. In some respects, the transition is as much a societal led response as one that is imposed by central government.

Table 6. Standard analysis assumptions across DDPP scenarios

Emissions	GHG reductions targets	As described in section 3.2.
	Carbon offsets	Not permitted; domestic action only.
	Sectoral coverage	All GHGs, including non-CO2 GHGs and international aviation and shipping (as important source under domestic legislation); see Appendix 1.
System wide	Discount rate	3.5% (for NPV calculation), as per UK's appraisal guidance (Green Book).
	Cost of capital	Investment annualisation rates of 10% commercial, & 5% private.
	Projection drivers	Central government sourced assumptions. GDP long term growth rate ~2.3% (OBR 2012); population rate 0.78%, declining to 0.36% by 2050 (UK ONS).* Industry drivers from DECC Energy and Emissions Projections model (EEP).
Resources	Commodity prices and potentials	For fossil fuels, cost estimates from global modelling with TIAM-UCL (Anandarajah et al. 2011) are used, differentiating between domestic and imported commodities. The world market price for crude oil reaches 90 $2010 per barrel in 2050; supply curves are implemented for domestic resources; bioenegy potentials are based on CCC (2011, Extended land use scenario).
	Gas resources	Supply curve for domestic resources based on results from TIAM-UCL (Anandarajah et al. 2011), including potential for shale gas.
	Electricity imports	Capacity capped at current (2010) levels.
End-use sectors	Transport growth rates	15% growth rate across different LEVs, using an initial market size value (seed) of 200,000 for cars, and 10,000 for HGVs / 25,000 for LGVs. Technology assumptions largely based on Ricardo-AEA (2012).
	Buildings	Heat pumps: Size issues and other factors restrict heat pumps to 60% of dwellings; District heating: limits based on building type density, and whether existing or new build.
	Industry	Range of measures described in section 6.3, including CCS, and primarily based on Griffin et al. (2013).

* *National Population Projections, 2010-Based Projections.* http://www.ons.gov.uk/ons/rel/npp/national-population-projections/2010-based-projections/index.html

Table 7. Model implementation of DDPP scenario

Ressources	Bioenergy	D-EXP	Peaking at 300 TWh in 2040, and then at 260 TWh by 2050 (CCC Extended land use scenario)
		M-VEC	Peaking at 460 TWh in 2040, and 430 TWh by 2050 (increased global import share assumed).
		R-DEM	Peaking at 300 TWh in 2040, and then at 260 TWh by 2050 (CCC Extended land use scenario)
	Hydrogen	D-EXP	No use in the buildings sector; penetration in transport sector post-2030
		M-VEC	No use in the buildings sector; penetration in transport sector post-2030. Production w/ CCS delay to 2040 (due to later deployment of infrastructure)
		R-DEM	No use in the buildings sector; penetration in transport sector post-2030
Power	CCS	D-EXP	Minimum 5 GW by 2030, to gain cost reduction in future years. Post-2030 permitted build rate of 2-3 GW per year
		M-VEC	No minimum build by 2030, and therefore more limited cost reduction in future years. Post-2030 build rate limited to 1 GW per year.
		R-DEM	Minimum 5 GW by 2030, to gain cost reduction in future years. Post-2030 permitted build rate of 2-3 GW per year
	Nuclear	D-EXP	Limit on cumulative new build of 35 GW. 1GW per year in 2020s, rising to 2 GW per year post-2030
		M-VEC	Higher CAPEX assumed, and more stringent build rates, limited to 0.5 GW/yr
		R-DEM	Limit on cumulative new build of 35 GW. 1GW per year in 2020s, rising to 2 GW per year post-2030
	Offshore wind	D-EXP	Minimum 20 GW by 2030, to gain cost reduction in future years. Permitted build rate of 2GW/year in 2020s, rising to 2.5 GW/year by 2050
		M-VEC	Minimum 20 GW by 2030, to gain cost reduction in future years. Permitted build rate of 2GW/year in 2020s, rising to 3 GW by 2050
		R-DEM	Minimum 20 GW by 2030, to gain cost reduction in future years. Permitted build rate of 2GW/year in 2020s, rising to 2.5 GW/year by 2050
End-use sectors	Transport	D-EXP	Lower costs of PHEV / EVs due to faster market uptake.
		M-VEC	Relaxed constraints on H_2 share in road vehicles. Higher costs of PHEV / EVs due to slower market uptake.
		R-DEM	Demand: For car passenger, rate of growth halved; 471 compared to 544 bvkm (2010 level 413 bvkm); 25% reduction in aviation growth rate to 2030, and 50% thereafter (as constraints tighten)
	Buildings	D-EXP	Moderate growth in building retrofit (as per CCC assumptions)
		M-VEC	Moderate growth in building retrofit (as per CCC assumptions)
		R-DEM	Stronger growth in conservation measures through retrofit, reducing building energy demand
	Industry	D-EXP	CCS: CCS infrastructure availability in 2030, limited to potential 15 $MtCO_2$.
		M-VEC	Delay of IND CCS infrastructure availability, with only limited penetration by 2035.
		R-DEM	CCS: CCS infrastructure availability in 2030, limited to potential 15 $MtCO_2$.

