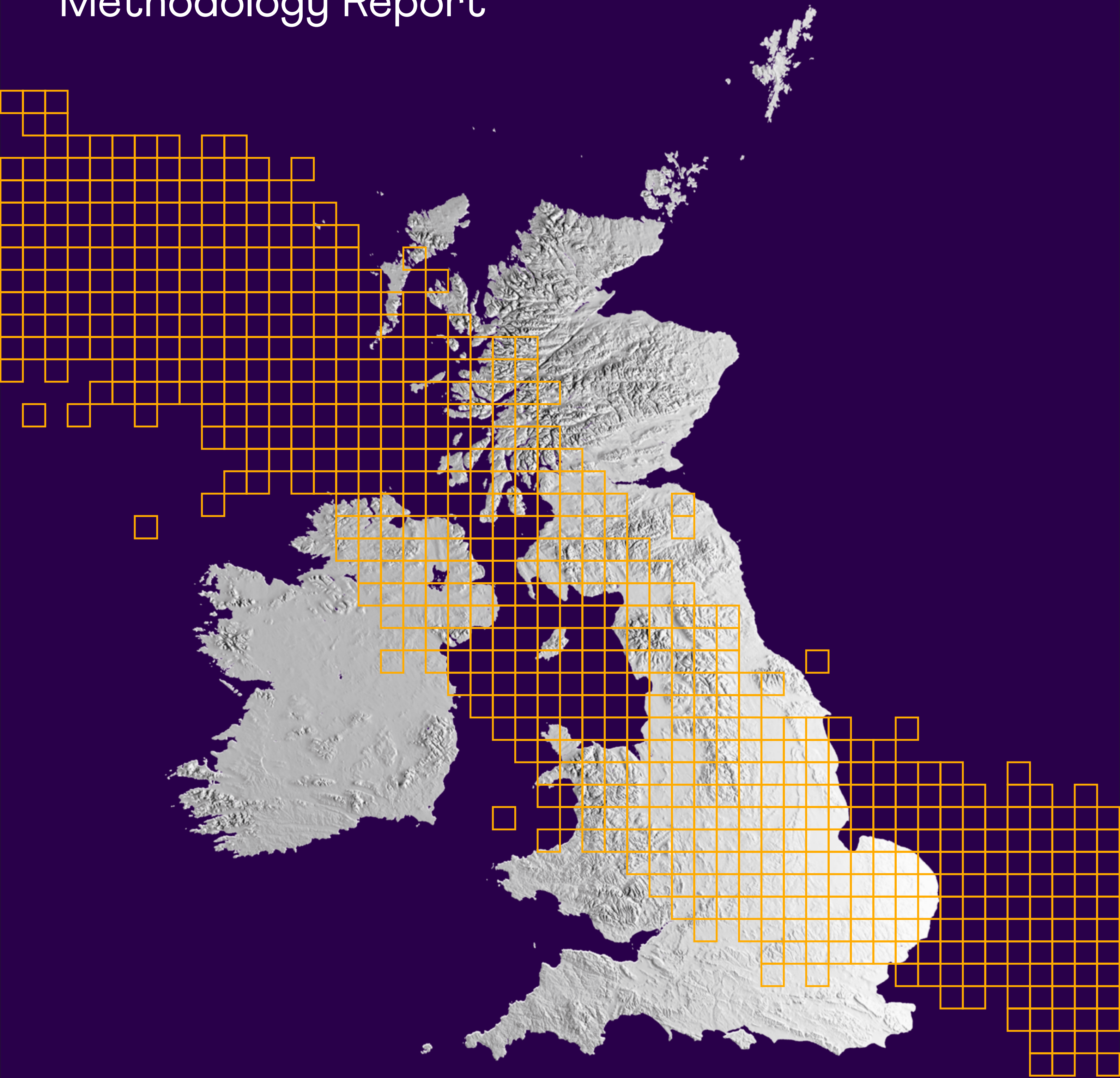
December 2020

The Sixth Carbon Budget
Methodology Report



Climate Change Committee

Sixth Carbon Budget - Methodology Report

Committee on Climate Change
December 2020

All enquiries related to this publication should be sent to: communications@theccc.org.uk

The Committee

The Rt. Hon John Gummer, Lord Deben,
Chairman

Lord Deben was the UK's longest-serving Secretary of State for the Environment (1993 to 1997). He has held several other high-level ministerial posts, including Secretary of State for Agriculture, Fisheries and Food (1989 to 1993). Lord Deben also runs Sancroft, a corporate responsibility consultancy working with blue-chip companies around the world on environmental, social and ethical issues.

Baroness Brown of Cambridge FRS
Deputy Chair

Baroness Brown of Cambridge DBE FREng FRS (Julia King) is an engineer, with a career spanning senior engineering and leadership roles in industry and academia. She currently serves as Chair of the CCC's Adaptation Committee; non-executive director of the Offshore Renewable Energy Catapult; and Chair of the Carbon Trust.

Professor Keith Bell

Keith Bell is a co-Director of the UK Energy Research Centre (UKERC), a Chartered Engineer and a Fellow of the Royal Society of Edinburgh. He has been at the University of Strathclyde since 2005, was appointed to the Scottish Power Chair in Smart Grids in 2013 and has been involved in energy system research in collaboration with many academic and industrial partners.

Professor Nick Chater

Nick Chater is Professor of Behavioural Science at Warwick Business School. He has particular interests in the cognitive and social foundations of rationality, and applying behavioural insights to public policy and business. Nick is Co-founder and Director of Decision Technology Ltd, a research consultancy.

Professor Piers Forster

Piers Forster is Director of the Priestley International Centre for Climate and Professor of Physical Climate Change at the University of Leeds. He has played a significant role authoring Intergovernmental Panel on Climate Change (IPCC) reports, and has a coordinating lead author role for the IPCC's sixth assessment report.

Dr Rebecca Heaton

Rebecca Heaton is responsible for Drax Group's efforts to mitigate climate change, ensuring that sound science underpins climate change polices and business strategy. She is also responsible for developing sustainability and climate change research programmes. Rebecca has a 20-year global career working at the interface between business, science and policy.

Paul Johnson CBE

Paul Johnson is Director of the Institute for Fiscal Studies and a visiting professor at University College London (UCL). He is widely published on the economics of public policy, and he co-wrote the 'Mirrlees review' of tax system design. He was previously Chief Economist at the Department for Education (2000 to 2004).

Professor Corinne Le Quéré FRS

Corinne Le Quéré is Royal Society Research Professor of Climate Change Science at the University of East Anglia (UEA), where she conducts research on the interactions between climate change and the carbon cycle. Corinne is currently the Chair of the French Haut Conseil pour le Climat.

Contents

The Committee is advising that the UK set its Sixth Carbon Budget (i.e. the legal limit for UK net emissions of greenhouse gases over the years 2033-37) to require a reduction in UK emissions of 78% by 2035 relative to 1990, a 63% reduction from 2019. This will be a world-leading commitment, placing the UK decisively on the path to Net Zero by 2050 at the latest, with a trajectory that is consistent with the Paris Agreement.

The Committee's advice on the Sixth Carbon Budget is based on an extensive programme of analysis, consultation and consideration by the Committee and its staff, building on the evidence published in 2019 for our *Net Zero* advice. The Sixth Carbon Budget advice consists of three CCC reports, as well as supporting data and evidence (see Report Map on next page).

A key part of the Committee's approach has been the construction of a set of self-consistent pathways, or scenarios, for emissions in each sector of the UK's emissions from now through to 2050. This *Methodology Report* contains a summary of the CCC's overall analytical approach to these scenarios, and a chapter for each sector of emissions, containing detail on the analysis and evidence used.

In addition to this Methodology Report we have also published:

- **An Advice report**: *The Sixth Carbon Budget – The UK's path to Net Zero*, setting out our recommendations on the Sixth Carbon Budget (2033-37) and the UK's Nationally Determined Contribution (NDC) under the Paris Agreement. This report also presents the overall emissions pathways for the UK and the Devolved Administrations and for each sector of emissions, as well as analysis of the costs, benefits and wider impacts of our recommended pathway, and considerations relating to climate science and international progress towards the Paris Agreement.[*]
- **A Policy Report:** *Policies for the Sixth Carbon Budget and Net Zero*, setting out the changes to policy that could drive the changes necessary, particularly over the 2020s.[†]
- **A dataset** for the Sixth Carbon Budget scenarios, which sets out more details and data on the pathways than can be included in this report.
- **Supporting evidence** including our public Call for Evidence, 10 new research projects, three expert advisory groups, and deep dives into the roles of local authorities and businesses.

For ease, the relevant sections from the three reports for each sector (covering pathways, method and policy advice) are collated into self-standing sector documents. A full dataset including key charts is also available alongside this document.

All outputs are published on our website (www.theccc.org.uk).

This report is not intended to present the results of the analysis – the key results are presented in the Advice Report, with a fuller set of results in the Sixth Carbon Budget Dataset (see report map on p9).

[*] CCC (2020) The Sixth Carbon Budget – The path to Net Zero.

[†] CCC (2020) Policies for the Sixth Carbon Budget and Net Zero.

We first set out our cross-cutting approach, and then step through our approach on a sector-by-sector basis across the following 12 Chapters:

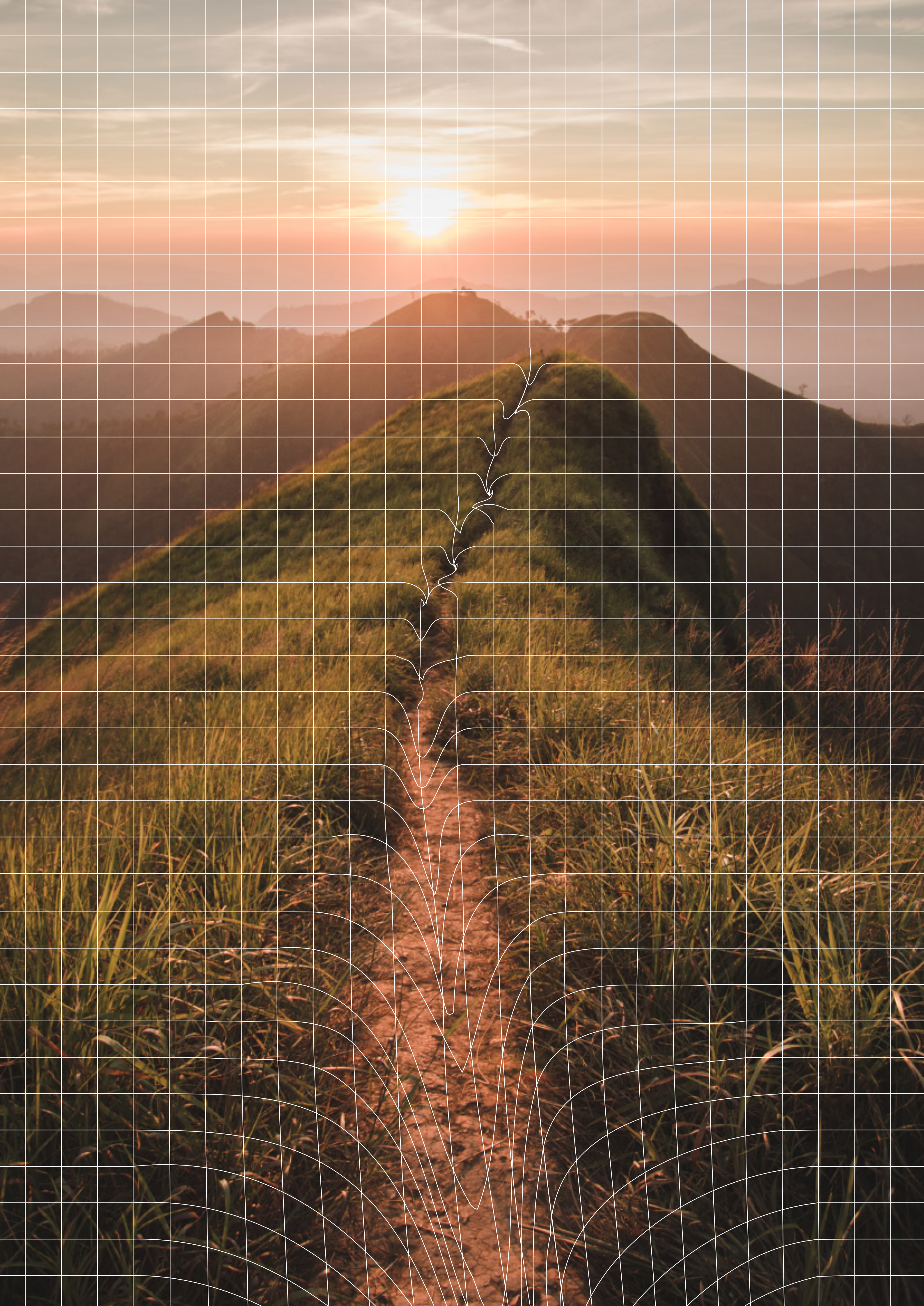
1) Introduction and approach to the Sixth Carbon Budget
2) Surface transport
3) Buildings
4) Manufacturing and construction
5) Electricity generation
6) Fuel supply
7) Agriculture and land use, land-use change and forestry (LULUCF)
8) Aviation
9) Shipping
10) Waste
11) F-gases
12) Greenhouse gas removals

Figure 1 Sixth Carbon Budget: Report map

Advice Report	**PART 1: The path to Net Zero**	**PART 2: Impacts of the 6th Carbon Budget**	**PART 3: International & Scientific Circumstances**	**PART 4: Budget Recommendations**	**POLICY REPORT: *Policies for the Sixth Carbon Budget & Net Zero***	**METHODOLOGY REPORT**
	Chapter 2: The UK path to Net Zero	**Chapter 5:** Investment, costs and benefits	**Chapter 7:** Contribution to the Paris Agreement	**Chapter 9:** The shape of the emissions path	**Chapter 1:** The overarching policy framework	**Chapter 1:** Approach to the 6CB analysis
	Chapter 3: Sector pathways to Net Zero	**Chapter 6:** A just transition to Net Zero	**Chapter 8:** Scientific context	**Chapter 10:** Recommendation s on the budget	**Chapters 2-11:** Sector policies for the 2020s	**Sector specific methodology chapters for:** Surface transport, Buildings, Manufacturing & construction, Fuel supply, Electricity generation, Agriculture & Land Use, Aviation, Shipping, Waste, F-gases, GHG removals
	Chapter 4: The path to Net Zero for Scotland, Wales & Northern Ireland		*Denotes chapter with sector-specific material*			
How we determine the Sixth Carbon Budget:	**Emissions pathways** **Targets for Scotland, Wales and Northern Ireland**	**Costs and benefits of climate action**	**The UK's contribution to the global effort**	**Budget level** **Inclusion of emissions from international aviation & shipping** **Carbon units**	**Cross-cutting policy recommendations** **Sector-specific policy recommendations**	**The Sixth Carbon Budget Dataset** containing all the numbers and detail behind the advice
Themes within the advice	*Choices around how we decarbonise* *Behaviour change*	*Just transition* *Competitiveness* *The role of finance* *Fiscal impacts* *Energy bills*	*Consumption emissions* *International climate finance*	*Emissions trading & use of credits* *International aviation & shipping*	*Public engagement* *The role of business, and local action*	
Supporting evidence	16 Committee meetings to scrutinise analysis, 3 independently chaired expert advisory groups on Health, Finance and Policy	Independent research on: • UK's international climate influence, • heat in buildings, • energy efficiency in buildings, • low-carbon industry, • industry policy, • heavy goods vehicles, • land use, • low-carbon hydrogen • macro-economic modelling.		Open call for evidence with 177 responses from businesses, academics, society groups and individuals	15 roundtables across power, manufacturing, transport, land use, digitalisation and greenhouse gas removals	New work on the roles for business and local authorities in delivering the Sixth Carbon Budget and Net Zero

Chapter 1

Introduction & approach to the Sixth Carbon Budget



Introduction and key messages

This chapter sets out the overarching analytical approach to the Sixth Carbon Budget advice.

This report accompanies the Committee's advice on the Sixth Carbon Budget (2033-37), and is where we explain our analytical approach behind our recommendations on the level of the budget and the UK's Nationally Determined Contribution (NDC) under the Paris Agreement. Here we describe how we used the latest available evidence to build emissions pathways that consider different ways for the UK to reach Net Zero, by 2050 at the latest.

This chapter summarises the approach to developing the scenarios and sets out important assumptions and approaches that are used across the economy. Chapters 2-12 then describe the scenarios, and key assumptions in each sector.

The key messages in this chapter are:

- **Multiple pathways are used to determine a range of ways for the UK to achieve its Net Zero ambitions by 2050**. The pathways are built on the latest available evidence in all areas and include choices on how the UK can reduce emissions towards the Sixth Carbon Budget (2033-37) and Net Zero.
- Core to these pathways is **achieving the highest possible ambition** for reducing emissions in a sector, while taking into account real-world constraints such as the need to build up skills, supply chains and manufacturing capability, and the economic lifetime of existing, high-carbon assets in the UK.
- **We compare our pathways to a world with no further climate action**, in order to estimate the impact of low-carbon technologies and behaviours, and the overall costs of the transition. We estimate investment costs, operating cost savings and overall annualised costs in a transition to Net Zero.
- **We use official projections for emissions, energy costs and GDP** to inform our pathways, and determine the key impacts.
- **We recognise the key uncertainties involved in developing scenarios** that stretch across multiple decades and note the impact that these uncertainties could have on future UK emissions. We use a conservative approach to these uncertainties, so that if reality turned out differently, emissions would be more likely to be lower than our pathways than higher.
- **We produce pathways for the whole of the UK as well as Scotland, Wales and Northern Ireland separately**, taking into account specific circumstances that affect the pace and overall level of decarbonisation for these nations.

This chapter is structured in four sections:

1. How we constructed the scenarios at an economy-wide level
2. General analytical approach
3. Projections and uncertainty
4. Determining emissions pathways for Scotland, Wales and Northern Ireland

1. How we constructed the scenarios at an economy-wide level

We explore multiple pathways for how the UK can reach net-zero emissions by 2050.

We developed scenarios for our Sixth Carbon Budget advice that explore a range of ways to achieve Net Zero, by 2050 at the latest. These scenarios build on our 2019 advice in our 2019 report *Net Zero: The UK's contribution to stopping global warming.*[1]

- In our 2019 advice on setting the Net Zero target, we presented a single ('Further Ambition') scenario for 2050 – this acted as a 'proof of concept', providing confidence that Net Zero could be achieved at reasonable cost without relying on major breakthroughs in technologies and behaviours.[*]
- For the Sixth Carbon Budget advice, we have developed four 'exploratory' scenarios that reach Net Zero emissions by 2050 in quite different ways, illustrating the range for how it can be achieved and exploring how the pace of emissions reductions can vary between sectors if particular uncertainties resolve themselves in different ways. These scenarios reflect judgements on the achievable and sensible pace of decarbonisation in the face of uncertainty and help build an understanding of how less success in one area could be compensated for elsewhere.
- We used those exploratory scenarios to identify a **Balanced Net Zero Pathway** to 2050 that keeps in play a range of ways of reaching that target.

The Further Ambition scenario assumed a certain amount of progress in respect of innovation and societal change, although these were relatively conservative. Greater contributions from societal/behavioural change and from innovation would reduce the challenges in achieving Net Zero emissions by 2050, by further reducing emitting activities (e.g. flying, livestock farming) and making emissions reduction cheaper and/or easier.

Our pathways use known solutions where they exist and minimise use of greenhouse gas removals.

As a general principle, consistent with the preferences expressed in the UK Climate Assembly[2], our pathways prioritise emissions reductions where known solutions exist and thereby minimise the need for the use of greenhouse gas removals (see Table 1.2 of the Advice Report).[3] This will tend to lead to lower overall cumulative UK emissions along the pathway to Net Zero and limit risks of over-reliance on being able to deploy removals sustainably at scale.

We initially constructed three 'exploratory' scenarios that reach Net Zero by 2050, one of which is similar to Further Ambition while the other two are more optimistic either on developments regarding behavioural change or improvements in technology costs and performance (Figure 1.1). Although to some extent these reflect choices on the way to Net Zero, they primarily reflect greater or lesser degrees of success on key policy priorities on the path to Net Zero – engagement of the public and businesses, and innovation:

- In the **Headwinds** scenario, we have assumed that policies only manage to bring forward societal and behavioural change and innovation at the lesser end of the scale, similar to levels assumed in our 2019 Further Ambition scenario. People change their behaviour and new technologies develop, but we do not see widespread behavioural shifts or innovations that significantly reduce the cost of green technologies ahead of our current projections.

[*] see Box 1.2 in Chapter 1 of the Advice Report for the key differences between the Further Ambition scenario and our Balanced Pathway

This scenario is more reliant on the use of large-scale hydrogen and carbon capture and storage (CCS) infrastructure to achieve Net Zero.

- In the **Widespread Engagement** scenario, we assume higher levels of societal and behavioural changes. People and businesses are willing to make more changes to their behaviour. This reduces the demand for the most high-carbon activities and increases the uptake of some climate mitigation measures. Assumptions on cost reductions are generally the same as in Headwinds.
- In the **Widespread Innovation** scenario, we assume greater success in reducing the costs of low-carbon technologies. This allows more widespread electrification, a more resource- and energy-efficient economy, and more cost-effective technologies to remove CO_2 from the atmosphere. Assumed societal/behavioural changes are generally the same as in Headwinds.

Our Balanced Pathway navigates through the range of possibilities we have identified.

We then constructed the '**Balanced Net Zero Pathway**', as a recommended scenario that reaches Net Zero by 2050. It was designed to drive progress through the 2020s, while creating options in a way that seeks to keep the exploratory scenarios open (see subsection (c) below). We also constructed a further exploratory scenario ('**Tailwinds**') that assumes considerable success on both innovation and societal / behavioural change and goes beyond the Balanced Pathway to achieve Net Zero before 2050. Table 1.1. contains an overview of sector choices that inform the scenarios.

In the process of developing five scenarios for the UK, we have produced a total of 70 sectoral pathways for the UK (Figure 1.2). We have taken steps to ensure that each of the sectoral scenarios represents a coherent picture at the economy-wide level, including what happens to infrastructure and operation of the electricity system. While these scenarios are designed to have self-consistent narratives, there is some potential to 'mix and match' strategies or compensate for under-delivery in one area with greater delivery elsewhere based on another scenario.