those from international aviation and shipping. The GHG emission factors for the combustion of fossil fuels are taken from the Greenhouse Gas Conversion Factor Repository (DEFRA & DECC 2014). Non-energy emissions from industrial processes are modelled as outputs of the respective process technologies in iron & steel, cement and ammonia production and technology-specific mitigation options (most importantly CCS technologies) are included. The remaining process-related emissions (about 25% of total emissions from industrial processes in 2010) from the non-ferrous metals and the non-metallic minerals industries are included in an aggregate manner as a function of total output of these industries and so far no mitigation options are included for these emissions.

HFC emissions are modelled as a function of the energy service demand for refrigeration in the residential, services and industrial sectors, and refrigeration processes with HFO-based refrigerants are available as a mitigation option. Land use emissions in the UK are expected to increase from -3.7 $MtCO_2e$ in 2010 to 4 $MtCO_2e$ in 2050; these can be reduced through reforestation in UKTM. Agricultural emissions from crops and livestock can be mitigated through a variety of abatement options which are taken from Moran et al. (2008). For more information on UKTM, see Daly et al. (2015).

Appendix 2. Characteristics of DDPP scenario narratives, and their model implementation

The characteristics of the different scenario narratives are described in Table 5 below, providing a coherent and consistent storyline for each pathway.

Table 6 lists the standard analysis assumptions used across all scenarios, while Table 7 outlines the scenario specific assumptions.

Standardised DDPP graphics for UK scenarios

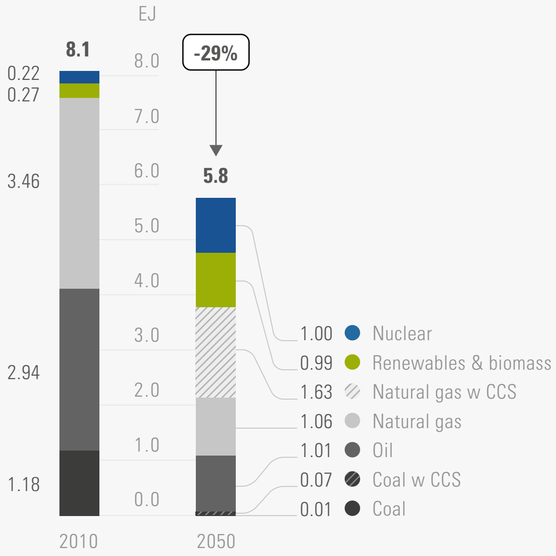
UK - Decarbonise & Expand

UK - Multi vector

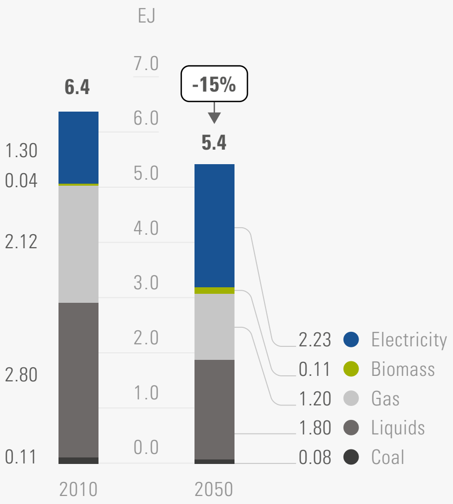
UK - Reduced Demand

UK - Decarbonise & Expand

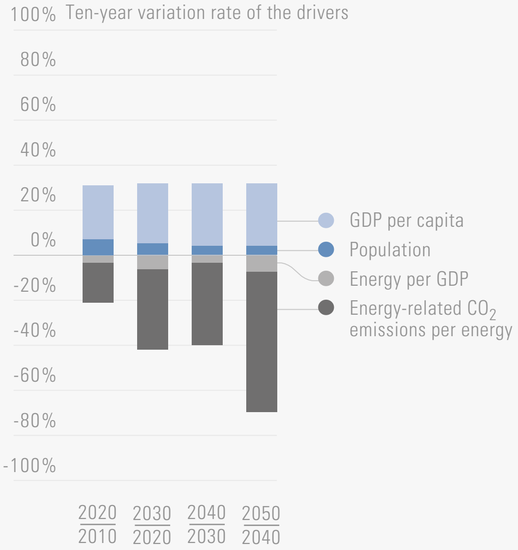
Energy Pathways, Primary Energy by source



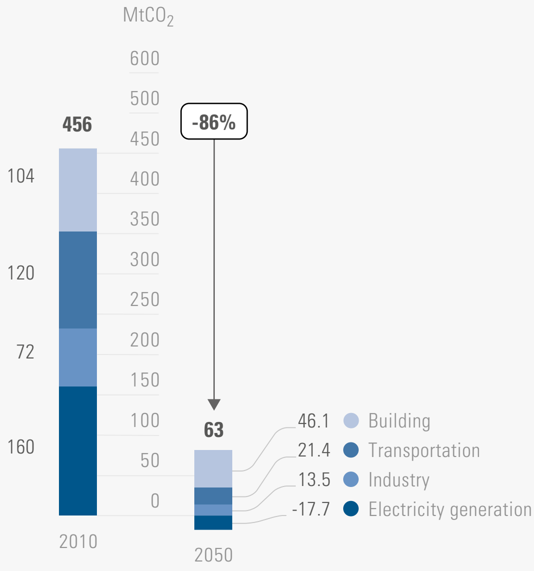
Energy Pathways, Final Energy by source



Energy-related CO_2 Emissions Drivers, 2010 to 2050



Energy-related CO_2 Emissions Pathway, by Sector



The Pillars of Decarbonization

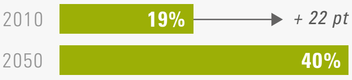
Energy efficiency

Energy intensity of GDP, MJ/$

Decarbonization of electricity

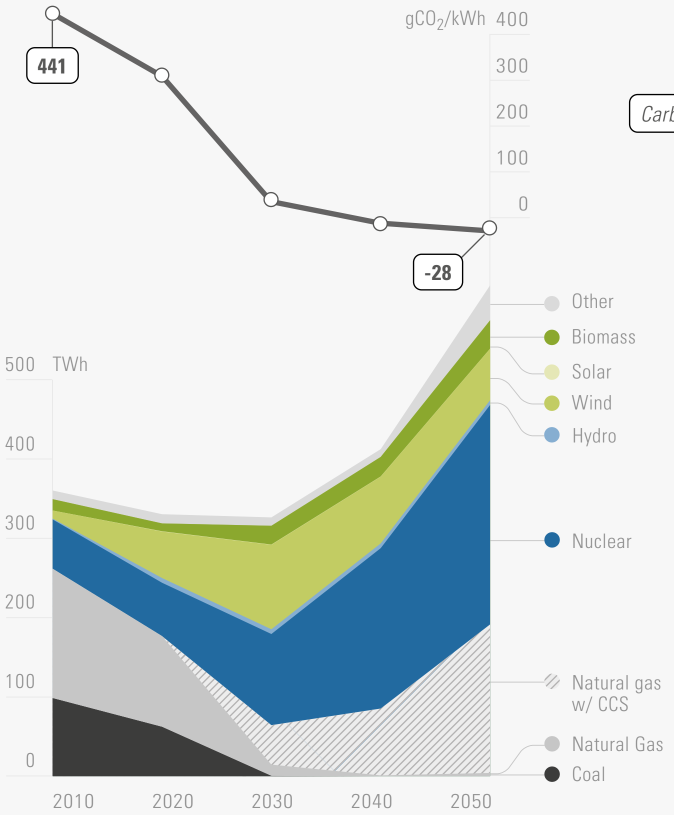
Electricity emissions intensity, gCO_2/kWh