Figure 1.1 Scenario framework for the analysis in this report

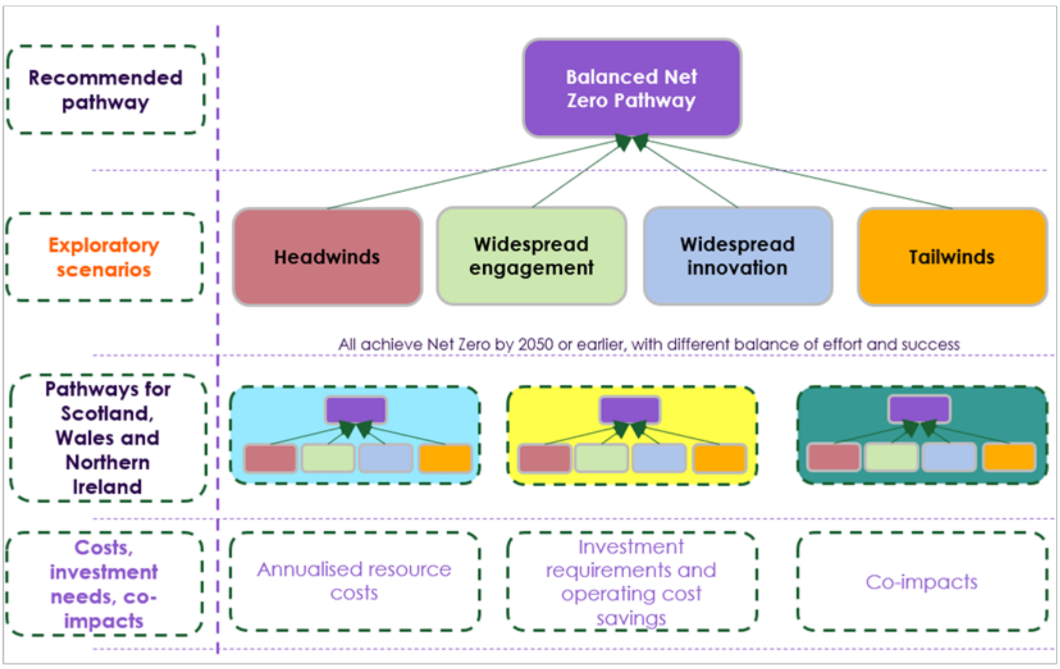
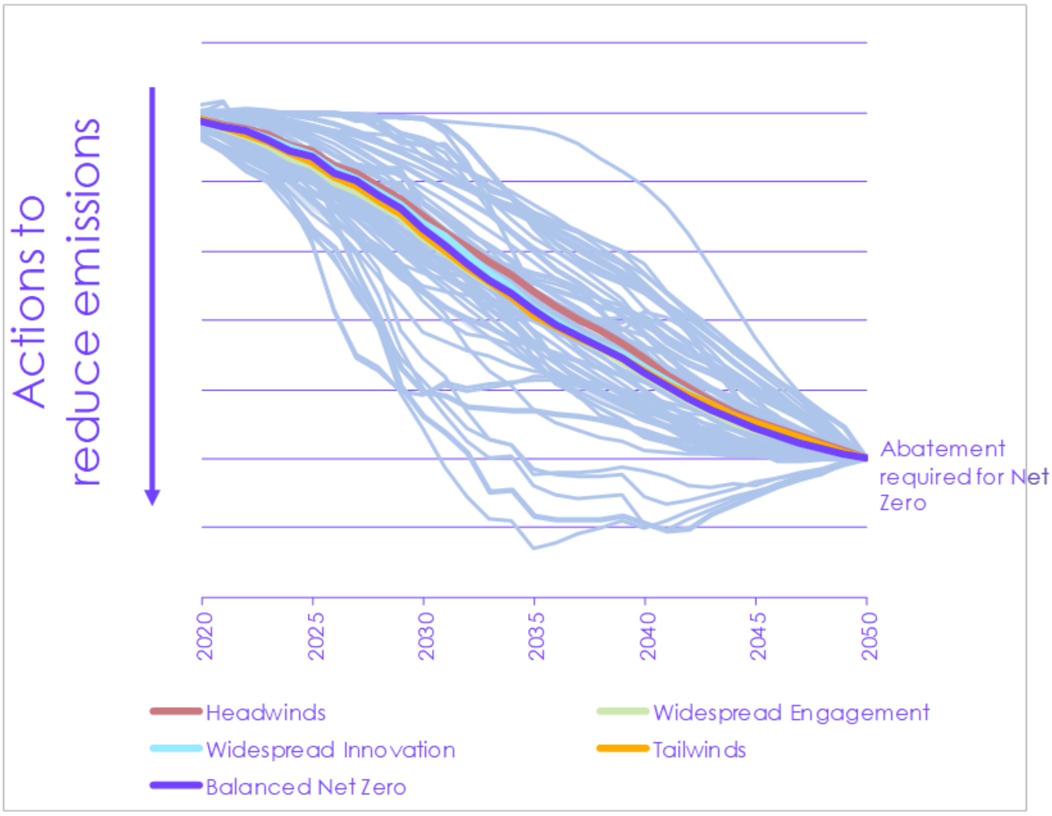


Figure 1.2 The five economy-wide scenarios are constructed from 70 individual scenarios for action across every sector of the economy



Source: CCC analysis.
Notes: Each individual line represents the path for new abatement in a sector between 2020 (effectively zero) and by 2050 where all sectors reach a level of abatement that is consistent with the UK getting to Net Zero. Not all sectors will get to zero emissions. Abatement in the fuel supply is greater in the 2030s than by 2050.

Table 1.1
Key sector assumptions across the scenarios

Sector *(Chapter number)*	Balanced Net Zero Pathway	Headwinds	Widespread Engagement	Widespread Innovation	Tailwinds
Transport *(2)*	**Electric Vehicles (EVs) reach 100% of sales of passenger vehicles in 2032.** **Lowest cost Heavy Goods Vehicles (HGVs) deployed.**	EVs reach 100% of sales in 2035. Hydrogen used in HGVs.	EVs reach 100% of sales in 2030. High demand reduction, modal shift and ride-sharing, leading to 34% lower car demand.	EVs reach 100% of sales in 2030. Electric HGVs.	EVs reach 100% of sales in 2030. Mix of HGVs deployed.
Buildings *(3)*	**Hybrid hydrogen scenario in homes, with 11% of homes using hydrogen for heat.** **Electrified heat networks.**	Widespread network conversion to hydrogen, with 71% of homes using hydrogen for heat. Smaller role for heat pumps across all buildings. Hydrogen used in heat networks.	Fully electrified scenario (including heat networks).	Hybrid hydrogen scenario in homes, with 10% of homes using hydrogen for heat. Heat networks fully electrified.	Buildings fully electrified, except for areas around industrial clusters which use H2 boilers. 11% of homes use hydrogen for heat.
Manufacturing and construction *(4)*	**Balanced H_2 & Electrification, + CCS.**	More blue hydrogen than electrification. Wider use of CCS on combustion emissions	Mostly electrification, some green and blue hydrogen.	Electrification and green hydrogen. Higher CCS capture rates.	Electrification and green hydrogen. Higher CCS capture rates.
Power generation *(5)*	**Renewables make up 80% of total electricity generation.**	Renewables make up 75% of total electricity generation. Lower electricity demand due to greater use of hydrogen in homes.	Renewables make up 85% of total electricity generation.	Renewables make up 80% of total electricity generation. Highest electricity demand.	Renewables make up 90% of total electricity generation.
Hydrogen production *(6)*	**Split of green and blue hydrogen production. Limited BECCS.**	High hydrogen demand. Mostly blue hydrogen production.	Low hydrogen demand. Mostly green hydrogen production.	Mostly green hydrogen production.	Mostly green hydrogen production and BECCS.
Agriculture and Land Use *(7)*	**20% shift away from red meat and dairy by 2030; 35% by 2050 (meat only).**	20% shift away from red meat and dairy. Annual tree-planting rates of	High level of diet change (50% by 2050) and food waste reduction (70%).	50% diet change with 30% of this from lab grown meat.	Diet change aligned to Widespread Innovation. Annual tree-planting rates of 70,000

	Tree-planting rates of 30,000 hectares per year to 2025, then 50,000 hectares/year after 2035.	30,000 hectares/year by 2035.	Tree-planting rates of 70,000 hectares/year by 2035, low yields, greater mix towards broadleaf	Annual tree-planting rates of 50,000 hectares/year by 2030. High yields, high mix of conifers	hectares/year by 2035, high yields.
Aviation *(8)*	**25% growth in aviation demand, no net airport expansion, and 25% use of low-carbon fuels by 2050.**	25% growth in aviation demand, and 20% use of low-carbon fuels by 2050.	15% reduction in aviation demand, no airport expansion, and 25% use of low-carbon fuels by 2050.	50% growth in aviation demand, and 50% use of low-carbon fuels by 2050.	15% reduction in aviation demand, no airport expansion, and 95% use of low-carbon fuels by 2050.
GHG Removals *(12)*	**BECCS used in generating power, hydrogen, biojet, energy-from-waste and industrial heat. Some DACCS.**	More BECCS used in power, hydrogen, and energy-from-waste. No DACCS.	BECCS used mostly in power generation and biojet production. No DACCS.	Similar split of uses as in the Balanced Pathway. Large use of DACCS.	More BECCS used in power and hydrogen. Large use of DACCS.

Notes: Shipping transitions to using ammonia as fuel in all scenarios. See sector chapters for choices on wastes and f-gases. Blue hydrogen is hydrogen produced through methane reformation with carbon capture and storage (CCS); green hydrogen is hydrogen produced through electrolysis.
BECCS = Bioenergy with CCS. DACCS = Direct Air Carbon Capture and Storage.

2. General analytical approach

The analytical approach described here is consistent with the approach used by the CCC since 2008.

The analytical approach for the Sixth Carbon Budget is similar to, and builds on, previous CCC analysis. It is consistent with the analytical approach that we have used since our first report in 2008 and advice on carbon budgets since then. In particular, the work done on the Sixth Carbon Budget builds on the Committee's Net-Zero advice in 2019, which looked at a snapshot of the UK economy in 2050, to determine whether reaching Net-Zero emissions was possible in the UK. Our advice on the Sixth Carbon Budget provides detail on all years between 2020 and 2050.

Our analysis asks a similar question to the Net-Zero advice: taking into account costs, technical feasibility and the need to scale up supply chains, how far can emissions in a given sector be reduced? The key differences between the two sets of advice being that in the new advice we are:

- Producing emissions and costs estimates for all years between 2020 and 2050, in particular for the period of the Sixth Carbon Budget (2033-37).
- Producing multiple pathways, in order to determine a 'balanced' pathway which forms the basis of our Sixth Carbon Budget recommendation.

a) Deciding which measures to include and when they are deployed

Emissions reductions depend on societal change (e.g. practices within organisations and individual choices) and technologies, which are key to enabling many of those changes. In respect of the latter, the Sixth Carbon Budget pathways consider both choices *between* alternative technologies and about *when* choices must be made and technologies deployed. In assessing both of these factors, we take account of the status and costs of low-carbon technologies and user preferences in the UK and around the world, and consider constraints to deployment of these technologies on their uptake in the UK.

i) Technology choice

Technology choice in our scenarios takes into account current status, global trends, barriers to uptake and interdependencies across technologies and sectors.

In all sectors the choice of low-carbon technologies to use in the scenarios builds on the technologies included in the 2019 *Net* Zero report, and is supplemented by new data and evidence produced since then.* The use of multiple scenarios in the Sixth Carbon Budget analysis allows us to compare alternative technological pathways, where clear and credible choices exist (e.g. the choice of hydrogen or electrification in HGVs). As in the Net-Zero report, the choice of what technologies to include in a scenario uses the latest evidence available in that sector to consider the following:

- **The current status**, cost and deployment level in the UK, and globally.
- **Opportunities for cost reduction and technology improvements**, or increased behaviour change
- **Barriers to uptake**, such as disruption to homes (e.g. housing retrofits) and local infrastructure (e.g. energy network upgrades).
- **Inter-dependencies between sectors**, such as the increased need for low-carbon energy, or additional infrastructure.

* See the subsequent sector chapters of this report for further detail on which technologies are included for each sector.

- **Impacts on consumption emissions** (e.g. arising from emissions in the supply chain of the technology or fuel).
- **Resilience to a changing climate**, including, for example, the need to avoid over-heating in the UK's buildings, the water footprint of energy generation technologies or the need to plant trees that can thrive in the different climatic conditions expected in the UK in future.

ii) Timing of deployment

The overriding principle of our scenarios is achieving the 'highest possible ambition' in each sector.

In some cases, deployment of measures increases at around their feasible limits since this is the only credible path to reach net-zero emissions by 2050. Where there is flexibility over the timing of a measure, the overriding principle is achieving the 'highest possible ambition' in each sector. This is determined by a range of factors (which will tend to point to earlier deployment) including:

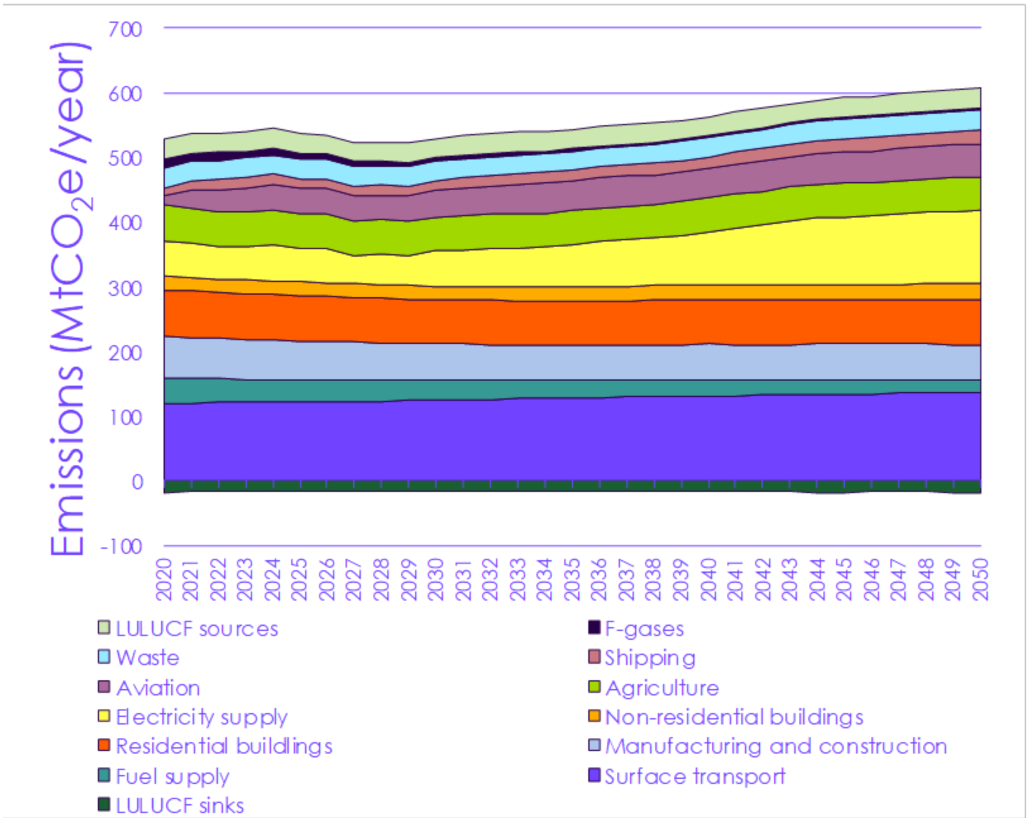
- **Lifetimes of existing assets,** including natural replacement cycles for assets such as vehicles, gas boilers and power stations, with a principle of avoiding scrappage of these assets before they reach their normal end of life, where possible.
- **Supply-chain development,** considering the status of current UK and global supply chains, supply chain deployment limits and the need for skills, manufacturing, deployment capacity and access to materials to increase over time.
- **Infrastructure implications,** including the availability of current infrastructure (such as network capacity for EV charging stations) and the need for additional infrastructure to be scaled up for the low-carbon technology to be deployed (such as CO_2 networks for carbon capture and storage).
- **Optionality**, such as the deployment date needed to keep open the option of being able to deploy a measure at scale in the long-term. For example, decarbonising all of the UK's 29 million residential buildings may not be considered feasible over a period of 10 years, but could be considered more plausible over a period of 20 years. Therefore if multiple options are available for low-carbon heating, these options would need to be determined by 2030 at the very latest in order to give sufficient time to scale up. In the meantime, progress can be made that both reduces emissions in the near term, while maintaining optionality.
- **Cost-effectiveness**, as judged against carbon values (see next section). This is a static measure and doesn't capture the full dynamics of a transition to net-zero, but it is useful in providing an indication of the *latest* date for deployment, which could be pulled forward by other considerations.
- **Innovation spillovers,** such as the plausibility of early investment in a technology reducing costs, or providing optionality for other sectors. For example, continued investment in renewables has reduced costs, and in the future may mean renewable electricity can be used for low-carbon hydrogen production for synthetic fuels.
- **Wider benefits** such as health benefits, air quality benefits, environmental benefits, and jobs.

b) Definition of and use of baselines

In order to determine the costs of decarbonisation we need to compare against a scenario where no further climate action is taken beyond today.

To determine the costs of decarbonisation we construct an additional scenario, which estimates what future emissions in the UK could be for each sector to 2050, if no further climate action is taken beyond today.* Emissions and energy demands are produced for this baseline, so we can then estimate the change between the baseline and our scenarios. Sector baselines are based on the Energy and Emissions Projections (EEP) 'Reference Policies' scenario produced by the Department of Business Energy and Industrial Strategy (BEIS) and complemented by CCC internal analysis (Figure 1.3). Typically, these baselines will ensure that currently funded low-carbon policies are taken into account (e.g. renewables with Government-backed contracts that have been deployed, or are expected to be deployed in the 2020s) but will not take into account unfunded policies or proposals, or significant additional uptake of low-carbon technologies from today. Descriptions of the baselines used in each sector are in the sector-specific chapters of this document.

Figure 1.3 Baseline emissions by sector in the Sixth Carbon Budget analysis



Source: BEIS (2019) *Energy and Emissions Projections 2018 (Reference policies scenario)*; CCC analysis
Notes: Emissions in the baseline have been adjusted for AR5 global warming potentials and the inclusions of peatland in the emissions inventory. Baseline emissions in electricity supply are due to baseline growth in energy demand, rather than electrification in our scenarios. LULUCF = Land use, land-use change and forestry.

* Note that previous CCC analyses, including the Net Zero report, and the CCC's advice on the Fifth Carbon Budget were based on baselines with no further climate action beyond 2009, to represent the total cost of climate action in the UK following the passing of the Climate Change Act in 2008. After over a decade of climate action in the UK, including uptake of renewable electricity, and energy efficiency improvements in homes, appliances and vehicles, we no longer think comparing low-carbon action to a pre-2009 baseline is a useful construct, and therefore compare future climate action against a scenario with no further climate action beyond today. In practice this means our baseline scenario is BEIS's 'Reference Scenario' rather than their 'Baseline Policies' scenario.

c) Use of carbon values

Carbon values can be used to express a monetary value for reductions in emissions, and are useful to compare against the abatement costs of technologies and behaviours in our scenarios.

Carbon values, typically expressed in £/tCO_2e, are used to express a monetary value for reductions in emissions of CO_2 and other greenhouse gases (weighted according to their Global Warming Potentials). They can usefully be compared to abatement costs, also expressed as a £/tCO_2e, of potential measures to reduce emissions (see section v below).

In our analysis, abatement costs are a key metric for choosing *between* different abatement options – if two options can be equally effective in reducing emissions, and one can do it more cheaply then it will generally be preferred. However, uncertainties over barriers to deployment and how future costs will develop mean that this is not always clear cut, so our scenarios explore wider use of different options, including those that we expect are likely to be more expensive.

Carbon values are used as a guide to deployment of low-carbon measures in our scenarios, alongside other considerations.

We compare abatement costs in each sector to each other and to carbon values to help ensure consistent effort across the economy and to prioritise cost-saving and low-cost emissions reductions early on. In theory, with a set of target-consistent carbon values, if all actions with a lower abatement cost are taken then the target will be met. Carbon values that rise steadily can guide a steady increase in action across the economy. However, this simplification does not capture the dynamics of how costs typically evolve, with early deployment being more expensive and costs falling over time. We therefore use carbon values as a guide alongside the other considerations set out in section ii.

- We include actions with higher abatement costs where deployment is needed to stay on track to the 2050 target and/or to drive down costs and build markets for increased deployment. For example, we expect retrofit of low-carbon heating to have a high abatement cost but it must start to scale up immediately if all homes are to reach zero emissions by 2050.
- We include actions that may have high abatement costs but are important to delivering wider health and environmental benefits or achieving social objectives. For example, we include deep retrofits to improve the energy efficiency of homes of the fuel poor, even where these are likely to be expensive.
- There are also many measures, like electric vehicles, energy efficiency and offshore wind, where abatement costs are already very low or even negative (i.e. they reduce costs). However, deployment constraints and the desire for stable investment programmes that avoid capital scrappage mean roll-out occurs over time in our scenarios.

Given the high ambition of the UK's Net Zero 2050 target and the requirement under the Paris Agreement to pursue 'highest possible ambition' it is appropriate to use a set of high carbon values:

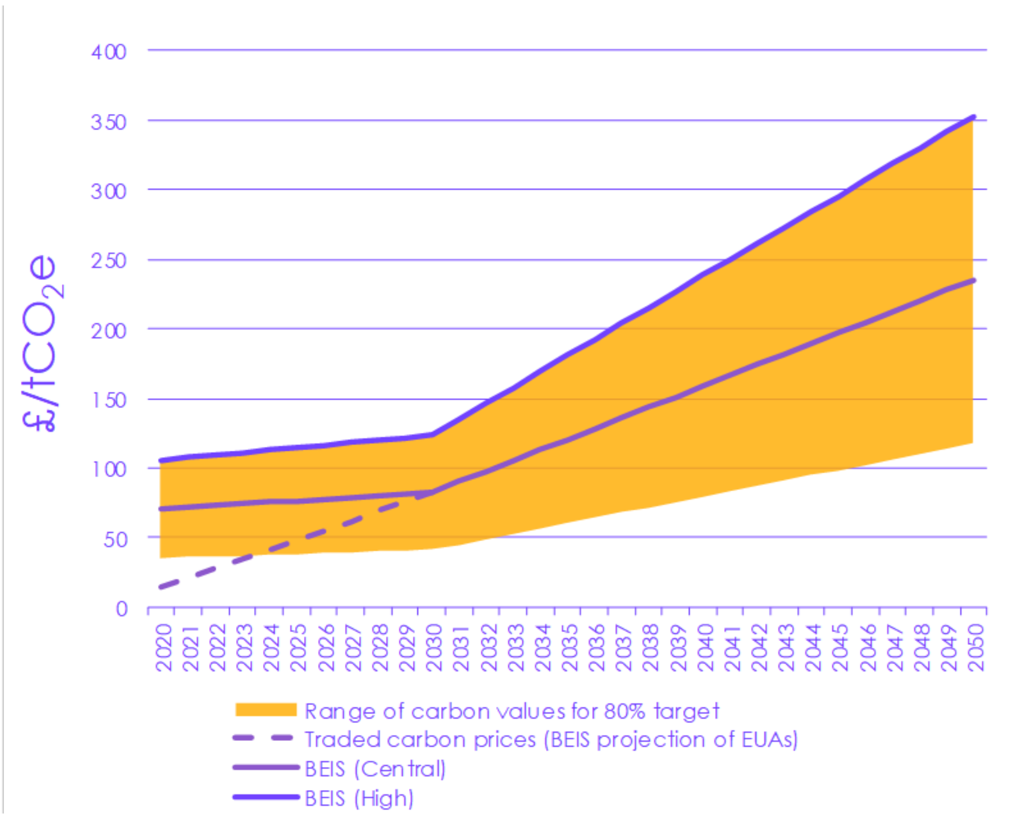
- The Government has published a range of carbon values for the UK's previous 'at least 80%' emissions reduction target by 2050, which have been used in policy appraisal as part of the Government's Green Book since 2007.[*] The 'central' carbon values published by BEIS for the 80% target reach £230/tCO_2e by 2050, with a low-high range of ±50% (Figure 1.4).

[*] Specifically, HMT (2018) *The Green Book*.

- At the time of the Sixth Carbon Budget analysis there were no official carbon values consistent with the Net Zero target, though the Government are intending to publish these over the coming months.
- Analysis for our 2019 *Net Zero* report, suggests carbon values by 2050 of between £300-450/tCO_2e:
  - The higher value is consistent with the upper end of the abatement costs we estimated under the Further Ambition scenario.
  - The lower value reflects the cost assumed for scalable greenhouse gas removal options (e.g. Direct Air Carbon Capture and Storage - DACCS), which would – if it can be deployed and scaled up as necessary – put a ceiling on the marginal abatement costs in reaching Net Zero. However, this cost estimate is highly uncertain, and comes with risks attached – it cannot be guaranteed that GGR technologies can be deployed at sufficient scale by 2050 to place a ceiling on the marginal cost.

In the absence of official carbon values that are consistent with the UK's Net Zero target, we used BEIS's 'High' carbon value projection which reaches £350/tCO_2e by 2050, within the range suggested by our Net Zero analysis. (Figure 1.4). However, the average cost of abatement in our scenarios is well below these threshold values.

Figure 1.4 Range of carbon values for an 80% reduction in emissions



Source: BEIS (2019) *Carbon values for policy appraisal*; CCC analysis
Notes: EUAs = EU allowances traded in the EU's Emissions Trading Scheme.

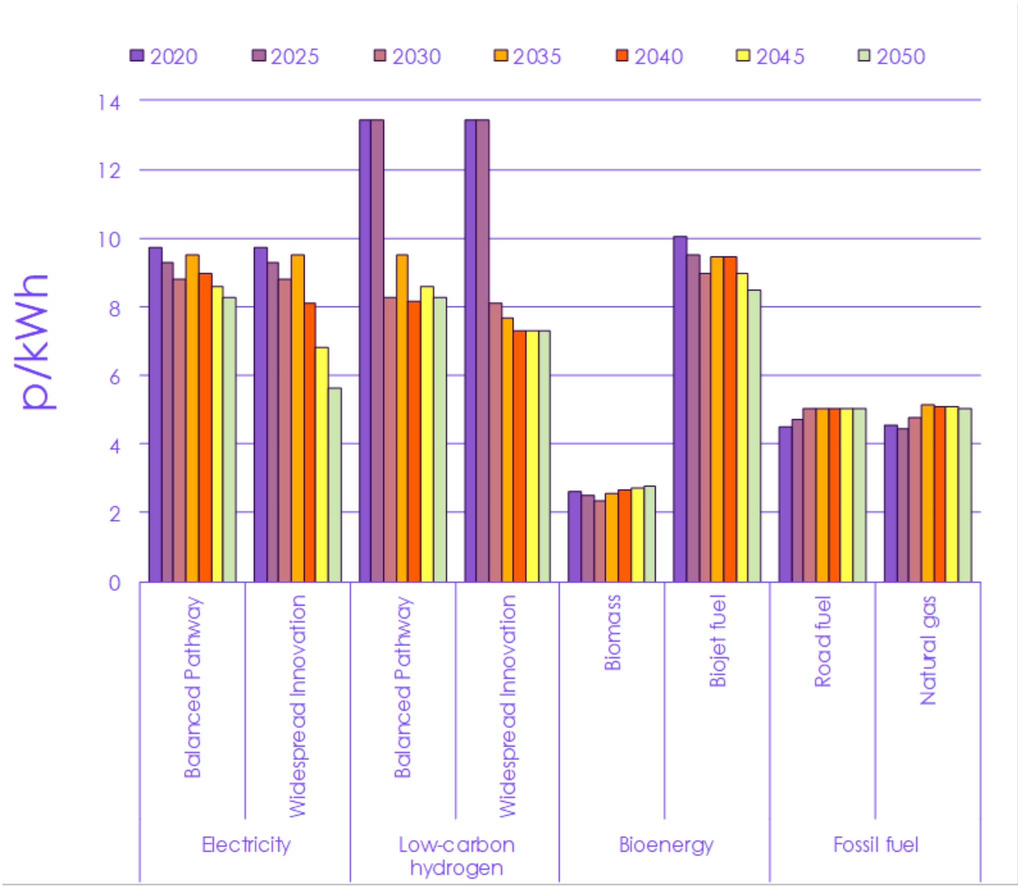
A key component of calculating abatement costs is the cost of energy used for both low-carbon and high-carbon processes.

d) Costs of energy used in our analysis

A key component of calculating abatement costs is the cost of energy used for both low-carbon and high-carbon processes. For the Sixth Carbon Budget analysis we created our own projections of future energy costs, based on previous analysis for our Net-Zero report, and the Government's latest fossil fuel price projections (Figure 1.5). These are intended to reflect the long-run variable costs (LRVCs) of using energy, which exclude transfers and fixed costs such as policy costs, profit, and supplier operating costs. We make some adjustments to these costs to reflect the impact of electrification of transport and residential heating (Box 1.1).

Based on a complete analysis for all energy-consuming sectors, we then re-estimated the costs of providing low-carbon hydrogen and electricity to those sectors. We added or subtracted any difference in these costs to the final cost numbers presented in our analysis. This adjustment made a difference of £2.7bn/year in the Balanced Pathway in 2050. Costs for power generation differed over the period between 2020 to 2050, but there was no significant difference in overall 2050 costs.

Figure 1.5 Costs of energy used in the Sixth Carbon Budget analysis



Source: BEIS (2019) *Valuation of energy use and greenhouse gas (Tables 9-13)*; CCC (2018) *Hydrogen in a low-carbon economy*.
Notes: Costs are Long-Run Variable Costs (LRVCs) for residential users including the costs of wholesale energy and any network costs. Costs for larger users are assumed to be lower due to purchase volume. Costs for the Balanced Net Zero Pathway were also used for the Headwinds scenario. Costs for the Widespread Innovation were also used for the Tailwinds scenario. Costs for Widespread Engagement not shown. Costs for fossil fuels were not varies across the scenarios. Road fuel is shown for petrol.

Box 1.1

Costs for low-carbon electricity in electric vehicles and low-carbon heat in residential buildings

In a 2019 report by Vivid Economics for the CCC, Imperial College modelled the impact of a rapid uptake of electric vehicles and heat pumps on the electricity system, finding that smart charging of electric vehicles or pre-heating with heat pumps can avoid significant costs to the electricity system - in particular, costs associated with upgrading electricity distribution networks. We use this analysis to produce a series of input electricity costs for modelling of electric vehicle and heat pump uptake. In the case of heat, we also include a seasonal factor reflecting the impact of providing electricity during peak winter periods.

Electric Vehicles

We assume that smart charging of electric vehicles can shift up to 80% of vehicle charging demand away from peak periods, based on National Travel Survey data on distances travelled by 8,000 cars over a seven-day period.

Electricity demand for space heating

- **Inflexible:** we assume that homes that cannot pre-heat (i.e. bring electricity demand for heating earlier), have no thermal storage, and that do not have a hydrogen/biofuel hybrid, cannot move energy demand away from peak time periods, and thus pay higher electricity prices on average. These inflexible electricity costs are a blended price that reflect the costs of paying peak prices 40% of the time and average costs of the Balanced Pathway 60% of the time.
- **Flexible:** we assume that all new homes, and a proportion of post-1952 existing homes, pre-heat up to four hours outside of peak hours. The same cost is used for homes with hydrogen/biofuel hybrid heat regardless of whether they can pre-heat. None of the homes subject to flexible costs have thermal storage. These flexible electricity costs include a discount of 10% on the average costs in the Balanced Pathway, due to being able to demand outside of peak periods.
- **Fully flexible:** homes with storage heaters or thermal storage (regardless of whether they can pre-heat) are assumed to be fully flexible, meaning that demand can be moved to match the moment when renewables are generating (and prices are lower). These flexible electricity costs include a discount of 15% on the Balanced costs, due to being able to demand outside of peak periods.

Electricity demand for hot water

- **Without hot water tank storage:** in this case, we assume that end-users cannot move away from peak time and thus pay higher electricity prices on average. We assume that end-users thus pay peak costs 80% of the time and baseline prices 20% of the time. The electricity costs reflect a blend of these two prices.
- **With hot water tank storage:** we assume that the consumption of hot water occurs up to 4 hours outside of peak hours.

Source: CCC analysis based on Vivid Economics (2019) Accelerated Electrification (Rapid HHP scenario) and Imperial College (2018) Analysis of alternative heat decarbonisation pathways. Element Energy for the CCC (2020) Development of trajectories for residential heat decarbonisation to inform the Sixth Carbon Budget.
Notes: Seasonal factor for heat is based on higher levels of gas-fired generation (15%) than our Balanced electricity costs (5%).

e) Costing methodology

The cost of meeting carbon budgets is determined by the additional costs of a low-carbon scenario compared to a scenario with no further climate action beyond today.

In order to calculate the costs of meeting carbon budgets, we estimate annualised abatement costs for each sector, which approximate the costs of building and running the relevant parts of a low-carbon economy. The cost of meeting carbon budgets is determined by the additional cost of the aggregated annualised costs for all sectors in a low-carbon scenario compared to the baseline scenario (no further climate action beyond today).

- **Annualised resource costs.*** The annualised costs estimated by the CCC are composed of capital investment costs (e.g. for new low-carbon technologies or industries), operating costs (e.g. for low-carbon fuels) and financing costs (the cost of capital – representing the cost of borrowing the money to finance the capital investments in the scenarios). These costs are intended to include the direct cost of building and installing low-carbon technologies, and operating them over the course of their lifetimes. The costs are then annualised over the lifetime of the technology to give an average annual cost. As for all of our cost estimates, we do not include the impacts of taxes or other transfers.
  - For example, costs in the transport sector would include the purchase cost of an electric vehicle, borrowing costs to finance that purchase, the costs of maintenance for the EV, and costs associated with refuelling the vehicle (including electricity generation costs, cots of building a charging infrastructure and network charging costs).
  - These costs are then compared to equivalent estimates for a fossil-fuelled vehicle. In both cases the costs include all costs expected to be incurred over the lifetime of the vehicle in our analysis.
- **Calculating levelised abatement costs.** The costs are then smoothed over the lifetime of the technology to give a levelised cost per tonne of GHG emissions abated (£/tCO_2e).
  - The CCC uses a Net Present Value (NPV) method to calculate the levelised costs of an abatement measure. This calculates a stream of annual costs over the lifetime of a technology, and discounts future costs.† These costs are then divided by the total avoided emissions ('abatement') over the lifetime of the asset, which is also discounted.‡

$$\text{£/tCO}_2\text{e} = \frac{\text{Net present cost of measure}}{\text{Total discounted lifetime abatement}}$$

  - This step does not change overall costs of the transition, but rather smooths the costs of abatement over the technology lifetime.
- **Calculating annualised resource costs.** The levelised abatement costs are then multiplied by the annual abatement for that measure in a scenario, giving a total annualised resource cost.

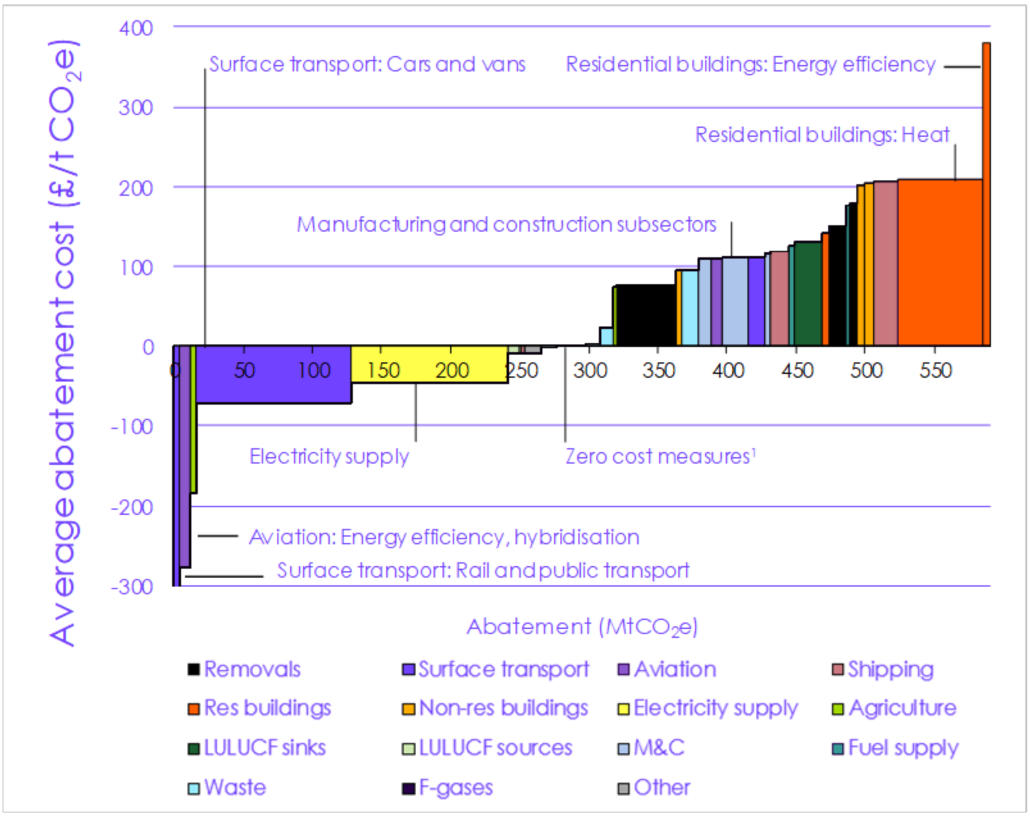
* All costs presented in the report are in real 2019 money.

† This is to account for the time value of money, in line with common valuation practices in business and Government. See, for example, HMT (2018) *The Green Book*. Costs are discounted using a rate of 3.5%.

‡ This ensures fair comparisons between measures with different lifetimes and allows for an equal 'weighting' of costs and abatement over the lifetime of the measure.

As an illustration, Figure 1.6 presents the costs of the measures in our Balanced Pathway against their levels of abatement in 2050.

Figure 1.6 Average cost of abatement across major subsectors in 2050



Source: CCC analysis.

Notes: Full dataset can be downloaded in the Sixth Carbon Budget dataset at www.theccc.org.uk. M&C = manufacturing and construction. LULUCF = Land use, land-use change and forestry. 1 - Aviation: Demand management and agriculture: behaviour change.

g) Costs as a percentage of GDP

GDP is not used to determine climate action in the scenarios, but is used to understand the overall cost impact of the scenarios.

Once all sectors have calculated the additional annualised costs of a low-carbon scenario, compared to a baseline scenario, we aggregate these costs to reach an overall cost. Chapter 5 of the Advice Report provides an overview of these aggregated costs, and compares them to the long-run GDP forecasts produced by the OBR (Figure 1.7 in section c) in order to report a cost as a percentage of GDP. This is the same basis used for the estimated costs of meeting the UK's climate objectives when the Climate Change Act was passed in 2008, which suggested overall costs would be around 1-2% of GDP in 2050. These cost estimates are lower than the costs we estimated in last year's Net Zero report (Box 1.2), which were around 1% of GDP.

The OBR's March 2020 estimates put 2019 GDP at £2.1 trillion in 2019 money, rising to £2.7 trillion per year by 2035, and £3.4 trillion per year by 2050.[4] We do not assume any costs in the baseline scenario resulting from either larger impacts from climate change resulting from higher global emissions, or from a failure of UK businesses to transition to Net Zero business models in line with those emerging across the rest of the world.

The costs should therefore be considered as illustrative, given that the counterfactual of 'no-action no-costs' appears increasingly theoretical.

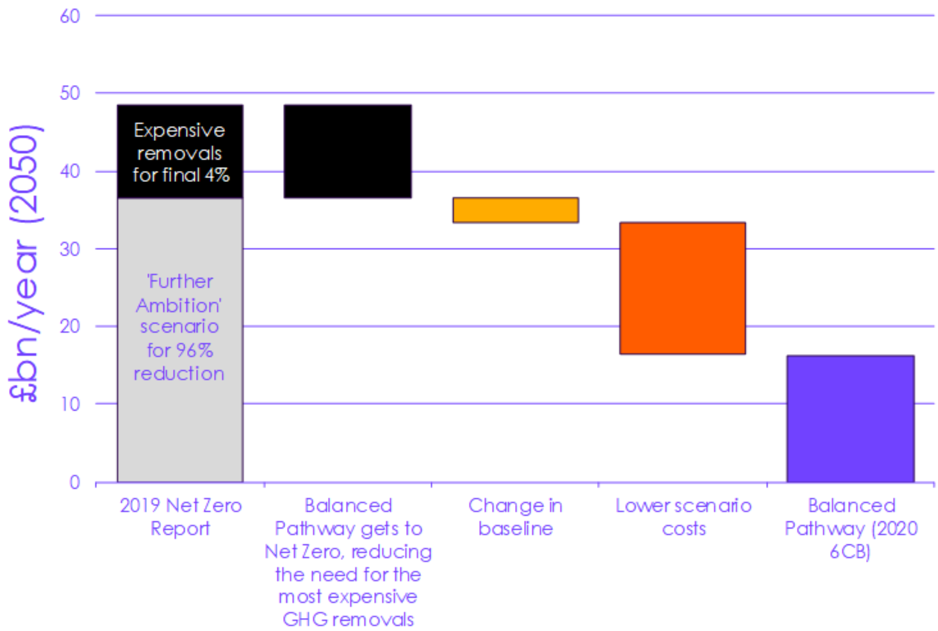
Box 1.2
Differences between annualised costs in 2050 in the Further Ambition scenario and the Balanced Net Zero Pathway

In determining our 2019 advice on whether the UK could reach Net Zero emissions by 2050, we developed a Further Ambition scenario as a snapshot of sources and sinks of emissions in the UK by 2050 (Box 1.2 of the Advice Report). This scenario was specific about how 96% of the emissions reductions could be achieved, compared to emissions in 1990, but noted that multiple measures would be needed for achieving the last 4% of emissions reductions. For the purposes of costing the scenario we assumed the remaining 4% of emissions reductions were delivered via emissions removals from Direct Air Carbon Capture with CCS (DACCS) at £300/tCO_2, making them one of the most expensive emissions reduction options in our scenarios.

Our new scenarios require less removals, and removals are also cheaper in our assessment this year. Further changes include a change in the baseline we compare the costs against, as well as lower costs in other areas. The key factors behind this are:

- **Engineered removals are lower in the Balanced Pathway**, due to lower residual emissions – particularly in manufacturing and construction and residential buildings – and a greater role for nature-based removals. Overall engineered removals are also cheaper. BECCS now costs an average of £90/tCO_2 and DACCS £180/tCO_2, instead of both being costed at a marginal £300/tCO_2 in 2050.
- **A change in the baseline** against which we compare our scenarios means that there is less overall emissions abatement required in our scenarios by 2050. This is mainly due to comparing our scenarios against a world with no further climate action from today, whereas we previously compared our scenarios against a world with no further climate action beyond 2009. This means that efficiency improvements in boilers, vehicles and appliances since then are now included in the baseline scenario, reducing the overall level of abatement required. We have costed this at the average level of abatement in the Further Ambition scenario, though in reality, as these efficiency improvements are low cost, this may overestimate the impact of these changes.
- **Lower costs for key technologies** has reduced abatement costs in many sectors. For example, the cost of offshore wind in our analysis is now £40/MWh in 2050 (in 2019 prices), compared to £51/MWh assumed in our 2019 analysis. As offshore wind accounts for 80% of the electricity generation in our scenario, this difference alone would account for over £5 billion per year of reduced costs.

Figure B1.2 Comparing annualised costs in 2050 in the Balanced Net Zero Pathway to the 2019 Net Zero report



Source: CCC analysis based on CCC (2019) *Net Zero*, and the *Sixth Carbon Budget*.

Notes: In some cases both the level of abatement and the cost for some measures has changed, so the balance between these categories is not precise.

h) In-year capital and investment costs

We have produced estimates of the in-year capital investment cost, and operational costs and savings in each year between 2020-2050.

Alongside our analysis of the annualised resource costs for meeting the Sixth Carbon Budget, we have produced estimates of the in-year capital investment cost, and operational costs and savings in each year between 2020-2050. These costs are for the year in which the investment or cost saving take place, and, unlike annualised costs, are not spread over the lifetime of the asset.*

- The **capital investment** numbers in our report are the additional in-year gross capital investment costs of building a low-carbon economy, compared to the investment in a counterfactual world with no further climate action (the 'baseline', as outline above).
  - The investment estimates represent the *additional* cost of purchasing or installing low-carbon technologies and providing the associated infrastructure for a low-carbon system, compared to a high-carbon system. We do not deduct reduced upstream investment, for example in reduced fossil fuel extraction (but the reduced costs of purchasing fossil fuels are included in our operating cost savings).
  - They are 'money out the door' each year, recognising that some assets take multiple years to build (e.g. a wind farm), and are presented in real £2019 values.