Electrification of end-uses



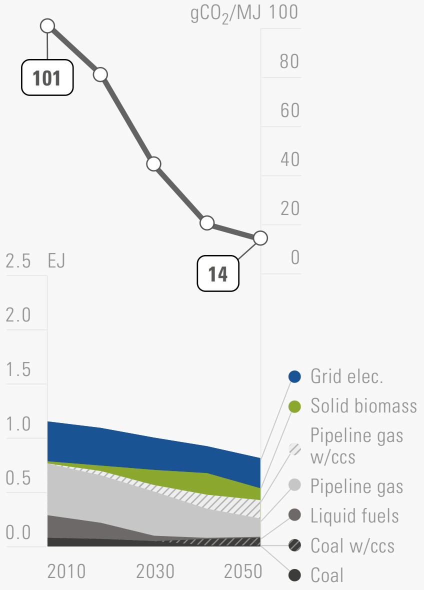
Share of electricity in total final energy, %

Energy Supply Pathways, by Resource

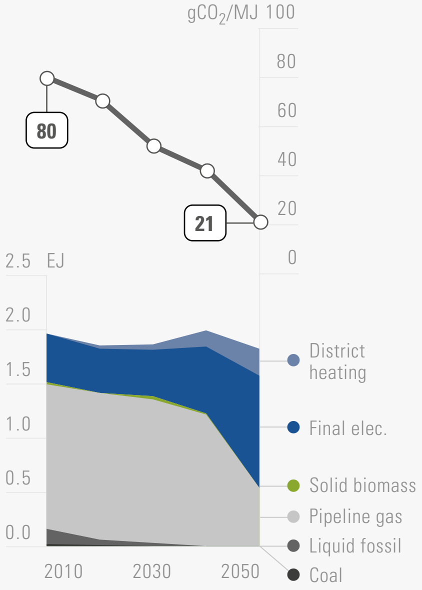


Electricity

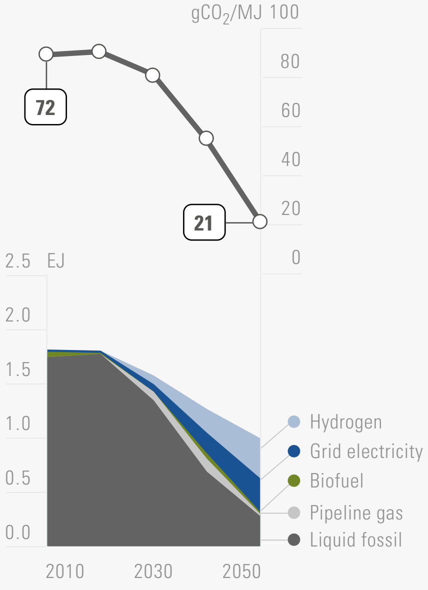
Energy Use Pathways for Each Sector, by Fuel, 2010 – 2050



Industry



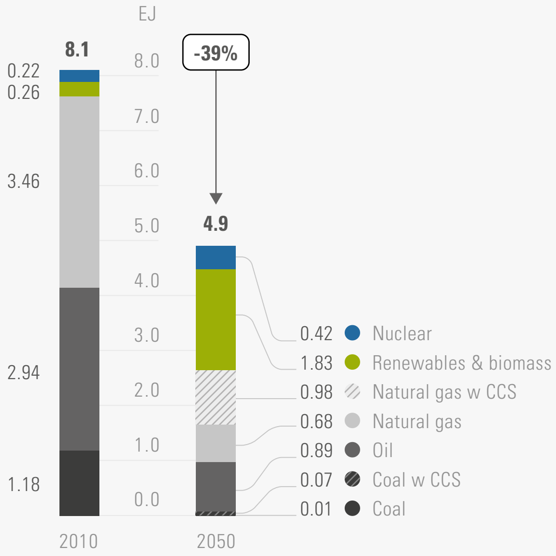
Buildings (residential)