    We do not attempt to split out supply-chain investments or development spending that may occur earlier in reality and may or may not take place in the UK.
  - The investment estimates do not include the costs of borrowing (this is included in annualised costs).
  - As an example, transport sector 'investment' includes the additional upfront cost (not the finance payments) in each year of electric vehicle purchases compared to if fossil-fuelled vehicles had been bought instead, to which we add costs of additional charging infrastructure. We do not include investment in factories to produce electric vehicles or their batteries, nor do we reflect lower investment in fossil fuel extraction, refining or distribution. This avoids double-counting costs that are components of the costs of vehicles and their fuels.
- The **operational costs and savings** set out in our advice are the in-year costs of running a low-carbon system as compared to a high-carbon one.
  - As the low-carbon system is typically more energy efficient, operational costs are generally cost saving and represent a pay back on the low-carbon investments.
  - The operating cost estimates represent additional costs or saving of running low-carbon solutions once they have been deployed relative to the cost of the high-carbon option they replace.

* In-year capital and operational costs differ from annualised costs in three ways: a) they are not spread over the lifetime of the asset b) they do not include the cost of borrowing money to finance investments and c) future costs and savings are not discounted.

– There are costs or savings each year. For example, the avoided maintenance costs of electric vehicles would be an operational saving, as would the savings in petrol and diesel to run the vehicle. The cost of buying the vehicle would not be included, as we include that in our estimates of investment.

Many of the technologies deployed during the transition have considerably lower running costs than the alternatives they replace.

Most of the costs of generating low-carbon electricity are in the upfront costs of building generation capacity (with the exception of generation with carbon capture and storage, where the fuel costs are more important).[5] Since those costs are included in our investment figures, we do not 'double count' the costs of using that electricity to power electric vehicles or heat pumps. We also allocate the small remaining operational cost for operating a low-carbon electricity system to the electricity sector.

a) Projections

Our analysis is based on the Government's projections for energy use, emissions and GDP, and is supplemented by additional evidence in each sector on the cost and performance of technologies in each sector. There is a range of conceivable uncertainties, where our assumptions generally err on the side of caution (i.e. if our assumptions are wrong it would tend to make the recommended budget easier to meet, and deeper emissions reductions possible).

We use a range of forecasts of GHG emissions and electricity demand, depending on the analytical tools appropriate to identifying abatement options across the various sectors:

- For most sectors (power, transport, residential and non-residential buildings, manufacturing and construction, fuel supply, aviation and shipping), our scenarios are based on detailed modelling of the sources of emissions.
- For other sectors (e.g. agriculture, LULUCF, f-gases and waste), our scenarios are based on baseline projections of GHG emissions and our assessment of the cost-effective abatement measures to reduce GHG emissions below this level.

We use Government forecasts of population, economic activity and fossil fuel prices:

- **Population.** We use the latest population projection from the Office of National Statistics (ONS). Under this projection, the UK's population is expected to grow by 6% from 66.8 million in 2019 to reach 70.8 million in 2035, reaching 73.6 million in 2050. This is equivalent to 29.5 million households in 2019, growing to 34.2 million by 2035 and 36.5 million by 2050 (Figure 1.7).

Our analysis has assumed that there is no lasting impact on GDP, an assumption at the optimistic end of the latest scenarios from the Office for Budget Responsibility (OBR).

- **Economic activity.** Future performance of the economy – and hence the level of economic activity that could cause emissions – is always uncertain to some degree. At the moment, the uncertainty is greater than usual, relating to how the economy will recover after the COVID-19 pandemic. Our analysis has assumed that there is no lasting impact on GDP, an assumption at the optimistic end of the latest scenarios from the Office for Budget Responsibility (OBR). This compares to the OBR's 'Downside' scenario for a lasting 6% hit to GDP (Box 2.3 of the Advice Report). GDP is not a driver of uptake of technologies in our scenarios and does not vary across scenarios, but a long-term impact on GDP would likely have an impact on emissions. While the pattern of emissions impacts under such a scenario is uncertain, a uniform 6% reduction in all emitting activity relative to the Balanced Net Zero Pathway would lead to emissions being 11 $MtCO_2e$/year lower in 2035, or 57 $MtCO_2e$ across the five-year Sixth Carbon Budget period. Previous estimates show that the financial crisis had a material impact on the UK's emissions over the Second Carbon Budget Period between 2013-2017 (Box 1.3).[6]

- **Fossil fuel prices.** Oil, gas and coal wholesale prices are projected to increase 20%, 68% and 1%, respectively, between 2019 and 2035. There is of course considerable uncertainty over these future trends - the projections range between a decrease of 25-30% on 2019 levels to an increase 35-40% - and how they will affect energy demand. Where possible, we use sensitivities to look at the impact of different fuel prices on uptake of technologies in our scenarios (see Chapter 2 of this report for an example in the surface transport sector).

Figure 1.7 GDP, household and population growth (2020 to 2050)

Source: OBR (2020) *Economic and Fiscal Outlook (March 2020)*; ONS (2020) *National Population Projections*; CCC analysis.

The lasting impacts of the pandemic are unclear, but may cause emissions to fall particularly if transport behaviours change.

Our analysis began in late 2019, before the impacts of the COVID-19 pandemic became apparent. While 2020 has seen some large changes in patterns of behaviour due to the COVID-19 pandemic and associated restrictions, it is unclear the extent to which these changes will endure. We have considered the impacts of COVID-19 most directly in the analysis of the aviation and shipping sectors, where the largest impacts on emissions have been observed.

- In the Widespread Engagement scenario, we have explored the impacts of some sustained societal and behavioural changes (e.g. a sustained reduction in business aviation demand, due to greater familiarity with video conferencing). This does not represent the full range of possible societal changes that result from the pandemic.

Our Balanced Pathway does not assume lasting behavioural changes from the pandemic.

- Given the lack of clear evidence on how much behaviour may change and for how long, in the Balanced Pathway we have assumed that behaviour patterns return to how they were before the pandemic. Sustained changes of the kinds seen during 2020 (e.g. increased working from home, more walking and cycling) could contribute to the changes required in our scenarios to reduce emissions. They would also have positive co-impacts for health.
- Our scenarios for aviation and shipping, where the impact of the pandemic has been immediately more clear, include an estimate of the impact of demand (and emissions) for these sectors in 2020, and assume that demand gradually starts to return to pre-pandemic levels over the next few years.

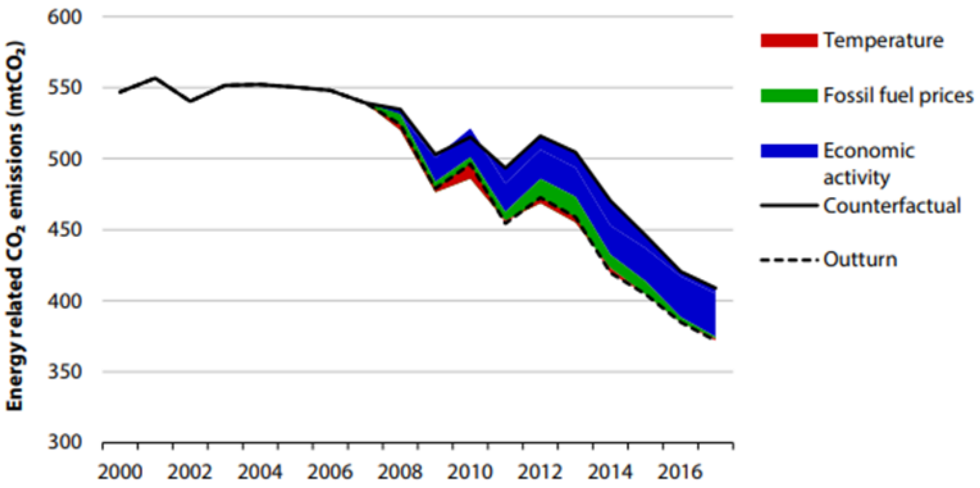
Box 1.3
The impact of the financial crisis on meeting Carbon Budgets 1, 2 and 3

In 2019 we commissioned Cambridge Econometrics to look at the key factors underpinning the outperformance of the Second Carbon Budget (2013-2017). This report provided a detailed quantitative assessment on the impact of 'conditions', or non-policy factors (e.g. GDP, fossil fuel prices, temperature), on emissions over the period 2013-2017, with a focus on the Second Carbon Budget, as well as insight on whether the main changes in those factors driving emissions down are permanent or transitory.

The report highlighted that accounting changes in the EU's Emissions Trading System (EU ETS) account for 296 $MtCO_2e$ of outperformance. For energy-related CO_2 emissions in sectors outside of the EU ETS, the key conclusions were:

- **The reduction in emissions over the Second Carbon Budget period was mostly explained by slower than anticipated economic growth**. The estimated impact of lower economic activity on the net carbon account was to reduce CO_2 emissions by around 110 $MtCO_2$ compared to the counterfactual, equivalent to 22 $MtCO_2$/year.
- **Changes in fossil fuel prices and air temperature also had an impact on emissions, though they were less of a driving force**. Over the Second Carbon Budget the combined impact of actual fossil fuel prices and temperature resulted in emissions being around 40 $MtCO_2$ lower compared to the counterfactual.

Figure B1.3 The impact of the financial crisis on meeting Carbon Budgets



Source: Cambridge Econometrics for the CCC (2019) *How the UK met its carbon budgets*.

b) Key uncertainties in our scenarios

Our scenarios do not assume that innovation produces unspecified breakthroughs to reduce emissions.

Our pathways are premised on scaling up currently known technologies and options to reduce emissions over the course of the 2020s, so that by the 2030s widespread uptake of low-carbon technologies, fuels and behaviours is possible, across all sectors of the economy. This takes into account the current status and future potential of technologies, building on global trends, and acknowledging that deployment of certain technologies in the UK will play a role in cost reduction.[*] However, we do not assume innovation produces unspecified breakthroughs to reduce emissions.

By creating a range of exploratory scenarios that meet Net Zero by 2050, we explore a broad range of future pathways for technology innovation and societal behaviour change. In particular the Widespread Innovation, Widespread Engagement and Tailwinds scenarios aim to explore the upper bounds of what is currently expected to be possible in terms of cost reduction, efficiency and behaviour change. If innovation occurs at a faster pace than that envisaged in our scenarios, then the UK's climate objectives could be achieved more easily, or more quickly. We have incorporated into our analysis a number of ways of treating uncertainty:

We use a conservative approach to these uncertainties, so that if reality turned out differently, emissions would be more likely to fall, than increase, compared to our pathways.

- We use a **conservative approach** so as to minimise the risk that the target we advise is not achievable, or only achievable at a much higher cost than our current estimate.
- We present **five scenarios to meet Net Zero** rather than a single one. This reflects that there are potentially different ways to meet the target.
- Our sector analyses generally identify **alternative ways** to achieve the same emissions result. For example, more low-carbon heat could be provided by hydrogen or hybrid heat pumps and less by pure electric heat pumps (and vice versa).
- **Transparency** about the main assumptions we have made, so that others can understand factors that have affected our results. Key assumptions are listed in the sector chapters of this report, and a full list of these assumptions is in the dataset published alongside this report.[7]
- **Identification of key uncertainties** that could affect our analysis (Figure 1.8)
- **Highlighting ways to manage the risk** that the future turns out less well than our scenario envisages. For example, keeping alternative ways to reduce emissions in play, until uncertainties can be reduced and the best strategy becomes clear.

Acknowledging this, further uncertainties inevitably remain:

- **Low-carbon energy.** Our scenarios include a range of cost reductions and efficiency improvements across low-carbon energy supply, including renewable energy, CCS, hydrogen (production and electricity generation), and bioenergy (Figure 1.5). Technology trends in these areas could result in costs and efficiencies that are outside the range of possibilities in our scenarios.

[*] see Chapter 9, section 3 c of the Advice Report for more on the role of innovation in our scenarios.

- **Key end-use technologies.** The cost and performance of key technologies in our scenarios could turn out differently in reality. Table 9.1 of the Advice Report has an overview of the key technological uncertainties in our analysis.
- **The level and rate of societal behaviour change** can be guided by policy, but will ultimately depend on how quickly attitudes and public acceptance change over time. This will be particularly important for the uptake of low-carbon technologies in people's homes, as well as changes in diets and attitudes to flying.
- **The pace of the global climate transition, and its impact on a changing climate** will determine the speed and cost of the UK's transition, as well as the impacts of a warming world for the UK. Chapter 7 of the Advice Report has an overview of the global transition to Net Zero. We have tried to take into account the impacts of a warming planet in our scenarios (Box 1.4).

Uncertainties can affect the cost and pace of emissions reduction, but given the breadth of pathways explored in our analysis, and the range of options contained within these pathways, we can be confident that Net Zero, and our Balanced Pathway for the Sixth Carbon Budget can be achieved across a range of eventualities.

Box 1.4
How we reflect the changing climate in our scenarios

A warmer atmosphere can hold more moisture, which can contribute to heavier rainfall and more frequent flooding, including outside of recognised flood risk areas. Higher temperatures will affect public health, infrastructure, business, farming, forestry and the natural environment.

Scenarios looking out over multiple decades must consider the impacts of a changing climate. We have done this in three key areas:

- **Buildings**. Changes in the UK's climate will impact on the energy demand of buildings between now and 2050. Impacts include reduced demand for heating, due to higher average winter temperatures, and increased demand for cooling during the summer months (see chapter 3). Additionally, we ensure that new build homes, and retrofits to existing homes, take into account an increased risk of overheating.
- **Agriculture and land use.** Where possible, we have sought to take account of the impact of climate change in our analysis. We include for example, the need to develop climate resilient food crops when considering yield improvements and ensuring appropriate tree species are planted in the right place. Additionally, climate change strengthens the case for restoring peatlands as they expected to be more resilient to warmer and drier conditions in the future, and emit less carbon than degraded peatlands.
- **Water use in energy generation technologies**. Climate change will likely lead to increased water scarcity during certain periods in the UK. Though most low-carbon energy is provided through renewable electricity in our scenarios, demand for freshwater cooling in CCS, nuclear and bioenergy plants could be affected. Our scenarios are not specific about the location of these technologies, but deployment will need to be cognisant of a future that's more water-stressed.

Source: CCC (2017) UK Climate Change Risk Assessment 2017

c) Changes to the UK Greenhouse Gas inventory

Changes to how UK emissions are estimated can make the budget easier or more difficult to meet. Where we know of changes in the near future, we have assumed the higher range of possible impacts.

All emissions data presented in this report account for forthcoming changes to the UK Greenhouse Gas Inventory for Global Warming Potentials (GWPs) and for peatlands. These changes have not been precisely determined yet, so we assume changes at the higher end of the currently estimated range. All values reported use GWPs from the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) with carbon-cycle feedbacks and we assume accounting for all peatland emissions adds around 21 $MtCO_2e$/year to the current UK inventory (Box 1.5). These changes will be implemented within the next five years.

Estimates of UK emissions will continue to change in the future as understanding of the science improves and the IPCC issues new guidance on reporting, and as UK approaches to estimating emissions develop. These changes could potentially shift the UK inventory in either direction. In the Committee's 2017 report on *Quantifying Greenhouse Gas Emissions* we identified an overall uncertainty in the emissions inventory of ±3%. Without knowledge on the scope or effect of future changes, these uncertainties fall into the wider range of uncertainties involved in setting the Sixth Carbon Budget (Figure 1.8).

Box 1.5
Forthcoming changes to the UK greenhouse gas inventory and further unknowns

Forthcoming changes to the emissions inventory include the addition of emissions from peatland and revision of the Global Warming Potentials (GWPs) used to aggregate greenhouse gas emissions:

- **Peatland (expected to be included in the UK inventory by 2022).**[8] The current inventory only captures about 1.3 $MtCO_2e$/year of emissions from peatlands, but all sources of peatland emissions will be included in the inventory in the near future:
  - The 'high' range of emissions from peatland would add around 21 $MtCO_2e$/year to the inventory in 2018 and would also increase the 1990 baseline by 21 $MtCO_2e$/year. This is the basis upon which targets in this report are recommended.
  - The 'low' range of emissions from peatland could add around 17 $MtCO_2e$/year to the inventory and would also increase the 1990 baseline by 17 $MtCO_2e$/year.
- **Global Warming Potentials (expected to be updated in the UK inventory by 2024).** These are used to aggregate different greenhouse gases together into a common metric, showing their equivalence to carbon dioxide. At COP24 in December 2018 the international community decided to standardise reporting under the Paris Agreement transparency framework using the GWP_{100} metric.[9] The values to be used are those from the IPCC Fifth Assessment Report (AR5), which contain two sets of values and it is not yet clear which will be used. Both are different from the AR4 values used in the current emissions inventory and will lead to an increase in the estimate of UK emissions:
  - The 'high' estimate of GWPs include climate-carbon feedbacks. Under this methodology, the size of the existing inventory would increase by around 19 $MtCO_2e$/year while the 1990 baseline would increase by nearly 47 $MtCO_2e$/year. This is almost entirely due to a 36% increase in the estimated global warming impact of methane (CH_4) emissions. This is the basis upon which targets in this report are recommended.
  - The 'low' GWPs do not include climate-carbon feedbacks, and would lead to a smaller increase in the size of the UK emissions inventory. The estimate of the existing inventory would increase by around 5 $MtCO_2e$/year while the 1990 baseline would increase by 10 $MtCO_2e$/year. Under this methodology CH_4 methane emissions have a 12% higher warming impact than the current estimate, while the warming impact of N_2O emissions is 11% lower.

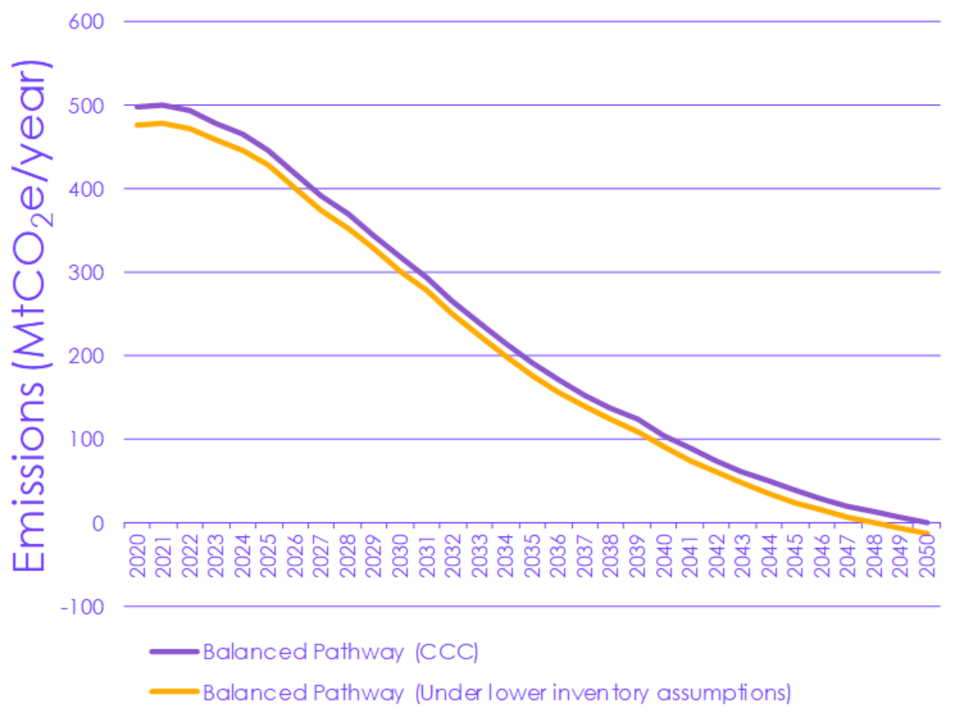
The two changes overlap because peatlands are a source of CH_4 and N_2O emissions.

The range for the total combined impact of the peatland and GWP changes is around an additional 27-70 $MtCO_2e$/year in 1990 and 23-42 $MtCO_2e$/year in 2019 compared to the current inventory.

Table B1.5
Impact of changes to Global Warming Potentials and peatland emissions estimates

Estimate of emissions in 2019 (480 $MtCO_2e$)...		**... plus changes to Global Warming Potentials.**	
		AR5 without carbon-cycle feedbacks ('low')	**AR5 with carbon-cycle feedbacks ('high')**
... plus changes to peatlands	'Low' range	502 $MtCO_2e$	518
	'High' range	506 $MtCO_2e$	**522 $MtCO_2e$ (basis for CB6 advice)**

Figure B1.5 The effect of known future inventory uncertainty on the Balanced Net Zero Pathway



Source: CCC analysis based on Chris Evans et.al. (2019) *Implementation of an Emissions Inventory for UK Peatlands and Shindell et al.* (2013) *Anthropogenic and Natural Radiative Forcing.*

Unknown future changes

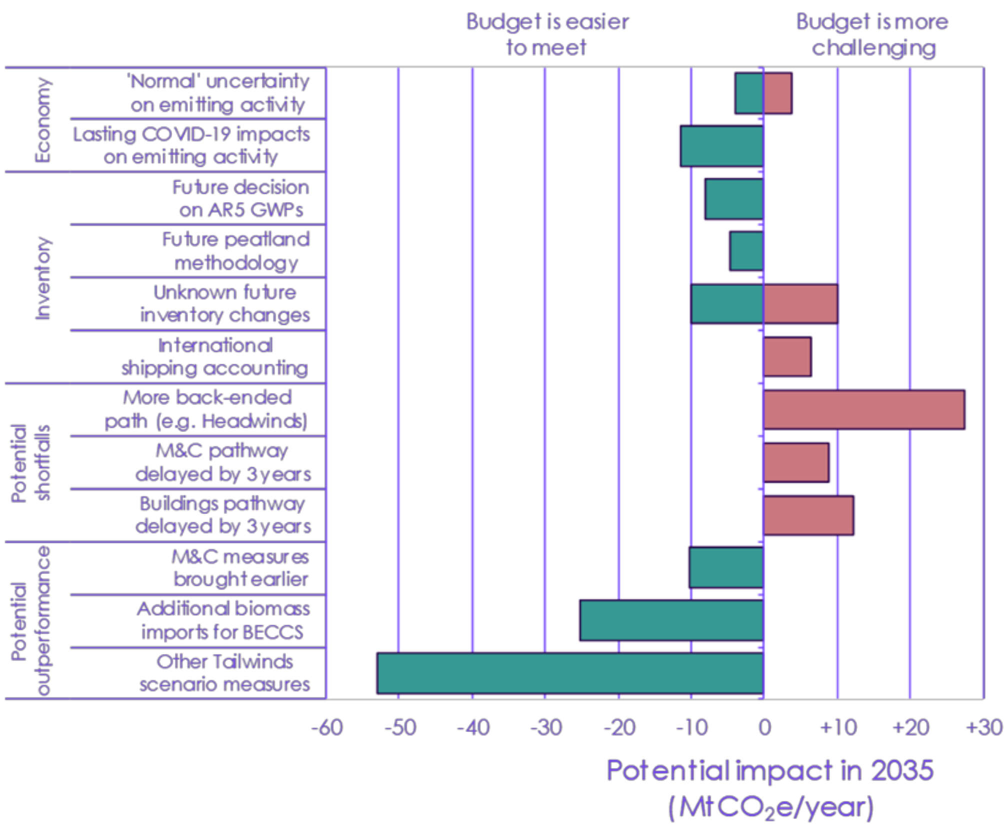
Beyond the changes that are currently expected to be incorporated into future UK greenhouse gas inventories, there will inevitably be further changes to be expected by 2035. In particular, there will be updated estimates of global warming potential values in future IPCC reports, including the 6th Assessment Report due in 2021. These newer values may be used within international greenhouse gas accounting methodologies by the time the Sixth Carbon Budget period begins. Although general uncertainty on emissions estimates is low, sectors with complex biological processes or diffuse sources such as waste, agriculture and Land Use, Land Use Change and Forestry (LULUCF) have higher uncertainty levels.[10] As further research identifies new ways to reduce these uncertainties, it is likely the emissions inventory will continue to change. Separately, estimates of emissions from sectors where proxies such as fuel sales are used to estimate emissions could be subject to change, if improved means of measurement are development.

The easiest way to overcome the uncertainties associated with future emissions is to make progress in reducing emissions

Our scenarios take into account a range of projections and uncertainties around how economic growth, energy costs and changes to how we measure emissions over the next 15 years might affect the overall level of emissions in our recommended Sixth Carbon Budget. In particular we have not assumed that the COVID-19 pandemic has a lasting impact on economic growth, and we have made conservative assumptions around the impact of coming changes to the UK's emissions inventory. If reality were to turn out differently, emissions would be more likely to fall, than rise, compared to our recommended Balanced Pathway.

The easiest way to overcome the uncertainties associated with future emissions is to make progress in reducing emissions. By building multiple exploratory pathways that meet the UK's Net Zero target, we can have greater confidence in how it can be met, and have identified areas for immediate action in every sector of the economy. The *Policy Report* that accompanies this advice identifies priority areas where policy can be developed to guide these actions.

Figure 1.8 Risks to achieving and opportunities to outperform the Balanced Net Zero Pathway in 2035



Source: BEIS (2020) *Energy and Emissions Projections 2019*; OBR (2020) Economic and Fiscal Outlook – March 2020; CCC analysis.
Notes: Emissions impact of COVID-19 based on a 6% reduction in emissions in 2035. Unknown future inventory changes include further changes to global warming potentials and other IPCC guidance that reflects future scientific understand of climate science. We previously estimated the uncertainty in the UK inventory as +3%. M&C = manufacturing and construction. BECCS = Bioenergy with carbon capture and storage.

4. Emissions pathways for Scotland, Wales and Northern Ireland

We produce pathways for Scotland, Wales and Northern Ireland, taking into account specific circumstances that affect the pace and overall level of decarbonisation for these nations.

Alongside our analysis of UK emissions pathways, we produce pathways and costs for Scotland, Wales and Northern Ireland, for each sector of emissions, and on an economy-wide basis.

These pathways, which feed directly into our UK-level analysis, are based on specific factors which determine the rate and overall level of decarbonisation achievable in each nation (Table 1.3). This includes:

- different levels of activity and emissions in each sector today;
- existing usage of land, and opportunities for land-based removals;
- existing infrastructure;
- opportunities to remove CO_2 from the atmosphere; and
- existing policies.

The methods of determining pathways for Scotland, Wales and Northern Ireland are set out in each chapter of this report.

Table 2.3
Developing pathways for Scotland, Wales and Northern Ireland

CCC sector	Methodology for allocating emissions and costs in UK scenarios to devolved administrations
Surface transport	• Road vehicle traffic (including HGVs) is based on the Department for Transport's (DfT) National Transport Model (NTM), which produces forecasts by GB country. The NTM model does not include Northern Ireland, so emissions there are scaled based on current vehicle-km use by vehicle type. • Line-specific rail electrification. • National Travel Survey (NTS) data are no longer collected, but our assumption on UK-average changes in travel behaviour is not expected to have a significant impact on DAs' emissions pathways.[11]
Electricity supply	• Our analysis uses a model of the GB network only. To allocate electricity supply emissions to Scotland and Wales, we sum the existing plant-level capacity and projected retirement dates for each generating technology and apply load factors to these based on changes in GB-wide load factors. For Northern Ireland, we forecast demand due to increased electrification and combine this with the Northern Ireland grid emission intensity from the most recent System Operator Northern Ireland (SONI) report.
Aviation	• Emissions are disaggregated by type of flight (international, domestic) and split by DAs' existing share of emissions in the inventory. DfT projections of individual airport demand, including the impact of airport expansion, impact overall UK demand management.
Shipping	• Emissions are disaggregated by type of journey (international, domestic) split by share of emissions in the inventory.
Residential buildings	• Low-carbon heat and energy efficiency measures are deployed in our scenarios using a housing stock model of the UK which integrates regional national housing survey data for England, Scotland, Wales and Northern Ireland, with an accurate mix of building attributes for each of those places. District heating is also modelled at devolved administration level.[12] • Measures for new-build, cooking decarbonisation and energy efficiency relating to lighting and appliances are modelled separately and scaled for DAs based on current energy demand for these services.
Non-residential buildings	• Analysis carried out at a UK level with abatement based on the Buildings Energy Efficiency Survey (BEES) for England and Wales, BEIS's heating study for England and Wales and UK-level district heat analysis. • Emissions pathways are based on existing share of direct emissions from non-residential buildings.

Manufacturing, construction and fuel supply	• Analysis of industry decarbonisation is based largely around site-level emissions data, so the analysis reflects the composition of industry in Scotland, Wales and Northern Ireland.[13] • Assumptions about availability of hydrogen and CO_2 storage will also include some (limited) site-specific considerations.
Agriculture	• UK baseline emissions projections are split, based on share of emissions in the current inventory. • On-farm measures are based on technical potential and cost effectiveness of measures at country level, based on SRUC modelling (including new measures in a 2019 update (for the Net Zero report) and a further 2020 update for the CCC).[14] • Abatement savings from energy use, diet change and food waste reduction based on existing sub-sector share of emissions in the NAEI inventory (Agricultural soils, Enteric fermentation, Livestock wastes, Liming & urea application, Machinery)
LULUCF	• Land use scenarios based on modelling of land across each country of the UK. Accounts for differences in existing land use and in land acquisition costs. Includes peatland, energy crops, afforestation (including on-farm) and forest management, with land released through more efficient farming, food waste reduction and diet changes.
Hydrogen use and production	• Various scenarios for hydrogen roll-out in different distribution networks of the GB gas-grid and industrial clusters over time, including the South Wales industrial cluster and Grangemouth. UK hydrogen production likely located near carbon capture and storage (CCS) clusters (if produced by methane reformation) or near sources of low-carbon electricity generation (if produced by electrolysis).
Waste	• Landfill fugitive emissions are based on DA-specific methane modelling resulting from DA landfill volumes and banning certain streams from landfill.[15] • Other waste sector emissions (e.g. wastewater, composting) are split from UK pathways based on historical share in the inventory.
F-gases	• Emissions are split based on the share of sub-sector F-gas emissions in latest NAEI inventory.

Endnotes

[1] CCC (2019) *Net Zero: The UK's contribution to stopping global warming*.

[2] Climate Assembly UK (2020) *The path to Net Zero.*

[3] CCC (2020 *The Sixth Carbon Budget*.

[4] OBR (2020) *Economic and fiscal outlook (March 2020)*.

[5] For simplicity, our calculations classify all costs of renewable electricity as investment costs.

[6] OBR (2020) *Economic and fiscal outlook (March 2020)*.

[7] See www.theccc.org.uk

[8] Chris Evans et al. (2019) *Implementation of an Emissions Inventory for UK Peatlands*.

[9] Myhre, G., D. Shindell, F.-M. Bréon, W. Collins, J. Fuglestvedt, J. Huang, D. Koch, J.-F. Lamarque, D. Lee, B. Mendoza, T. Nakajima, A. Robock, G. Stephens, T. Takemura and H. Zhang, 2013: Anthropogenic and Natural Radiative Forcing. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

[10] CCC (2017) *Quantifying-Greenhouse-Gas-Emissions.*

[11] CCC (2017) *Building a low-carbon economy in Wales*.

[12] Element Energy for the CCC (2020) *Development of trajectories for residential heat decarbonisation to inform the Sixth Carbon Budget.*

[13] Element Energy (2020) *Deep decarbonisation pathways for UK industry.*

[14] Scottish Rural College (2020) *Non-CO2 abatement in the UK agricultural sector by 2035 and 2050* and Centre for Ecology and Hydrology (2020) *Updated quantification of the impact of future land use scenarios to 2050 and beyond.*

[15] Based on Ricardo's MELMod model for the National Atmospheric Emissions Inventory (NAEI)I.

Chapter 2

Surface Transport

Introduction and key messages

This chapter sets out the methodology used to generate the surface transport sector pathways for the Committee's advice on the level of the Sixth Carbon Budget. The results of our scenarios, including emissions pathways, technology uptake, costs, investment and co-benefits are presented in the accompanying Advice Report. The policy implications of our analysis are detailed in the accompanying Policy Report. A full dataset including key charts is available alongside this document. For ease, the methodology, results and policy implications have been collated in a single report on the surface transport sector, which is available from the Sixth Carbon Budget section of the CCC website.

The key messages from our analysis for surface transport are:

- **Background.** Total emissions from surface transport in 2019 were 113 $MtCO_2e$, comprising 22% of total UK GHG emissions. These are primarily tailpipe emissions from fossil-fuelled road vehicles, with cars (68 $MtCO_2e$), vans (20 $MtCO_2e$) and heavy-goods vehicles (HGVs) (19 $MtCO_2e$) the largest contributing types**.**
- **Demand reduction and modal shift.** There are opportunities to reduce demand for car travel, through both societal and technological changes (such as shared mobility and increased home-working) and by enabling journeys to be shifted onto lower-carbon modes of transport. In addition, there is potential for logistics and operations improvements to reduce demand in road freight.
- **Conventional vehicle efficiency.** Emissions from conventional vehicles can be reduced through efficiency improvements. This includes more aerodynamic and lighter-weight designs, retrofitting drag-reduction improvements and eco-driving training.
- **Zero-emission vehicles.** Achieving decarbonisation of surface transport will require a sector-wide transition to vehicles that produce zero tailpipe emissions. For cars and vans, battery-electric vehicles are now widely available and are likely to become cost-saving by the late-2020s. For HGVs options include battery-electric vehicles, hydrogen fuel-cells and electric road systems. Continued electrification of the rail network, together with hydrogen, battery-electric and hybrid trains, will also play a significant role.
- **Analytical approach.** We have derived our assumptions in each area based on a detailed review of available evidence. This includes consideration of research across the sector that has been produced since our advice on the Fifth Carbon Budget, analysis of recent market developments and trends, analytical modelling conducted within the CCC, new research to assess options for road freight decarbonisation and extensive stakeholder engagement. These assumptions are combined to produce our Balanced Net Zero Pathway and four exploratory scenarios, which explore alternative pathways to deliver emissions reductions across the surface transport sector.

We set out evidence in the following sections:

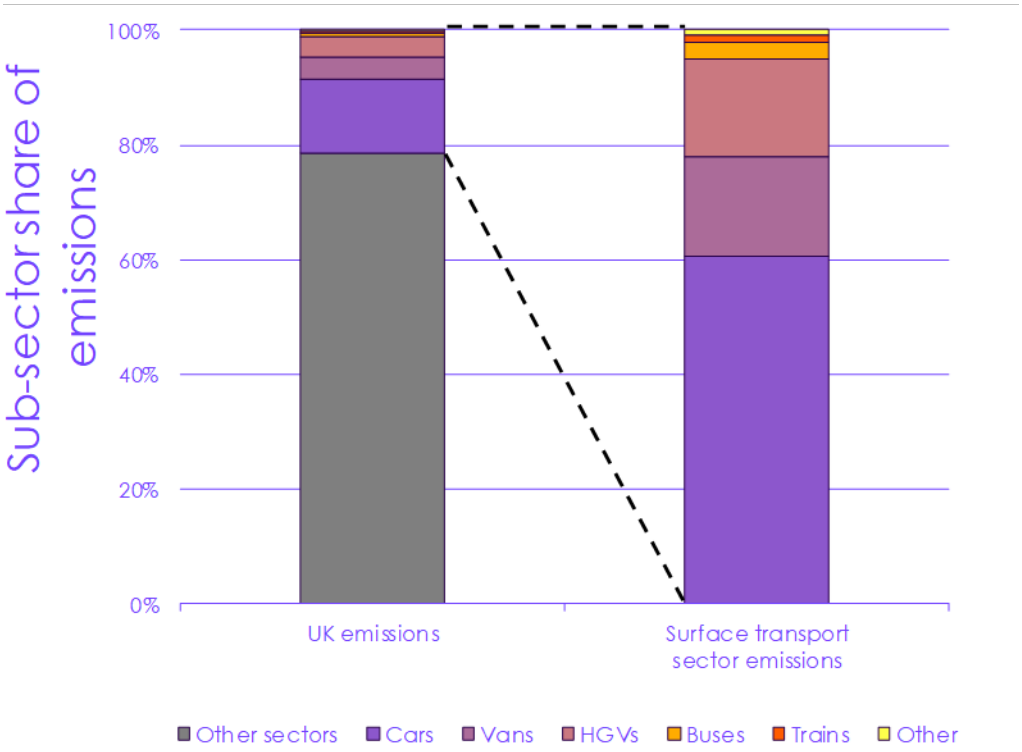
1. Current and historical emissions from surface transport
2. Options to reduce emissions in the transport sector
3. Approach to analysis for the Sixth Carbon Budget

a) Current surface transport emissions

Surface transport is currently the UK's highest emitting sector.

Emissions from surface transport in 2019 were 113 $MtCO_2e$, which accounted for 22% of total UK GHG emissions (Figure 2.1). This makes surface transport the UK's highest emitting sector.

Figure 2.1 Breakdown of surface transport sector emissions (2019)



Source: BEIS (2020) *Provisional UK greenhouse gas emissions national statistics 2019*; CCC analysis.

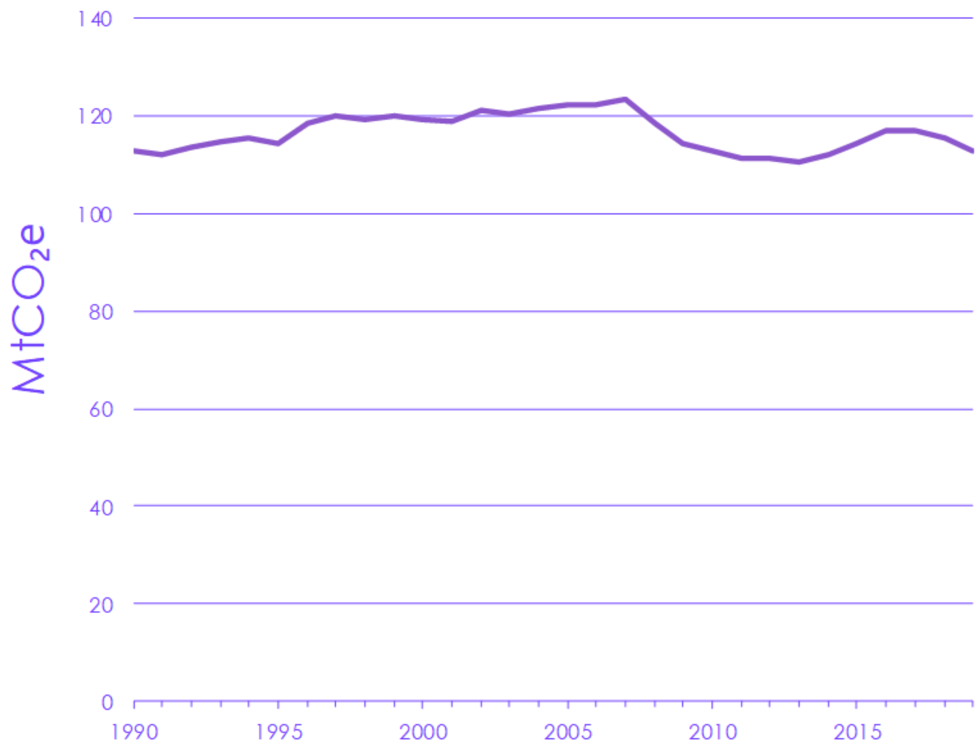
Car travel dominates surface transport emissions, followed by vans and HGVs:

- Cars account for 61% (68 $MtCO_2e$) of surface transport emissions and a larger share (78%) of UK road travel (in terms of vehicle-kilometres).
- HGVs account for 17% (19 $MtCO_2e$) of total surface transport emissions, despite making up just 5% of road vehicles. This is due to their comparatively large average mileage and weight.
- The remaining emissions are shared between vans (17%; 20 $MtCO_2e$), buses (3%; 3 $MtCO_2e$), rail (2%; 2 $MtCO_2e$) and other surface vehicles (1%; 0.9 $MtCO_2e$).
- Emissions are predominantly CO_2 (99%), with the remaining emissions being N_2O and CH_4 from the combustion of fossil fuels.

b) Trends and drivers in surface transport emissions

Emissions from surface transport have largely been flat since 1990 (Figure 2.2).

Figure 2.2 Surface transport GHG emissions since 1990



Source: BEIS (2020) *Provisional UK greenhouse gas emissions national statistics 2019*; CCC analysis.

The rapid increase in sales of SUVs has driven an increase in average new car emissions over recent years.

Total distance travelled increased by 17% since 1990, roughly in line with population growth.[1] Efficiency of new cars had also been steadily increasing since 1990 but this reversed between 2017-19, driven by the rapid increase in purchases of higher-emitting vehicles, particularly sports utility vehicles (SUVs), whose market share has risen from 7% in 2007 to 25% in 2019. This growth has more than offset the benefit delivered by the increase in sales of electric vehicles (EVs) from 1.9% to 3.1% during 2017-19.[2]

2. Options to reduce emissions in the transport sector

Delivering Net Zero emissions across the UK by 2050 will require reducing surface transport emission to near zero. This will require a combination of behavioural change, efficiency improvements to fossil fuel vehicles and the introduction and uptake of zero-carbon technologies. Several key decisions will need to be made both in the lead up to and during the Sixth Carbon Budget period in order to determine the trajectory that the country follows towards achieving Net Zero.

This section sets out these options and presents the latest evidence on their feasibility, risks and costs in the following sections:

a) Demand reduction and modal shift, which considers how behavioural and societal shifts could lead to reduced or changed demand for travel.

b) Conventional vehicle efficiency, which discusses improvements to conventional vehicles that can make them more fuel-efficient.

c) Zero-emission vehicles, which explores the technological options available for delivering transport with zero tailpipe emissions and the expected rates of uptake of these vehicles across different transport sectors.

a) Demand reduction and modal shift

i) Reducing demand for car travel

Passenger car journeys currently account for 78% of vehicle-kilometres travelled and 61% of emissions in the UK. Reducing demand for car travel offers significant potential for reducing emissions, with associated benefits for congestion, air quality and health. We looked at four factors that could contribute to a reduction in private car travel:

Home-working, local working and internet shopping all offer the potential to reduce the total number of journeys that each individual undertakes.

- **Societal and technological changes.** This includes factors such as increased home-working, increased use of IT and technology and continuing trends towards greater use of internet shopping. Relative to the baseline*, our scenarios assume that there is potential for a 1-4% reduction in total car mileage by 2030, and between 4% and 12% by 2050[3], from societal behaviour change and technology. These are based on the latest academic evidence and CCC analysis of travel data.

Trends towards increased home-working and videoconferencing have been accelerated during the COVID-19 pandemic.

  – The National Travel Survey[4] shows that 25% of car mileage is for commuting purposes and 11% is for business. Even before the COVID-19 pandemic, there was a gradual increase in the prevalence of home-working and videoconferencing, but the need for social distancing has seen rapid movement in this area. In April 2020, 47% of people did some work at home[5], while a recent study[6] has estimated that 43% of UK jobs can be done entirely from home. Other factors that could impact demand in this area include growth in the gig economy or movement towards living closer to workplaces.

* The baseline scenario represents the growth in emissions that we would expect to see in the absence of any action to reduce emissions across the sector. See Section 3 a) i).

– The average number of shopping trips per person had been declining steeply until recent years[7]. Moreover, average shopping trip length for cars has fallen, which could be related to the shift towards online retail (which could account for up to 50% of sales by 2030[8]). This may be partially offset by increases in leisure journeys and by the extra van traffic required to deliver online purchases.

- **Increase in car occupancy.** Shared mobility (e.g. shared cars and shared trips) can also reduce car travel demand. These are uncertain but our scenarios assume that there is scope for average car occupancy to increase from 1.6 today to up to 1.7 by 2030 and up to 1.9 by 2050.

  – Current utilisation rates of shared mobility are low, at around 3-4% of journeys[9], while two-thirds of trips are undertaken with just the driver in the vehicle and average car occupancy is 1.6.

  – High-occupancy vehicle lanes are one example of local interventions that can encourage car-sharing. Studies have shown these to reduce vehicle trips by between 4% and 30% in certain cases.[10]

  – Social pressure to increase car occupancy could play a role as the public becomes increasingly environmentally aware. More companies may begin to encourage car-sharing schemes for commuters.

  – A variety of shared mobility innovations could play a role in increasing occupancy. These include car clubs, real-time ridesharing apps and ride-pooling.