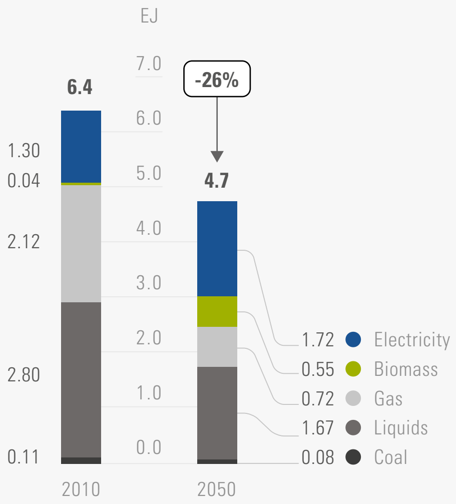
Transportation

UK - Multi vector

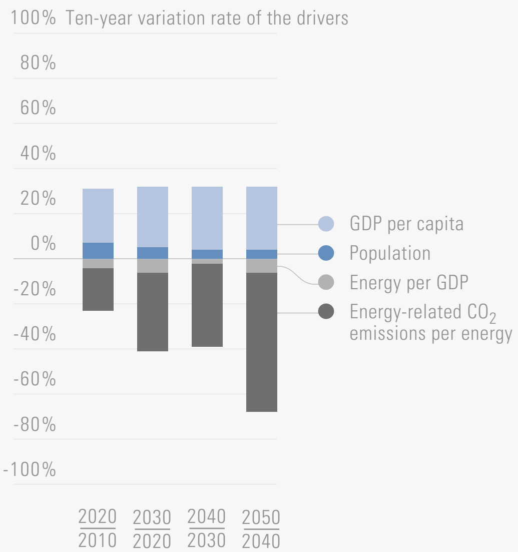
Energy Pathways, Primary Energy by source



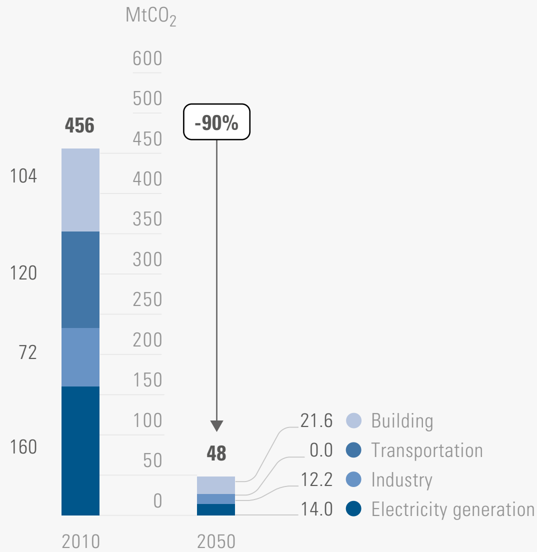
Energy Pathways, Final Energy by source



Energy-related CO_2 Emissions Drivers, 2010 to 2050



Energy-related CO_2 Emissions Pathway, by Sector



The Pillars of Decarbonization

Energy efficiency

Energy intensity of GDP, MJ/$

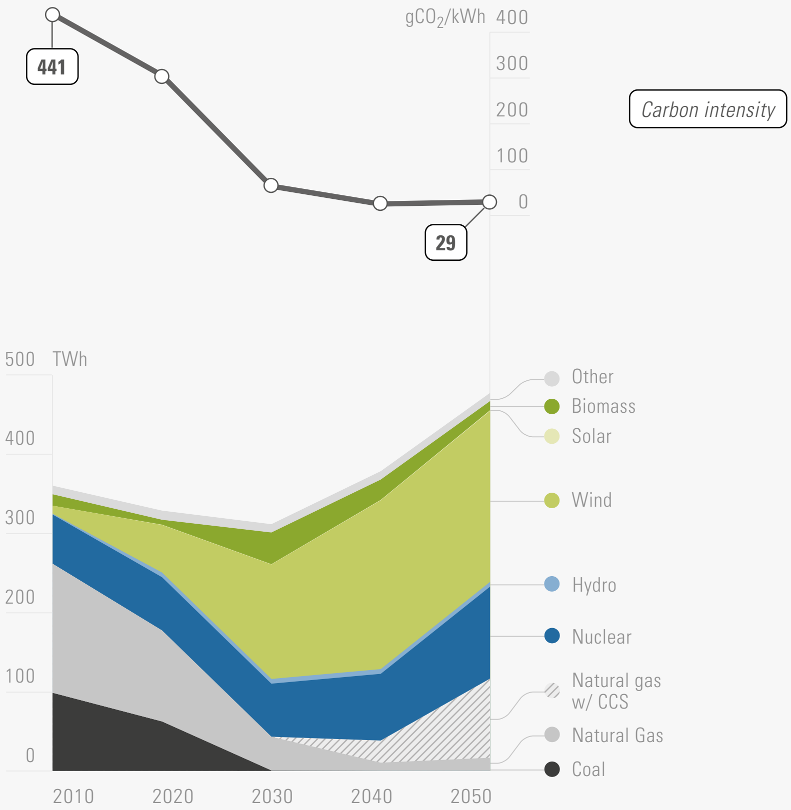
Decarbonization of electricity

Electricity emissions intensity, gCO_2/kWh

Electrification of end-uses

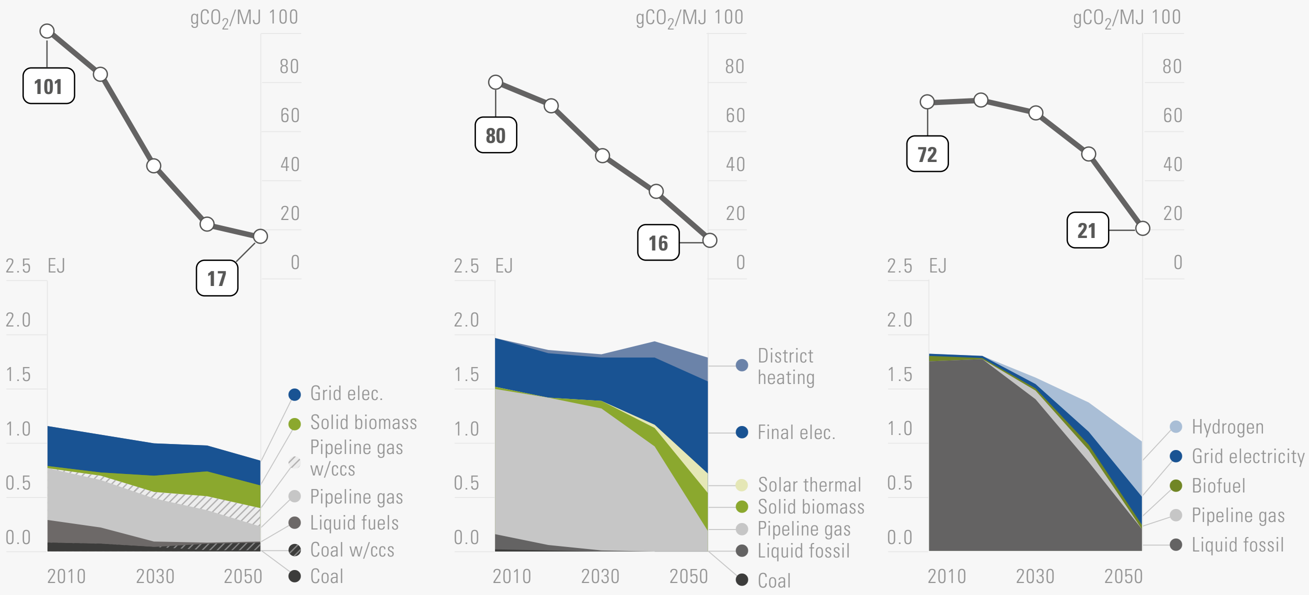
Share of electricity in total final energy, %

Energy Supply Pathways, by Resource



Electricity

Energy Use Pathways for Each Sector, by Fuel, 2010 – 2050



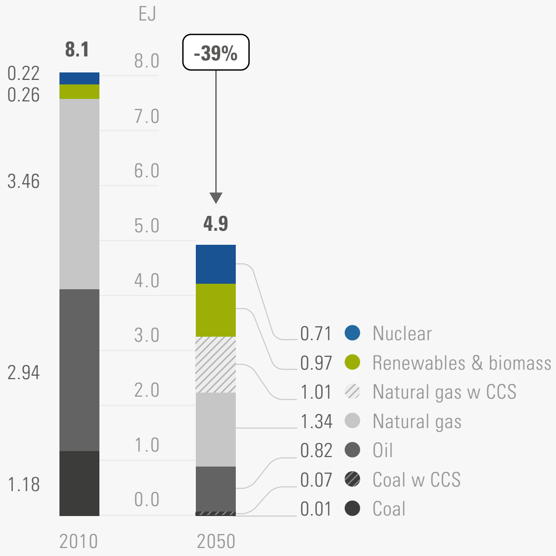
Industry

Buildings (residential)