- **Modal shift to active travel.** Walking trips have increased in recent years, cycling has been relatively flat, while trips taken by bus have declined. We assume that 5-7% of car journeys could be shifted to walking and cycling (including e-bikes) by 2030, rising to 9-14% by 2050. These assumptions translate to lower percentages of distance, given that the shortest trips are the most likely to switch.

Comparison between UK cities and with other countries shows that there is substantial scope for increased cycling.

  – The total number of cycling trips undertaken has remained fairly constant at around 1-2% of all journeys over recent years4, although the average distance of each cycling journey has increased. Based on international comparisons and experience in some UK cities, there is scope to encourage more trips by bike. In the Netherlands, 26% of all journeys are cycled, while in Germany the proportion is 10%.[11] In UK cities with high levels of cycling (for example Oxford and Cambridge), cycling rates can be up to 29%.[12]

  – In 2019, 7% of car journeys were less than 1 mile, while a further 17% were between 1 and 2 miles.[13] A recent study[14] based in Cardiff concluded that walking or cycling could realistically displace around 41% of car journeys of less than 3 miles.

  – DfT's recent cycling and walking plan for England[15] sets out a vision for high-quality infrastructure and other measures (for example cycle parking at stations and loans for bikes) to encourage significant uptake of active travel. This sets out a future in which half of all journeys in towns and cities are cycled or walked, up from 29% today.

E-bikes could allow even some longer journeys (up to 9 miles) to switch from car to cycling.

- E-bikes offer considerably greater range, so if they become widespread then there may be potential to shift a greater number of journeys away from cars.[16] We assume that this could enable e-bikes to displace car journeys of up to 9 miles (in contrast to a maximum of 4 miles assumed for conventional bicycles).
- In considering how many trips and what share of car-kilometres could be switched to these modes, we considered evidence on the types of trip that could be easiest to switch. This is a function of length, purpose, age group and time of trip. An assumption was then applied on the proportion of trips in each category that could switch, based on analysis of National Travel Survey data.
- Active travel schemes have been implemented in several regions across the UK in recent years (Box 2.1).

Public transport offers a lower-carbon alternative for many journeys in urban areas. A reliable, properly funded service needs to be provided to encourage uptake.

- **Modal shift to public transport.** There is scope to switch some car journeys onto appropriate public transport, particularly in urban areas. Our scenarios assume that between 2-4% of car-kilometres by 2030 can be switched, increasing to 5-8% by 2050.
  - Bus and rail account for 5% and 4% of all journeys respectively[4]. A recent study found that public transport usage within major cities could rise by 6% by 2030.[17]
  - We assess that around 9-12% of trips could be shifted to buses by 2030, increasing to 17-24% by 2050. This is based on applying a series of filters, including whether a journey is in a rural or urban area, to determine the number of trips that could be suitable for switching onto public transport.
  - During the COVID-19 pandemic, many forms of public transport have experienced a sustained drop in demand, which has continued after the lifting of travel restrictions. Car usage has recovered more quickly.[18] There is a risk that reduced public confidence in public transport could reduce the potential to shift journeys away from cars in the medium term (see Section 3(c) for further discussion of this risk).

The combined effect of the above factors is a reduction in demand of 7-16% of total car-kilometres in 2030 and 12-34% by 2050 compared with baseline demand.

- The UK Climate Assembly recommended a reduction in the amount we use cars by 2-5% per decade[19], relative to today's levels. The demand reduction assumed in our Widespread Engagement scenario is consistent with the more ambitious end of this range.
- We also take account of the risk of higher travel demand, which we model in the Widespread Innovation scenario. This is detailed below.

Our analysis also considers potential rebound effects where the reduction in car operating costs resulting from the switchover to electric vehicles leads to an increase in total kilometres travelled:

- Most estimates suggest a rebound effect of 10-30% for road transport, although some researchers indicate that this may be conservative for EVs.[20] This means that 10-30% of energy savings are offset through additional mileage. We assume this range in our scenarios.

Increased use of consolidation centres and innovative vehicles could reduce van demand.

For vans, we assume much smaller levels of demand reduction, reaching 3-4% from 2030 onwards. This is focussed on the parcel-delivery sector, where changes are already happening:

- Van travel is the fastest-growing sector, with total van-kilometres having increased by 71% since 2000.[21] At least a quarter of this is due to the growth in online shopping.[22]
- Several delivery companies have begun to introduce small electrified vehicles, such as e-cargo bikes and micro-vehicles, for last-mile delivery in UK cities. Within dense urban areas there is significant potential for such vehicles, along with improved logistics and consolidation, to reduce emissions and alleviate congestion.
- The Energy Saving Trust found that 33-50% of urban deliveries could be shifted to cargo bikes or e-cargo bikes.[23]
- Collaboration between operators on the same route has been shown to reduce delivery operations by around 14% in urban areas.[24]

Case studies and modelling have demonstrated a strong economic case for switching from cars to walking and cycling.

Evidence suggests that there are cost-savings from switching from cars to walking and cycling, with cost-benefit ratios of 3 to 4, including social benefits on factors such as congestion, health and air quality (Box 2.1). However, the two main sources of evidence on this are unlikely to be directly applicable to our scenarios:

- The Sustrans model, developed by the University of Copenhagen, excludes the cost of cycling infrastructure.
- The Cycling and Walking Investment Strategy (CWIS) model, used by DfT and developed by Transport for the Quality of Life, is unlikely to be suitable to our more ambitious scenarios as there are likely to be threshold effects as infrastructure is built and public attitudes towards cycling change.

We have taken a conservative approach and assumed that there is zero net cost to the economy of switching from cars to walking and cycling. This is reasonable as the cost of provision of improved walking and cycling infrastructure is expected to be substantially outweighed by the benefits through reduced cost of travel, better air quality, lower congestion and improved health and wellbeing.

Box 2.1
Demand-side case studies – costs and benefits

We assessed two models to estimate the costs and benefits of active travel:

- **Sustrans Societal Gain Model.** This expresses the economic benefits of cycling as a gain to the individual and society and is based on extensive cycling data in Copenhagen, together with UK costs. It estimates the net value of cycling and driving, considering the benefits and disbenefits of both modes across a number of elements:
  - Costs include travel time, vehicle and infrastructure operating expenditure and congestion.
  - Benefits cover prolonged life, health, local air quality, noise and greenhouse gases.

  This model estimates the total private benefit of cycling versus cars as £0.4 per mile, and the total social benefit as £0.9 per mile, with a benefit-to-cost ratio above 4. A drawback is that the model does not include capital expenditure on vehicles or infrastructure. The latter is important where larger cycling infrastructure is needed to incentivise cycling.
- **CWIS Active Travel Investment Models.** These were developed for DfT by Transport for the Quality of Life.

They can be used to assess the impact on the level of cycling and walking of different types of policy intervention and different levels of capital and revenue investment, over the period 2020-40. Data are drawn from the National Travel Survey, Active Lives Survey and School Census and cover different intervention types and scenarios. Costs and benefits are similar to those in the Sustrans model but also cover infrastructure and vehicle capex. This model estimates a benefit-to-cost ratio of cycling versus driving of around 3.

There have been several active travel initiatives implemented across the UK:

- **Waltham Forest.** £27 million of TfL funding was invested, encouraging walking, cycling and improving public spaces, with the aim of it becoming a 'mini Holland'. Measures included introducing segregated cycle lanes on seven major routes, introducing a zero-emission cargo bike delivery service, delivering cycle training to 15,000 people, 15 new parks and planting of more than 660 trees. Benefits included residents walking and cycling for an extra 41 minutes each week[25], an increase in life expectancy of around 7-9 months for residents and improved air quality due to a reduction in NO_2 by between 15-25% and $PM_{2.5}$ by 6-13%.[26]
- **Greater Manchester.** The Bee Network vision[27] is the longest planned walking and cycling network in the UK, with significant funding and new measures to encourage active travel. The programme costs £1.5 billion and is to be delivered over ten years.
  - Estimated benefits are valued at £6.0 billion and include: 45,000 cars taken off the road each year; over £100 million in economic benefits to the area; prevention of serious health issues, saving the NHS an estimated £3.7 million per year; better air quality; and reduced GHG emissions. The estimated benefit-to-cost ratio is 4.
  - Measures include: protecting 435 miles of main road corridors and town centre streets; cycling corridors; new interchanges, increasing access to bikes; and creating filtered neighbourhoods where movement of people is prioritised over cars and driving through is restricted to residents.
- **Cycle-to-work.** It is estimated that the cycle-to-work scheme has encouraged over 1.6 million commuters to cycle to work. In June 2020, there was a 120% increase in the number of people joining the scheme, compared to the previous year. Scheme users save £780 per year on their commute on average, totalling an estimated saving of £390 million per year. 64% of employers felt that the scheme also had a positive impact on staff health.[28]

ii) Connected and autonomous vehicles

The impact of connected and autonomous vehicles on travel demand is highly uncertain.

Connected and autonomous vehicles (CAVs) are an emerging technology which could have a significant impact on levels of demand for road transportation.[29] However, impacts are highly uncertain and could increase or reduce travel:

- Autonomous vehicles could extend road travel to those previously unable to travel by car, including people who currently do not hold a driver's licence.
- The ability to use in-vehicle time productively (e.g. for work or leisure) or more comfortably could reduce the value that users place on travel time. This could make people willing to make more regular or longer trips.
- More efficient driving and dynamic routing could effectively increase road capacity, freeing up road space for more cars.
- CAVs could drive the development of new business models. For instance, greater uptake of ride-sharing, platooning of freight services or empty-running (where a leg of a truck's journey is completed with no payload) of vehicles to areas of demand could all become more feasible.

The timing of introduction of CAVs and level of technology readiness are highly uncertain. The Transport Systems Catapult's market sizing estimates suggest that CAVs could comprise between 5% and 58% of UK vehicle sales by 2035, with a central assumption of 31%. Similarly, estimates by DfT[29] determine that road traffic growth could be between 30 percentage points below and 36 above their reference scenario, depending on how the market engages with CAV technology.

Given this uncertainty, we consider the potential impact of CAVs in our Widespread Innovation scenario, in which we adopt the assumption that CAVs reduce car occupancy in line with DfT's private travel scenario (a reduction of 13% by 2050). This leads to around a 20% increase in car-kilometres by 2050 (equating to an overall increase in car-kilometres of 5% above baseline levels, after also considering all of the demand-reduction assumptions discussed above). This was to test the robustness of our decarbonisation pathways to higher demand, with the Widespread Engagement scenario being more ambitious on demand reduction.

iii) More fuel-efficient driving

Initiatives to encourage more fuel-efficient driving are important to help reduce emissions in the short term.

Vehicle emissions depend on the style in which the vehicle is driven, and it is possible to reduce emissions through technology and more efficient driving:

- Since 2014-15, it has been mandatory for all new cars to be fitted with Gear Shift Indicators and Fuel Consumption Meters. Respectively, these reduce fuel consumption by 1.5% and 0.3-1%.[30]
- Reducing speeds can also improve fuel-efficiency. Driving at 70mph rather than 80mph can use up to 25% less fuel, while limiting speeds to 60mph can save a further 15%.[31] We estimate that full enforcement of 70mph speed limits could reduce overall fuel consumption by 2%, while reducing these limits to 60mph could reduce fuel consumption by 7%.
- Training drivers in eco-driving styles has been seen to deliver fuel-efficiency improvements and several other benefits. For example, since introducing vehicle telematics and speed limiters and launching their Young Driver Academy, British Gas have seen a 14% reduction in overall fuel consumption.[32] Across light vehicles, we assume that eco-driving can offer an efficiency saving of 8% for up to 20% of drivers who adopt these styles.

Likewise, scope for improved driving efficiency exists within the HGV sector:

- There are several design options. For example, retrofitting drag reduction devices to existing HGVs can improve aerodynamics by up to 19%[33], while recent changes to weights and dimensions regulations will allow an additional 80-90cm of cab length for safety and efficiency measures, which could allow designs that are 3-5%[34] more aerodynamic.
- Driver training in and use of eco-driving is also possible in the HGV sector.
- Our scenarios assume that 50-100% (central 80%) take-up of a range of comprehensive measures to improve driving efficiency is possible, based on a study by Centre for Sustainable Road Freight.[35] In total, these can offer efficiency savings ranging from 13% for a small rigid HGV up to 22% for an articulated HGV.

iv) Improvements in freight operations

A range of data- and logistics-driven improvements could be possible in the freight sector, consolidating journeys and improving efficiency.

In 2019, 154 billion tonne-kilometres of goods were moved by road in the UK.[36] UK logistics operators already aim to maximise efficiency and minimise costs, but there are opportunities to go further, estimated within our scenarios at 9-11%:

- Increasing availability of data (e.g. through vehicle telemetry) could increase the efficiency savings that can be made through route optimisation. Standardisation of data formats across the industry may allow further steps to be made towards optimal consolidation and load pooling.
- Urban consolidation centres allow goods to be delivered to one central location on the outskirts of a built-up area. Their use would reduce the need for larger vehicles to travel into congested town centres and would allow consignments to be consolidated into fewer journeys for final delivery. Trials[37] have shown urban consolidation centres to be able to reduce the number of vehicle movements by 50-85% and to be cost-effective.
- Relaxing delivery time restrictions could allow some deliveries to avoid hours of peak congestion, speeding up delivery times and improving efficiency.
- Empty-running has slowly increased over recent years, up to 30% in 2019.[38] This may be partly attributable to accelerating delivery time expectations and the increasing reliance on just-in-time supply chains. Relaxing these could allow better consolidation and increase backhaul opportunities.
- The World Economic Forum[39] forecasts that further growth in e-commerce and faster expected delivery times could lead to a 36% increase in urban last-mile deliveries by 2030. They found that a combination of increased use of lockers, allowing delivery vehicles access to bus lanes and dynamic analytics-based rerouting could reduce emissions by 10% and costs by 30%.
- Analysis conducted for the CCC by the Centre for Sustainable Road Freight estimated that, in total, improved logistics could reduce emissions by between 9% for small rigid HGVs and 11% for articulated HGVs by 2030.

Rail freight could be used more in the short term as a lower-carbon way of moving goods.

There is also potential for emissions reduction through modal shift of freight:

- Moving freight by rail can be up to 76% more environmentally friendly than road haulage.[40] The total tonne-kilometres moved by rail in 2019-20 was 27% lower than in 2013-14[41], demonstrating that there is capacity to shift freight transport onto the railways. DfT's Rail Freight Strategy[42] laid out the potential for rail freight to increase by around 12% (maximum 69%) by 2030.
- In the short term, this could aid decarbonisation of the freight sector. In the longer term, however, zero-emission HGVs are expected to become available across the road haulage sector sooner than it will be possible to completely remove diesel from rail freight.

b) Conventional vehicle efficiency

i) Reducing tailpipe emissions in new road vehicles

Our analysis uses slightly higher emissions figures for new conventional cars in 2030 than we assumed for the Fifth Carbon Budget, in recognition of the recent growth in SUV market share.

Efficiency of new conventional cars and vans has improved in the past two decades, but this progress has stalled in recent years, with average emissions of new vehicle increasing since 2017. This trend will need to be reversed to meet existing new car CO_2 regulations and to deliver our Balanced Pathway:

- Average new car CO_2 emissions fell from 181 gCO_2/km to 120 gCO_2/km from 2000-16. Since then it has increased, reaching 128 gCO_2/km in 2019.[43]

- This has been driven by the increase in purchases of larger vehicles, such as SUVs. While sales of minis/superminis fell between 2016 and 2018, the market share of SUVs increased from 16% to 24%. Although there has been a shift away from diesel cars in recent years, the impact of this on new car emissions intensities has been limited. The gap between petrol and diesel car emissions has fallen over recent years, and in 2019 average new diesel CO_2 emissions were higher than for petrol cars.

- EU regulations require average emissions of new cars to meet 95 gCO_2/km from 2021, with a 15% reduction from 2021 levels by 2025 and a 37.5% reduction by 2030.[44] DfT has signalled its intention to retain emissions standards that are at least as ambitious* as those in the EU.[45]

- Similar regulations apply to vans, requiring a fleet average of 147 gCO_2/km in 2021, followed by a 15% reduction by 2025 and 31% by 2030. Average van emissions in 2018 were 167 gCO_2/km, 16% lower than in 2011.[46]

WLTP measurements are often not fully representative of real-world driving. The industry will need to ensure that this does not undermine consumer purchasing confidence in reported range figures for electric vehicles.

- The 2017 move from the New European Driving Cycle (NEDC) to the World harmonised Light-duty vehicle testing Procedure (WLTP) provided a more up-to-date test profile which better represents typical modern driving conditions and thus reduces the gap between test-cycle and real-world emissions. This gap is expected to grow due to driving style evolution, new technologies and flexibilities within the testing system – we estimate that it could reach 26% by 2030.[47] We take this into account in our modelling.

- Analysis for the CCC shows that real-world efficiency of new conventional cars and vans could improve by 12% by 2030, through measures such as hybridisation, smaller engines and more lightweight construction (Table 2.1).

- The scope for efficiency improvement beyond 2030 is limited and the associated marginal cost is likely to increase.

Zero-emission technologies for HGVs are further from market than for cars and vans and are expected to take longer to become widespread. Therefore, there is a greater role for conventional efficiency improvements in delivering medium-term emissions reductions within this sector:

- We estimate that there is potential for heavy-duty vehicle (HDV) efficiency improvements from 11% (for buses) up to 21% (for HGVs) by 2030, driven by uptake of measures such as hybridisation, heat recovery and low rolling resistance tyres, as well as the use of lighter materials. There is likely to be limited further scope for improvement beyond this.

- Urea is emitted from the tailpipes of Euro IV, V and VI HGVs, where it is used for NO_x control.[48] While these emissions are equivalent to less than 1% of a typical HGV's emissions, we include their impact in our analysis.

* In practice, the formula for applying this target at a manufacturer-level will be based on the average weight of the vehicles sold by that manufacturer as compared to the EU average. Since the UK's average vehicle mass is heavier than the EU's, the average target in the UK will be slightly higher than this 95 gCO_2/km level.

Table 2.1 Real-world CO_2 intensity of new petrol and diesel vehicles in gCO_2/km (% change from 2020)			
	2025	**2030**	**2035**
Cars	118 (-6%)	110 (-12%)	Not on sale
Vans	170 (-6%)	160 (-12%)	Not on sale
HGVs*	589 (-11%)	518 (-21%)	521 (-21%)
Buses	908 (-5%)	857 (-11%)	857 (-11%)

Efficiency improvements to new conventional vehicles are cost-effective, low-regret abatement measures.

These measures are cost-effective and will continue to be so in the medium term. Our analysis estimates the current abatement cost of efficiency improvements at -£83/tCO_2e for cars and -£7/tCO_2e for vans, with costs of £15/tCO_2e and £14/tCO_2e in 2030, remaining below BEIS carbon values.

The high annual mileage of many larger HGVs means that fuel savings are higher, and the economic case is even clearer, with the average abatement cost of efficiency improvements falling to -£59/tCO_2e by 2030. As these measures are cost-saving or low-cost and are needed to meet regulatory obligations, they are low-regret abatement measures that we include in all scenarios.

ii) Biofuels

Use of sustainable biofuels has the potential to reduce transport emissions in the short and medium term:

- Unleaded petrol available on UK forecourts currently contains up to 5% bioethanol, a blend known as E5. DfT proposes to introduce E10[49] (up to 10% bioethanol) as the default 95-octane 'premium' grade petrol at forecourts from 2021. Our scenarios assume widespread use from 2021, which could reduce car emissions by up to 1% (0.3 $MtCO_2e$/year) by 2030.
- The proportion of biodiesel in UK forecourt diesel has risen from 3.7% in 2018 to 5.3% in 2019 and 6.7% in the first half of 2020. 76% of this biodiesel was produced from used cooking oil.[50] Growth in commercialisation of advanced biofuels could offer the potential to further increase this share within the HGV sector up to around 10% by 2030 and 15-20% by 2040.

Given that the optimal decarbonisation technology for the HGV sector is not yet certain, biofuels are likely to play a role for a longer period of time in this sector than for cars and vans.

Biomass is a valuable limited resource. Our analysis[51] finds that its best use in driving emissions abatement across the economy is through uses that maximise carbon sequestration (e.g. in industry and with CCS). Our scenarios assume that biofuels will play an important transitional role in reducing emissions from surface transport, but that use is limited post 2040 as they are best used in other sectors.

iii) Electrification of rail

Around 40% of the UK's rail network is currently electrified, with the remainder of the network using diesel trains. Options exist to improve diesel train efficiency by 2050:

- Analysis[52] suggests that mild hybridisation can reduce diesel engine emissions by 25% from typical current levels of 0.8 $kgCO_2$/kWh, while the use of stop-start technology, selective engine shutdown and advanced driver advisory systems can contribute a further 20% reduction (primarily applicable to passenger services, which stop and start more frequently). Further innovations, including better heating/cooling, cruise control and improved aerodynamics could offer a further 10% in the longer term.[53]

* The increase in the CO_2 intensity of new diesel HGVs after 2030 is due to an assumed gradual shift in purchasing towards larger vehicles.

- For vehicles that cannot be transitioned away from diesel (which could include heavy plant machinery), the use of biodiesel in place of fossil fuel diesel could provide a lower-carbon alternative.

Continued gradual electrification of the railway will allow electric trains to run on more of the network.

To meet the ambition set out in our scenarios, rail will need to be decarbonised further, with gradual electrification up to 55-60% of the network by 2050:

- Analysis by the Rail Delivery Group[54] shows that already-committed schemes would be expected to increase electrification to 50% of the network by 2039, which could increase the proportion of the passenger fleet using electrical power by 10-20% by 2050.
- Only a small proportion of rail freight is currently hauled by electric locomotives, due to the need to be able to travel widely across the network. However, research[55] has suggested that targeted electrification of 515km of track could allow two-thirds of rail freight to be electrically hauled.

Battery-electric and hydrogen trains may be suitable for routes that cannot be electrified.