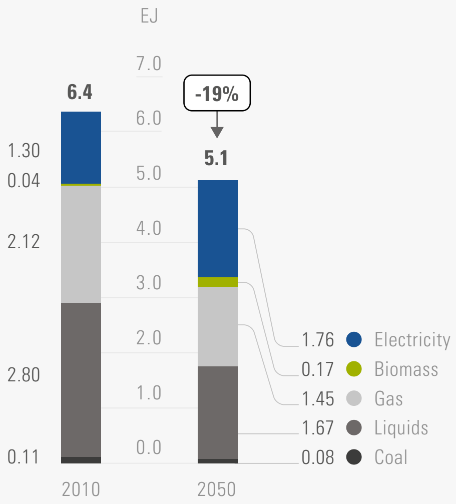
Transportation

UK - Reduced Demand

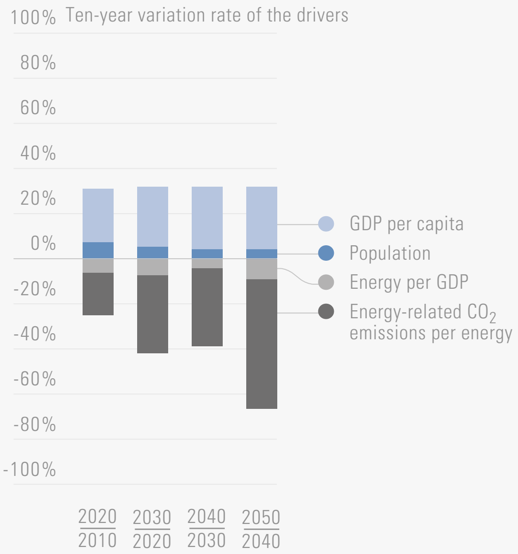
Energy Pathways, Primary Energy by source



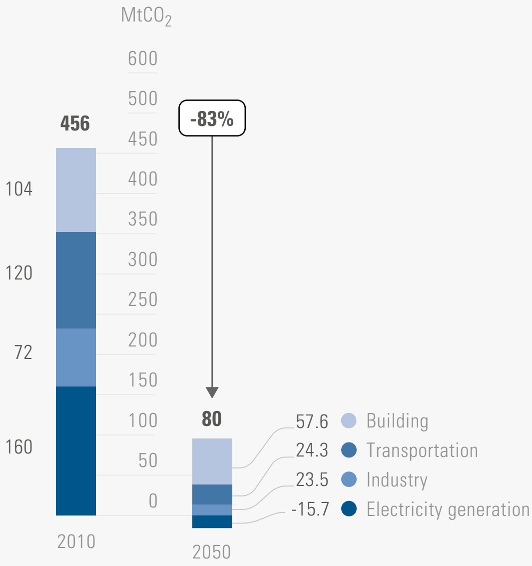
Energy Pathways, Final Energy by source



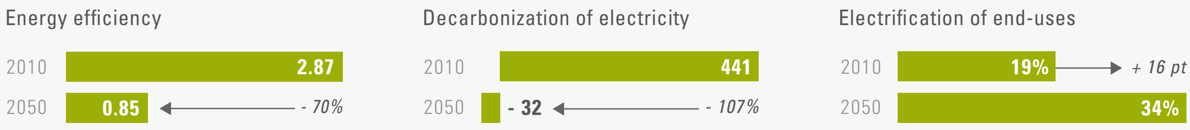
Energy-related CO_2 Emissions Drivers, 2010 to 2050