Battery-electric and hydrogen technologies could be suitable for some routes:

- In 2019, Vivarail unveiled a battery-electric train with 60-mile range, while in July 2020, Hitachi and Hyperdrive Innovation signed an agreement to form a battery development hub in the North-East of England. Further innovation offers the potential to extend battery ranges over the coming years.
- While such battery-only models are likely to be suitable only for category A[*] operations[56] (around 25-30% of remaining diesel passenger vehicles), bi-mode battery-catenary configurations could expand this suitability.
- Two Alstom hydrogen trains have been operating in Germany since 2018, while 2019 saw the first mainline test of the HydroFLEX prototype in the UK.
- As with battery-electric models, hydrogen is likely to be suitable for category A trains and in future potentially lighter-duty category B trains56, which together comprise around 25-50% of remaining diesel passenger vehicles. Hybridisation approaches may offer the potential to extend this coverage across categories B and C and to freight vehicles, but this is likely to be dependent on technological innovation.
- Both hydrogen and batteries offer low energy densities compared to diesel.[57] The high energy requirements of freight trains mean that these traction methods could require additional wagons simply for storing fuel or batteries. For this reason, we do not assume uptake of these modes in the freight sector within our scenarios.

It is not yet certain what combination of technologies will be optimal, with different studies suggesting different combinations of options. For example, Network Rail analysis[58] suggests electrification of a further 13,000km of track[†], battery operation on around 800km and hydrogen operation on around 1,300km. Whereas the Rail Industry Decarbonisation Taskforce[52] found that Net Zero emissions could be achieved with electrification of around 8,500km of track, while making greater use of battery-electric and hydrogen trains and of biodiesel out to 2050.

[*] Category A covers shorter-distance self-powered trains, generally with maximum speeds below 75mph. Categories B and C are middle- and long-distance self-powered trains, with capability up to 90-100mph and 100-125mph.

[†] Rail electrification is typically measured in terms of single-track kilometres, i.e. one kilometre of twin-track railway being electrified would count here as two kilometres of electrification.

c) Zero-emission vehicles

Widespread deployment of zero-emission vehicles (ZEVs) will be needed to meet Net Zero. In this section, we set out evidence on the technological characteristics, impacts and costs of zero-emission options for cars, vans and heavy-duty vehicles.

i) Electric cars and vans

Battery-electric cars offer considerably lower lifecycle emissions than conventional vehicles, and these reductions are likely to increase.

Battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs) entered the UK market in the early 2010s and now make up around 5% and 3% of new car sales during 2020 to-date.[59] BEVs already offer considerable lifecycle emissions savings compared with Internal Combustion Engine (ICE) vehicles, and by 2030 we expect embedded production emissions to be around the same as current ICE vehicles. By contrast, recent evidence[60] suggests that real-world emissions of PHEVs could be two to four times type-approval values which, at the upper end of this estimate, could make PHEV driving emissions similar to those of ICE cars (Box 2.2).

Box 2.2
Life-cycle emissions from electric vehicles

Although production of batteries means that the manufacture of UK BEVs today is more carbon-intensive than for a comparable ICE, the significant reductions in operational emissions mean that a BEV's total lifecycle emissions are substantially lower (Figure B2.2).

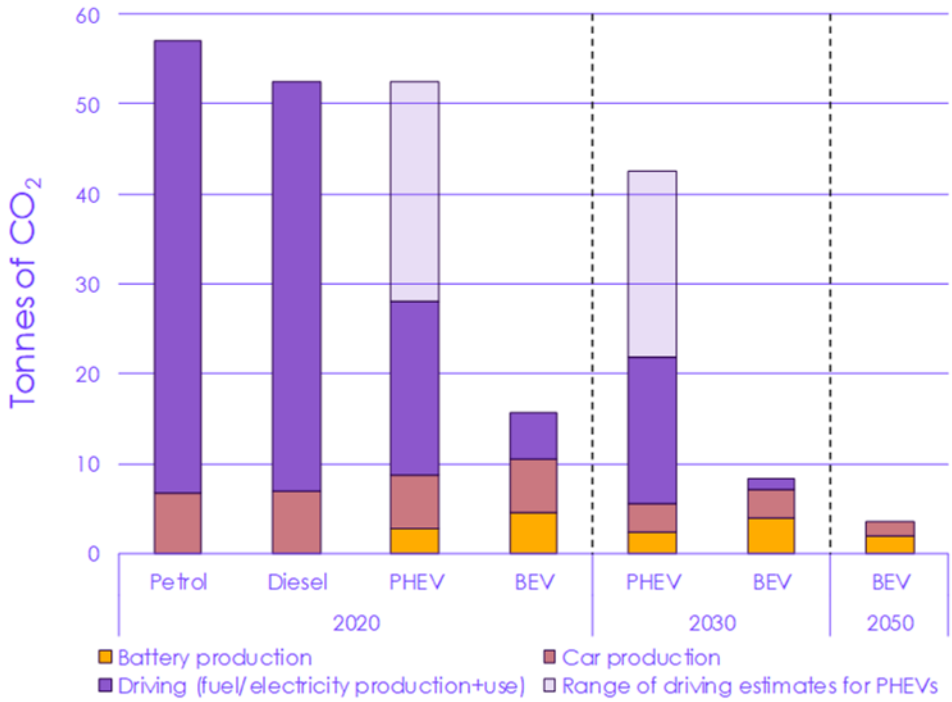
- Operational emissions account for just under 90% of petrol and diesel cars' total lifecycle emissions, compared to under 50% of total emissions of BEVs today.[61]
- While we expect to see some fuel efficiency improvements for fossil fuel vehicles to 2030, driving emissions for BEVs are expected to decrease much more (by around 60%) as the carbon intensity of the UK grid electricity reduces.
- Our analysis shows that BEVs, powered with today's UK average electricity, repay the 'carbon debt' from the production of their battery within slightly more than a year and save more than 35 tonnes of CO_2 over their lifecycle versus a conventional equivalent.

PHEVs have the potential to reduce emissions if they drive mainly on electricity. However, a recent study by the International Council on Clean Energy (ICCT) suggests this is not the case, bringing real-world emissions of PHEVs more in line with those of fossil fuel vehicles.

- Based on a study of real-world driving of around 100,000 PHEVs, ICCT found that real-world driving emissions were two to four times higher than type-approval values. This was true for both the NEDC and the WLTP test cycles.
- The largest difference between test-cycle and real-world emissions was found for company cars, where charging is less frequent, but mileage higher.
- The real-world share of electric driving for PHEVs is about half of that assumed in type-approval tests on average. For all private cars in the study, the ratio of kilometres driven on electric power to combustion engine kilometres is 69% under NEDC testing but 37% for real-world driving. For company cars (only sampled in Germany and the Netherlands), the average ratio under NEDC was 63% versus 20% in real-world driving.
- Private users in Germany were found to charge their PHEVs on average three out of four driving days. For company cars, charging takes place every second driving day.

A remaining challenge for all electric vehicles is around end-of-life battery use.[62] Strengthening battery collection, recycling and recovery will help with raw material supply and availability (Box 2.3). The carbon impacts of end-of-life battery use or disposal are not included in Figure B2.2 due to limited accurate evidence.

Figure B2.2 UK lifecycle emissions of fossil fuel and electric cars



Source: CCC analysis based on T&E (2020) *Analysis of electric car lifecycle CO_2 emissions*; ICCT (2020) *Real-world usage of plug-in hybrid electric vehicles*; EEA (2018) Electric vehicles from lifecycle and circular economy perspectives.

Notes: Based on medium-sized cars driven in the UK. For PHEVs, a range of estimates have been considered, based on high and low estimates from T&E and ICCT, along with CCC modelling. This range is shown with the light-purple column. The breakdown for BEVs in 2050 has been estimated by CCC based on the breakdowns for other categories.

Battery-electric cars and vans are now widely available in the UK, across most manufacturers and a range of vehicle sizes.

Electric vehicle (EV) technology is developing quickly and we expect uptake of BEVs to grow to between 90-100% of new sales by 2030:

- **Availability:** The supply of different EV models is increasing, widening consumer choice. Evidence suggests that raw materials and supply chains will be able to scale up quickly enough to enable this to continue (Box 2.3).
  - Worldwide, 105 new BEV models and 38 new PHEVs were launched in 2019.[63] A further 293 BEVs and 137 PHEVs are planned by 2022.
  - In the UK, there were 14 BEV car models from 14 manufacturers and 8 BEV van models from 2 manufacturers available in 2015. By 2020, these increased to 37 BEV cars from 20 manufacturers and 18 BEV vans from 14 manufacturers. There are at least 8 upcoming BEV car models, from 5 different manufacturers, in the next year.
  - Delivery times for EVs have fallen rapidly over the past year[64], with waiting times for all models now within 12 weeks, compared with over a year for some models in 2019. This is comparable to waiting times for new conventional vehicles.

Electric cars are considerably more energy-efficient than ICEs. By 2035, we expect BEVs to average 0.5 MJ/km. This compares to current ICE efficiencies of 1.7-2.2 MJ/km.

- **Fuel efficiency:** While EVs are already three-times more energy-efficient than ICE vehicles, technological improvements can deliver further efficiency improvements in the next decade.
  - Measures such as aerodynamics and weight reduction, as well as battery technology development, can improve fuel-efficiency.
  - Our analysis suggests real-world BEV efficiency can improve by around 12% to 0.5 MJ/km by 2035. PHEV efficiency will be lower at 0.9 MJ/km.[65]

Battery ranges are likely to reach 350-400 km by 2030, which will be enough to allay range anxiety.

- **Driving range:** Battery technology is progressing rapidly, and typical BEV ranges could reach around 350-400 km (220-250 miles) by 2030, with larger cars most likely to have longer battery range and van range slightly lower (Table 2.2). As range improves and battery costs reduce, EVs are well placed to become a viable option for all consumers.
  - The average range of a new BEV today is around 300 km.[66] While this is skewed upward by the luxury models, there are a significant number of vehicles across all size with ranges exceeding 200 km.
  - As battery costs reduce (see Figure B2.5), manufacturers are likely to increase battery capacity, leading to greater range. The IEA forecast[67] average driving range to reach 350-400 km by 2030.
  - Research has shown that a driving range of 370 km is sufficient to eliminate 'range anxiety' among consumers.[*] As range approaches this threshold, manufacturers may choose to make EVs cheaper rather than to improve range further. For some drivers, affordability will be more important than long driving range and it is important that EVs are appropriately sized to meet the needs of different market segments.
  - We expect electric-only range for PHEVs to remain at around 40 km, with drivers driving in electric mode around 50% of the time (Box 2.4).
  - The larger weight, size and payload of vans means that they require larger batteries to offer a comparable range. Therefore, van ranges are likely to remain slightly below those of cars.

Table 2.2
Average real-world driving range of a typical new battery electric vehicle in km

	2020	2030	2040	2050
Car – small	289	361	434	500
Car – medium	300	375	450	500
Car – large	349	436	500	500
Van	250	350	375	400

Significant deployment of public charging infrastructure, including on-street charging for those without private car-parking and inter-urban chargers for charging during long journeys, will be needed in the 2020s and 2030s.

- **Infrastructure availability:** Provision of charging infrastructure is key to enabling the high uptake of EVs across the UK. We expect around 260,000-480,000 public chargers to be required by 2040 across our scenarios (Figure 3.1.b in the Advice Report; Table 2.3 for Balanced Pathway assumptions).
  - A recent survey[68] of UK motorists found that 69% are discouraged from switching to an EV due to a perceived lack of charging infrastructure.

[*] 'Range anxiety' is the concern that an EV will not have sufficient usable range for the consumer's purposes and may suddenly and unexpectedly run out of charge.

The number of public electric vehicle charge points has grown more than five-fold since 2015, to 18,000 today. We expect this to increase around ten-fold by 2030.

- There are currently over 18,000 public charge points in the UK, of which over 3,000 are rapid chargers.[69]
- Around 70% of car owners have access to off-street parking and so will be able to recharge their vehicle at home. These typically cost up to £1,000 to install today (although a Government grant will contribute up to £350), and we expect this cost to fall to around £850 by 2030 and £680 by 2040. We include these costs in our estimates of the capital expenditure on the vehicle.
- For the remaining 30% of car users, extensive provision of on-street charging will be necessary. We estimate that there will need to be around 140,000-270,000 on-street/local chargers by 2030, increasing to 250,000-460,000 across our scenarios by 2040. This is based on an extensive model developed by Systra for the CCC in 2018[70], updated with latest assumptions on EV costs and range.
- A network of rapid charge points (in particular along the strategic road network) will enable users to recharge reliably during longer journeys. Companies such as Ecotricity already provide a network of individual chargers at motorway service stations, while Gridserve is due to open the UK's first electric forecourt later this year. Our scenarios anticipate the installation of 8,000-15,000 chargers in interurban locations by 2030, rising to 10,000-20,000 by 2040.
- On a similar scale, analysis by Transport and Environment[71] found that the UK would require 370,000-500,000 public chargers by 2030.

Table 2.3
Total public charging infrastructure in our Balanced Pathway in thousand units

	2020	2030	2040	2050
On-street/local	17	270	460	520
Inter-urban	0.5	8.5	10	10.5
Total	18	280	470	530

Electric vehicle charging will add substantial demand to the electricity grid. Smart charging and possibly vehicle-to-grid schemes can mitigate the impact of this.

- **Network upgrades:** Electricity demand among road vehicles in our scenarios will increase from 1 TWh in 2020 to 92 TWh by 2040, which will require network reinforcement, appropriate planning and timing of which is important for this to be achieved cost-effectively.
  - This increased demand will require reinforcement of the distribution network. It is expected to be more cost-effective to proactively ensure that networks are able to cope with increased demand, rather than to wait until demand outstrips capacity.[72] Thus, our scenarios assume that these upgrades begin in the 2020s and do not constrain EV uptake.
  - Our analysis suggests that the cost of these reinforcements will lead to a 2p/kWh increase in the average price of electricity used for vehicle charging during the 2030s. This is included in our cost estimates.

– The scale of upgrades required can be reduced (but not eliminated altogether) through effective use of smart charging. This can smooth the new peaks in residential demand resulting from home charging and shift charging demand into off-peak periods.[73] Further, the introduction of vehicle-to-grid schemes could offset up to 85% of the remaining peak EV demand[74], depending on uptake.

Battery-electric cars are expected to reach upfront cost parity with conventional vehicles by 2030. They will be cost-saving on a total cost of ownership basis by the late-2020s.

- **Costs:** Our analysis shows that the upfront cost of a BEV will reach parity with an ICE in 2030, while the significantly lower running costs mean that BEVs will be cost-saving before then (Figure 3.1.h in the Advice Report).

  – A typical BEV is currently around 34% more expensive to purchase than a comparable conventional vehicle. For a £20,000 vehicle, this means that a BEV version would be likely to attract a cost premium of around £6,800. The Government's plug-in car grant would currently contribute up to £3,000 towards this difference.

  – Battery costs currently make up at least 30% of the upfront cost of a BEV. Battery costs will continue to reduce during the 2020s (Box 2.5).

  – As a result, we expect BEVs to reach upfront cost parity with comparable ICE vehicles in 2030. By 2040, a typical medium-sized BEV is expected to be around £500 cheaper than an ICE vehicle.

  – Electric drivetrains have fewer moving parts than ICEs, meaning that they will typically have lower servicing and maintenance costs. For a typical medium-sized car, we estimate an annual saving of £170.

The electricity required to power an electric vehicle is significantly cheaper than petrol or diesel.

  – BEVs can offer significant annual fuel cost savings. Over the assumed 14-year lifetime of the vehicle, a typical medium-sized BEV will save almost £1,000 in fuel costs (£750 in discounted terms), excluding fuel duty and the impact of carbon emissions. If taxes are included, then the cash value of the saving to the owner increases to around £6,700 (£2,200 over the first five years of ownership).

  – By contrast, a medium-sized PHEV will be around £300 more expensive to purchase in 2030, will offer zero maintenance savings and gives lifetime fuel savings of only £300 (£2,400 in cash terms including taxes).

  – Similarly, we estimate that BEV vans will also reach upfront cost parity with ICE vans around 2030 and will be around £1,400 cheaper by 2040. Due to their typically higher mileage, a new BEV van in 2030 will realise higher lifetime fuel savings of around £2,800 (£14,600 including taxes).

A new battery-electric car purchased in 2030 will have a negative abatement cost of -£38/tCO_2e.

From a societal perspective*, our analysis suggests that BEV cars are likely to become cost-effective by the late-2020s, while the higher fuel savings for vans mean that BEV vans will become cost effective by the mid-2020s. By 2030, the average abatement cost of a new BEV will be negative at -£38/tCO_2e for cars and -£43/tCO_2e for vans. Thereafter, they will continue to become even more cost-effective, reaching -£84/tCO_2e for cars and -£48/tCO_2e for vans by 2050.

* Including cost of the vehicle and cost of fuel (excluding taxes), discounted at the social discount rate of 3.5% p.a.

Battery-electric vehicles will make up over 90% of all new car and van sales by 2030.

Based on these cost advantages, we expect BEVs to make up the majority of new sales by 2030 across all scenarios (Figure 3.1.e in the Advice Report):

- The above factors are important determinants of the rate at BEV adoption and are used in our modelling of consumer decision-making (Box 2.6).
- All of our scenarios assume no sales of new petrol or diesel cars, vans or PHEVs from 2035 at the latest (2032 as the central assumption).
- Across our scenarios, we estimate that BEVs could make up 24-56% (central assumption 48%) of new car and just over half of new van sales in 2025 and 90-100% (central assumption 97%) in 2030. PHEV sales fall from 25% in 2025 to 1% by 2030 to meet the phase-out date assumptions in our scenarios.

By 2035, over half of the fleet of cars and vans on the road in the UK will be battery-electric.

- New BEV sales will take time to feed through to the fleet as the average car remains in use for around 14 years. In our analysis, BEVs will comprise 27-37% of the car and van fleet in 2030, rising to 56-67% by 2035 and 81-88% by 2040 (central assumptions 35%, 65% and 87% respectively).
- For comparison, the National Grid's Future Energy Scenarios[75] have slower initial take-up, but this rises quickly in the 2020s with 11-36% BEV penetration across the fleet in 2030, 30-81% by 2035 and 61-99% by 2040.

Box 2.3
Supply of raw materials for EV batteries

To meet the Paris Climate Agreement, the level of EV production in the UK and globally will need to increase significantly from current levels. For example, global production could rise to 40-90 million vehicles annually by 2030 compared with around 2 million today. Global supplies of key raw materials for battery production such as cobalt, lithium, aluminium, graphite and manganese will need to scale up significantly, but are expected to remain a low proportion of estimated global reserves (e.g. lithium demand for EVs could be 1-2% of global reserves).

The CCC wanted to explore issues around the challenges and opportunities for future raw materials supply globally and for the UK. In March 2020 we sent a questionnaire to key stakeholders asking for views and evidence. We received a range of responses from academics, industry and research bodies. The key findings were:

- There are plentiful global supplies of raw materials to supply the growing battery market. The issue is around scaling up, particularly around 2025-30. Developing new mining opportunities and new supply chains will be crucial to meeting that demand.
- Changes to battery chemistry will take time and lithium nickel manganese cobalt oxide (NMC) batteries are expected to dominate for the next decade. Appropriate sizing of batteries and standardisation of manufacturers' battery chemistries would improve resource efficiency and enable higher levels of recycling and reuse.
- Security of supply and of raw materials for batteries can be enhanced by: supporting R&D of batteries and recovery technologies; localising more of the supply chain in the UK and linking battery and EV manufacturers; having a clear assessment of how best to reuse batteries; and developing competitive, large-scale UK recycling facilities.
- A certification scheme for ethical sourcing of raw materials would help to address issues around working conditions, low pay and use of child labour in mines.

Box 2.4

Real-world PHEV operations

While PHEVs are often advertised as low-emission vehicles, recent studies by Transport and Environment[76] and the International Council on Clean Transportation[77] show that PHEVs emit two- to four-times more during real-world driving than test values. This makes their real-world emissions more comparable with conventional vehicles than with ZEVs.

- Typical real-world emissions from PHEVs are around 117 gCO_2/km, compared to 165 gCO_2/km for ICE cars.
- Typically, PHEVs are not charged as often as they could be, reducing the share of kilometres driven on electricity.
- Even when PHEVs are supposed to be in zero-emission mode, the car does not drive using only the electric motor and continues to use its engine, emitting CO_2.
- The ICE in a PHEV will typically turn on in situations that require high power.[78] For example, in each of the UK's top-ten selling PHEVs, turning climate control on engages the ICE.

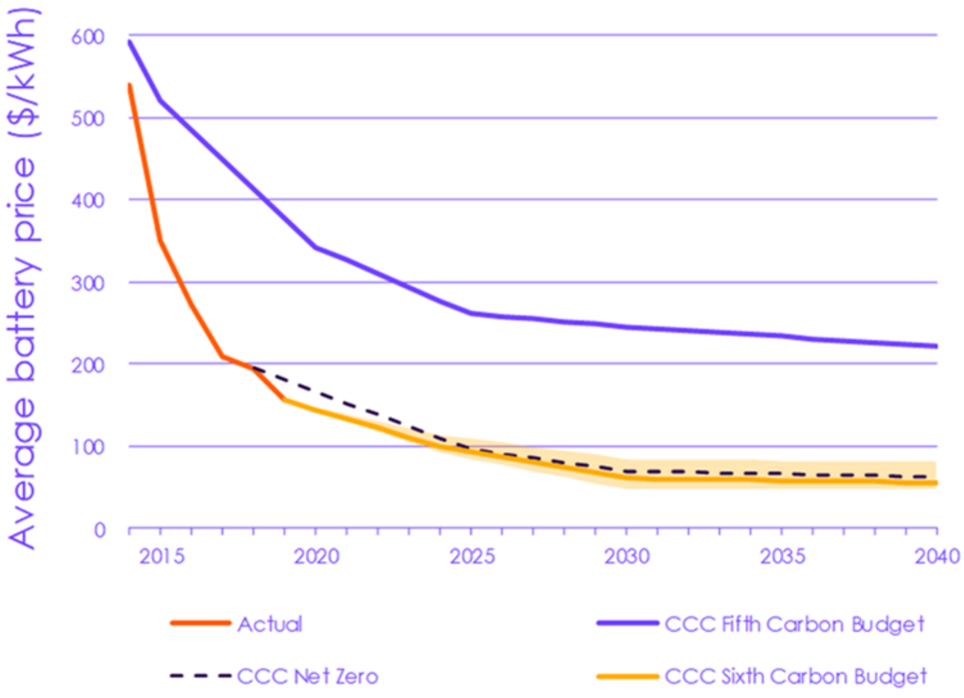
Box 2.5

Battery cost assumptions

Battery costs currently make up around one-third of the cost of a typical BEV. Changes in battery cost will thus have a significant impact on the cost of a BEV.