Energy-related CO_2 Emissions Pathway, by Sector



The Pillars of Decarbonization

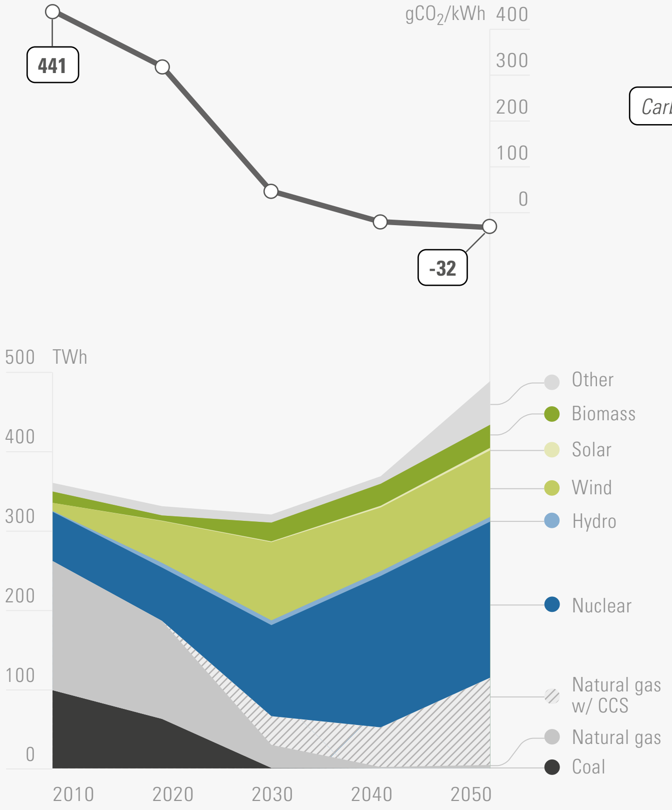


Energy intensity of GDP, MJ/$

Electricity emissions Intensity, gCO_2/kWh

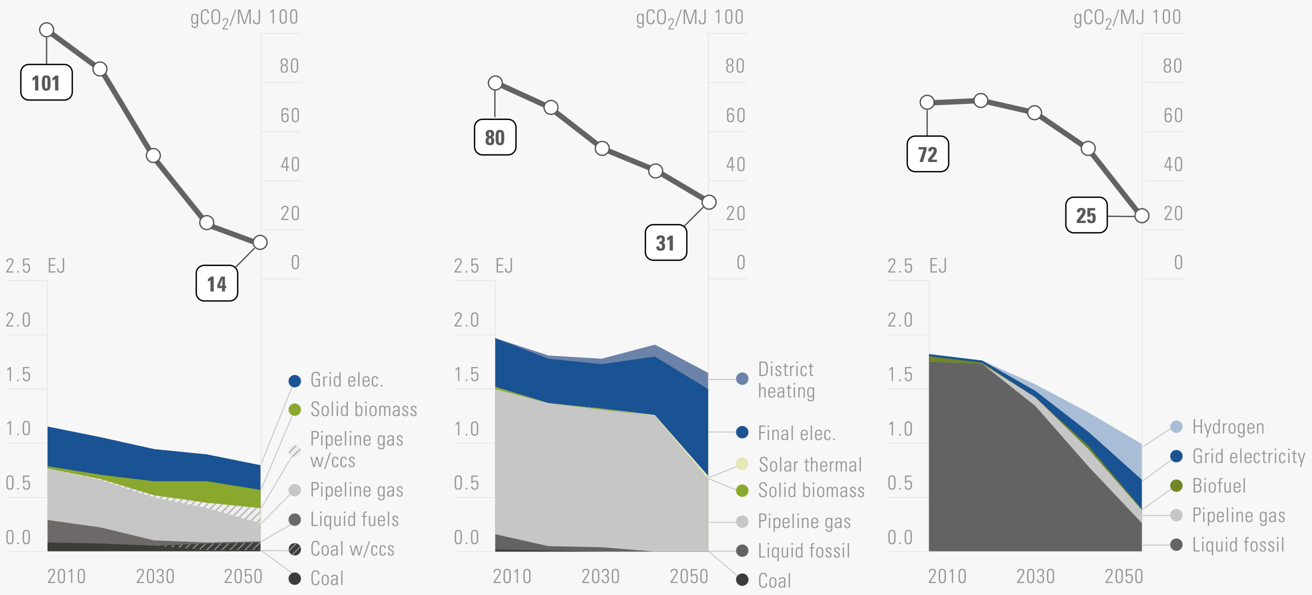
Share of electricity in total final energy, %

Energy Supply Pathways, by Resource



Electricity

Energy Use Pathways for Each Sector, by Fuel, 2010 – 2050



Industry

Buildings (residential)

Transportation

Acronyms

BECCS	Bioenergy with CCS
BEVs	Battery Electric Vehicles
CAT	Centre for Alternative Technology
CCAs	Climate Change Agreements
CCC	Committee on Climate Change
CCS	Carbon Capture and Storage
CfDs	Contracts for Difference
CNG	Compressed Natural Gas
COP21	21st session of the Conference of the Parties to the UNFCCC
DDPP	Deep Decarbonisation Pathways Project
DECC	Department of Energy & Climate Change
DTI	Department of Trade and Industry
ECO	Energy Company Obligation
EMR	Electricity Market Reform
ETI	Energy Technologies Institute
ETSAP	Energy Technology Systems Analysis Programme
EU ETS	European Union Emissions Trading Scheme
H_2FC	Hydrogen Fuel Cell
HGVs	Heavy Goods Vehicles
IA&S	International aviation and shipping
IEA	International Energy Agency
LDVs	Light Duty Vehicles (cars, vans)
LEVs	Low Emission Vehicles
OLEV	Office of Low Emission Vehicles
PHEVs	Plug-in Hybrid Electric Vehicles
RCEP	Royal Commission on Environmental Pollution
RHI	Renewable Heat Incentive
SMR	Steam Methane Reformer
TIMES	The Integrated MARKAL-EFOM System
UKERC	UK Energy Research Centre
UKTM	UK TIMES Model
UNEP	United Nations Environmental Programme
UN SDSN	UN Sustainable Development Solutions Network