- Advances in battery technology and manufacturing, together with market expansion, have driven more rapid falls in battery prices than previously expected. Further reductions are anticipated.
- Our assumptions are based on Bloomberg New Energy Finance price projections[79], which show the average price per kWh falling below $100 in 2024 and to $61 by 2030.
- Beyond 2030, we assume further gradual reductions down to $53/kWh in 2050. In our Widespread Innovation scenario, this minimum price is reached by 2030.
- The cost of battery packs for HGVs and buses is assumed to be higher, because of the use of different battery chemistries and constructions to achieve greater durability and the reduced economies of scale within this market. A bottom-up analysis conducted by Element Energy80 estimates that costs today are around $470/kWh and are expected to fall to around $155/kWh by 2030 and $83/kWh by 2050.

Figure B2.5 Average battery cost for electric vehicles, actual and forecast to 2040



Source: Bloomberg New Energy Finance (2019) *Battery Price Survey*; CCC analysis.
Notes: Our central projection (orange line) follows the BNEF forecast. The shaded area around this shows the range between the low battery pack prices assumed in the Widespread Innovation scenario and our upper price sensitivity based on further price reductions being only 75% of central forecasts. These battery costs are for battery-electric cars and vans.

Box 2.6
Updated assumptions in charging and uptake modelling

In our decarbonisation pathways analysis, we have updated existing models for EV uptake (developed by Element Energy) and EV infrastructure requirements (developed by Systra). Here we describe the approach and key changes.

EV uptake modelling. Our EV uptake paths are based on a decision model that simulates likely consumer behaviour when purchasing a new vehicle. The primary assumptions are:

- **Tax/subsidy gradient between ICEs and EVs.** Our pathways assume that during the 2020s, a differential between ICEs and EVs from subsidies, benefits-in-kind and taxes remains (reducing from 2020). Over time, we would expect this gradient to shift from EV subsidy to ICE taxation.
- **New conventional vehicle sales phase-out**. Our scenarios explore the impact that different phase-out dates could have. Our Balanced Net Zero Pathway assumes a phase-out date of 2032, compared to 2030 in Widespread Engagement/Widespread Innovation/Tailwinds and 2035 in Headwinds. Modelling assumes that these phase-out dates are accompanied with EV percentage sales targets for suppliers as well as a market response reducing the supply of new petrol and diesel models available to UK customers as the phase-out date is approached.

EV infrastructure modelling. Our modelling of infrastructure requirements uses two models: a 'parking-based model' which calculates public charging infrastructure required in towns and cities and an 'inter-urban model' which determines public charging points needed to facilitate long-distance travel. For our Sixth Carbon Budget analysis, we consulted with industry experts, manufacturers and broader stakeholders to produce a range of credible input assumptions to these models and mapped these to our scenarios.

Some assumptions are constant across the two models:

- **Cost of building charging infrastructure.** In all scenarios except Widespread Innovation, the cost of deploying charging infrastructure, including the associated network upgrades, is assumed to be the same as present-day values. This is likely a conservative assumption. In the Widespread Innovation scenario, the cost of building charging infrastructure falls by 5% every 5 years.
- **Number of trips.** In all scenarios, we begin with Government projections of future trip demand by region. In each of our scenarios, we explore the potential for varying levels of demand reduction due to increased use of public transport, modal shift etc.
- **EV percentage uptake.** EV uptake is determined by the uptake modelling (see above). We assume that regional differences in current EV uptake remain during the 2020s but dampen over time as percentage roll-out increases.
- **Battery capacities and vehicle ranges.** In most of our scenarios, we assume that the majority of new vehicle sales have battery capacity greater than 350 km by 2030, in line with industry trends. To reflect possible market segmentation, our Widespread Engagement scenario continues to sell EVs with ranges as low as 150 km in 2050.

The parking model deploys three speeds of charger – 7kW, 22kW and 50kW – to serve drivers, and incorporates some additional specific assumptions:

- **Target service level.** The model assumes that when an EV parks around town, it will try to charge irrespective of its level of charge (a 'top-up'). The percentage of time that a charger is available to do this for the duration needed is the target service level. Our Balanced Pathway assumes that the acceptable service level for EV drivers remains the same as at present. The Widespread Engagement scenario explores a future where drivers are more comfortable with forgoing a top-up, and the Widespread Innovation scenario expands the charging network to allow more regular topping-up.
- **Percentage of drivers with home charging.** In all scenarios, it is assumed that the percentage of EV drivers with home charging increases to the percentage of households that have off-street parking.

The inter-urban model deploys three speeds of charger – 50kW, 150kW and 350kW – and includes the following specific assumptions:

- **Range anxiety.** When making a long trip, behaviour suggests that new EV drivers are uncomfortable making trips close to the range capacity of their vehicle, and that a degree of this effect remains. This means that the maximum used range of EVs is lower than their actual range. The percentage buffer that new and experienced drivers allow is known as the range anxiety factor. All our scenarios assume that range anxiety factors fall over times as EVs become the norm, however our Widespread Engagement scenario accelerates this effect.
- **Charging compatibility.** High-speed chargers require a compatible EV. The highest-speed chargers currently have low levels of compatibility. Our scenarios all assume that by 2035, all cars and vans making long-distance trips are compatible with rapid chargers. In our Widespread Innovation scenario, compatibility increases more quickly.

ii) Zero-emission HGVs and buses

Continued advancement of battery technology is likely to make battery-electric technologies suitable for widespread heavy-duty use in the coming decade.

Decarbonisation of the transport sector will require widespread uptake of zero-emission HDVs by 2040 to enable almost full decarbonisation of the fleet by 2050.

We commissioned Element Energy[80] to consider pathways to decarbonising this sector (Box 2.7). The study showed that each of battery-electric vehicles, electric road systems and hydrogen fuel-cells could play a role within this sector and it is too soon to say with certainty which technology choices will be cost-optimal.

Battery-electric HDVs. If battery technology continues to advance quickly, then it is projected to become suitable for many HDV applications within ten years. This is explored in our Widespread Innovation scenario.

- Packaging sufficient battery range into the vehicle is a major challenge with battery-electric HGVs. The volumetric and gravimetric densities of a battery pack are 50-60 times lower than those of diesel.

  This means that, even correcting for an electric drivetrain's higher efficiency, batteries take up considerably more of the vehicle's size and weight allowances than diesel. This is a particular challenge for certain designs of HGV (including articulated trucks) and for buses, where available space is limited.

- While models developed over the coming years may provide enough range for some smaller HGVs[81], some larger HGVs can drive up to 800 km in a single day and are heavier. Covering this range without the need to recharge would greatly increase the vehicle's cost and reduce the space and weight available for the payload.

- Research conducted by Ricardo for the CCC[82] emphasised the need to develop infrastructure that would be suitable for HGV use. This analysis estimated that each depot would require 0.3-0.85 chargers per vehicle, in addition to around 130 strategically located ultra-rapid chargers.

Ultra-rapid chargers suitable for HGVs will be required across the strategic road network to support the use of battery-electric vehicles on longer routes.

- In practice, long-distance vehicles are likely to require at least 400 km of independent range, plus the provision of sufficient density of HGV-suitable ultra-rapid chargers to be able to recharge ahead of mandated breaks (every 4.5 hours). Element Energy found that would require a network of recharging points at least every 50 km on the UK's strategic road network.

- If this were available and battery technology develops sufficiently, then battery-electric HGVs could make up 19% of all new sales in 2030, increasing to 82% by 2035. Large articulated HGVs are likely to be slowest to adopt this technology, due to their greater range requirements and limited spare capacity.

- Battery-electric buses are already being deployed[83], often due to local authority efforts to reduce air pollution.

  This means that costs are falling relatively quickly, and total cost of ownership (TCO) parity is likely to be reached in the early-2020s. As such, uptake is expected to be faster than for HGVs, and could reach up to 68% of sales in 2030 and 100% by 2035.

- Aircraft support vehicles are similar to small rigid HGVs. In line with the analysis for them, it is therefore likely that electric vehicles will be suitable for all new sales of aircraft support vehicles by the mid-to-late-2030s.

Catenary systems avoid the need for lengthy recharging and are a more mature technology. However, such systems require substantial infrastructure and may become uncompetitive.

Electric road systems. Electric road systems (ERS), consisting of overhead catenary to which HDVs can connect via a pantograph to draw power directly or recharge, can offer operational benefits to operators. However, once other zero-emission technologies become widely available, the use of an ERS may become expensive relative to other options. Our Widespread Engagement scenario considers the sector if there is large-scale ERS deployment.

- Both Germany and Sweden have an operational ERS (of 10 km and 2 km in length, respectively), while Siemens now offer a commercial ERS product.[84] ERS is similar to the overhead wires used for rail electrification, so it is a proven commercial technology.

- ERS technology could be attractive to fleet operators who are concerned about the impact of the need to recharge their vehicles on operations. Being able to recharge while driving would mitigate these concerns.

- To recoup the significant infrastructure investment from limited users, an ERS operator would need to charge relatively high electricity prices. This may drive fleet operators to prefer depot- or public-charging where possible.

- Recent research[85] laid out a plan by which ERS could be deployed across 7,500 km of the strategic road network, beginning in 2025 and completing by the late-2030s. This would cover 65% of HGV-kilometres (18 billion kilometres) at a cost of around £1-1.5m per kilometre. The Ricardo work, by contrast, assumed a more modest 3,600 km of ERS infrastructure, with a similar unit cost.

- Element Energy's analysis expects that once an ERS network is fully deployed (assumed to be 2045), then ERS becomes the most cost-effective option for around one-fifth of HGVs operating on the longest routes. This could lead to uptake rising from 24% of new articulated trucks in 2040 to 33% in 2045, with a small percentage of large rigid HGVs also using the system. Smaller HGVs are expected to prefer the lower electricity prices of depot-charging, as this should cover their range requirements by this time.

- ERS infrastructure could help meet range requirements of longer-distance buses and coaches, reaching up to 50% of total sales from 2035 onwards.

Hydrogen vehicles offer a similar operational profile to current vehicles and are attractive for operators who require long ranges.

Hydrogen fuel-cell vehicles. Hydrogen offers the closest user experience to current diesel operations. Given sufficient hydrogen refuelling infrastructure, fleet operators would be able to fill up vehicles either in-depot or from filling stations en route as currently, or both. Hydrogen is also a particularly attractive solution for vehicles requiring longer independent range. Its widespread deployment is considered as part of our Headwinds exploratory scenario.

- There are currently 11 hydrogen refuelling stations in the UK, with a further 5 planned.[86] These mostly cater for light-duty vehicles, for which hydrogen consumption per vehicle is low. There is potentially a stronger business case for hydrogen in the HDV sector, due to the higher fuel consumption.

- Energy storage poses a challenge, although not to the same extent as for batteries. Pressurised hydrogen tanks are relatively space-inefficient and cannot efficiently be divided to fit into available space within the vehicle.

- The energy storage challenge is likely to be quicker to resolve for hydrogen than for batteries. This could allow hydrogen-fuelled vehicles to meet most operators' range requirements (potentially even delivering independent ranges of up to 800 km for an articulated truck with additional space allowed for fuel storage within the trailer) more quickly than electrification.

- This rapid potential is seen in a partnership between Hyundai and H2 Energy, which aims to deploy 1,600 hydrogen HGVs in Switzerland by 2025.

- By 2050, the Ricardo analysis expects that around 500-600 hydrogen refuelling stations would be required to support the use of hydrogen by larger HGVs only. If smaller vehicles were to use hydrogen in preference to electrification, this could increase to around 1,000.[87]

- With this infrastructure, Element Energy's analysis shows that hydrogen uptake could be relatively quick, reaching 77% of larger HGVs by 2035 and 99% by 2040. Hydrogen could also be suitable for smaller HGVs, but the cheaper running costs of depot-charged BEVs will likely be more attractive.

- London currently has 8 hydrogen buses operating, and UK manufacturer Wrightbus recently announced plans to manufacture 3,000 hydrogen buses. Hydrogen bus sales could ramp up relatively quickly, potentially reaching up to 69% of all sales by 2030 and 95% by 2035.

- Hydrogen cars already exist in the market[88], while hydrogen vans have also been demonstrated.[89] If there were to be significant rollout of hydrogen refuelling infrastructure to support the HDV sector, then it is conceivable that hydrogen-fuelled smaller vehicles may also see further development.

- The decarbonisation potential of hydrogen in transport is intrinsically linked to the wider hydrogen strategy.

If public infrastructure for all three technologies were deployed, battery-electric vehicles are expected to become cost-optimal for all operators by 2050.

Mixed infrastructure deployment. In a model in which all three technology options are developed simultaneously, BEVs were found to be cost-optimal by 2050, but hydrogen fuel-cell vehicles had a significant role in meeting the range requirements of many operators in the early-2030s (Table 2.4). This is the basis (in modified form*) for our Balanced Pathway and Tailwinds scenario.

- In the early-2030s, the range provided by a hydrogen vehicle is likely to be greater than a comparably priced BEV. Furthermore, most operators' range requirements can be met through in-depot refuelling, allowing uptake of hydrogen vehicles prior to full public refuelling infrastructure deployment.

- For short-range HGVs and buses, BEV sales are likely to grow quickly from today.

- TCO is relatively competitive between BEVs and hydrogen vehicles from 2025 to 2035. However, once an ultra-rapid charging network is deployed, HDVs with smaller batteries become viable due to the ability to recharge en route. This makes BEVs increasingly more cost-effective than hydrogen vehicles from 2035 onwards.

- Hydrogen HGVs may retain a significant portion of the market, however, due to operators who have invested in hydrogen infrastructure being 'locked in' to that technology and because of its lower operational complexity. Small fleets may also choose hydrogen as it allows 100% public refuelling rather than requiring charge points to be installed in the depot.

- ERS is currently the most mature technology and would be the most suitable to decarbonise the HDV sector today. However, supply of zero-emission HDVs is likely to be limited by original equipment manufacturer (OEM) production until the early-2030s. By this point, we expect hydrogen costs to have reduced and battery technology to have improved – if this occurs, then ERS is likely to be uncompetitive with these technologies for most operators' requirements.

- Under this mixed model, around 330 public ultra-rapid charge points, 100 hydrogen refilling stations and up to 90 km of ERS network are expected to be required by 2035. In addition to this, around 140,000 depot chargers would be needed. These comprise the majority of the expected infrastructure costs at £1.1 billion, with the public infrastructure provision costing an additional £200m. By 2050, the cumulative cost of HGV infrastructure is expected to have risen to around £9.8 billion.

* The Balanced Net Zero Pathway follows this mixed technological roll-out but assumes that a substantial ERS network is not developed due to its low uptake. The Tailwinds scenario considers how much this mixed model's uptake could be accelerated with maximum rates of infrastructure deployment and technological development.

Table 2.4 Uptake of zero-emission technologies among HDV sales if all solutions progressed (% of all new sales)				
	2020	2030	2040	2050
Battery-electric	<1%	13%	50%	71%
Hydrogen	0%	11%	48%	26%
ERS	0%	<1%	1%	2%

It is too soon to tell which will be the most cost-effective and feasible solution for heavy-duty vehicles. Large-scale demonstrations are needed in the coming years.

Given the state of market development and uncertainty over costs, it is too soon to tell which will be the most cost-effective and feasible solution for HDVs. Large commercial-scale demonstrations, involving hundreds of vehicles and lasting at least 1-2 years, should be planned and implemented over the coming years to further test deployment of each technology and produce real-world data on costs and operational feasibility.

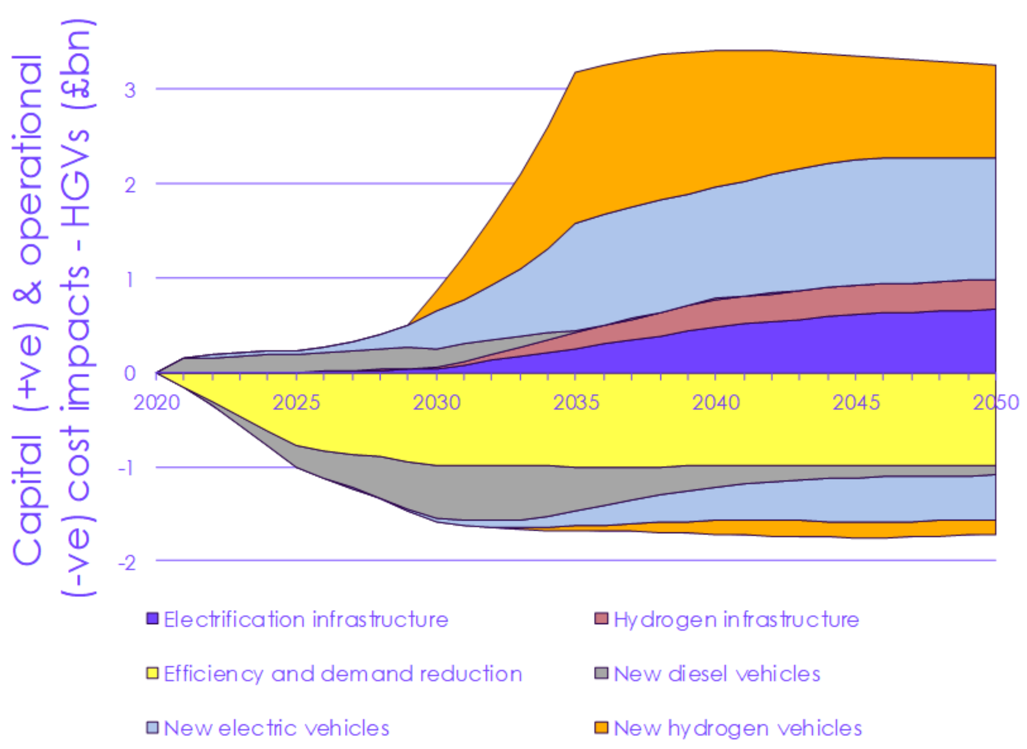
The high upfront cost of zero-emission HDVs means that our analysis does not expect them to become cost-saving from a social perspective before 2050, but they are cost-effective against current expected carbon values:

- The unit abatement cost of a new articulated HGV in 2035 is estimated at £64/tCO_2 for a BEV and £178/tCO_2 for a hydrogen vehicle. By 2050, these could reduce to £26/tCO_2 and £110/tCO_2. These are below expected carbon values in these years, meaning that they represent a good value means of abatement.
- Due to the high upfront costs, we expect there to be TCO shortfall of £24,000-33,000 for a private owner of a rigid truck in 2035 relative to a diesel vehicle, with only higher-mileage articulated HGV owners realising a TCO saving. For smaller HGVs, TCO parity may take until 2050 to be reached.

Significant Government support will be needed to incentivise widespread timely uptake of zero-emission options across the HDV sector.

- Government support or significant market development will be needed to bridge this gap, in order to ensure that diesel sales are phased out in time that diesel vehicles do not continue to remain in circulation beyond 2050.
- Our uptake modelling assumes that sufficient support is in place to ensure TCO parity in 2035 across all scenarios.
- Under our Balanced Pathway assumptions, annual investment (both public and private) in infrastructure and new vehicles will need to ramp up to around £3.2 billion per year in 2035. As more ZEVs are taken up, operational savings will offset some of these costs (Figure 2.3).

Figure 2.3 Additional capital and operation Expenditure associated with HGVs



Source: Element Energy and Ricardo modelling for the CCC.
Notes: Chart displays in-year societal capital and operational cost impacts relative to the baseline. Segments above the horizontal axis represent additional capital expenditure (infrastructure and the purchase of new vehicles), while segments below the horizontal axis represent operational cost savings (reduced consumption, efficiency improvements and fuel / maintenance cost savings).

Box 2.7
HDV uptake trajectory modelling

Our analysis of decarbonisation of the HDV sector is based on research that we commissioned from Element Energy, which built upon previous work by Ricardo. The research considered several alternative zero-emission powertrain options:

- BEVs, using either just in-depot or a combination of in-depot and public recharging.
- Hydrogen fuel-cell vehicles, refuelling either in-depot or at public refilling stations.
- ERS, with power drawn to either a battery or a hydrogen fuel-cell.

It then considered how key variables such as fuel costs and technology development would be expected to evolve under five scenarios:

- Hydrogen refilling stations are deployed as the only public refuelling option for HDVs, and BEV technology does not develop in a way that is suitable for HDV use.
- Ultra-rapid chargers are the only public refuelling option for HDVs, and hydrogen is not available for use in HDVs.
- ERS is the only public refuelling option for HDVs, although both BEVs and hydrogen fuel-cell vehicles are available for use, relying solely on in-depot refuelling.
- All three public refuelling options are deployed, alongside in-depot refuelling.

- All three public refuelling options are deployed at an accelerated rate, alongside in-depot refuelling, and manufacturers accelerate zero-emission HDV production.

Infrastructure in each scenario is assumed to be deployed in line with demand (based on the uptake modelling below), according to the Ricardo modelling.

Within each scenario, the model begins by looking at which available powertrains in which range capacities can feasibly be packaged into eight vehicle sizes – four sizes of rigid trucks, two sizes of articulated trucks, buses and coaches – in each year. It then applies a series of filters to determine the optimal technology mix in each year:

- **Range suitability.** Tests the distribution of vehicle daily distance requirements against the range available through each technology option, to determine what proportion of each vehicle type each option is suitable for.
- **TCO suitability.** For the subset of the vehicle distribution that remain, the model then calculates the TCO under each available powertrain option. All options that have TCO cheaper than diesel pass through, while a proportion (decreasing with the size of the TCO excess) of more expensive options are allowed through to reflect possible non-financial reasons for ZEV uptake.
- **TCO ranking.** For each vehicle size and year, the suitable technology options are ranked in TCO order, from cheapest to most expensive.
- **Technology selection.** For the technology ranked first, the number of vehicles of this type to be chosen is simply the number that passed through the suitability filters. For each technology that is not ranked first, the final number is the number who passed through each technology filter but did not pass range suitability for every cheaper technology. This equates to every vehicle choosing the cheapest option that meets its range requirements.
- **OEM supply constraints.** Available supply is expected to scale up in line with the timescales seen in the UK for BEV cars, towards the goal of being able to support 100% zero-emission sales by 2040. If there is insufficient supply to meet the number of vehicles passing through the above filters, then they must select their next highest ranked option instead.

These filters are used to model uptake of each zero-emission vehicle option under each of the five scenarios. These uptake profiles are used in our analysis.

The previous section set out the range of options that could contribute to decarbonisation of the surface transport sector. Achieving near-zero emissions across the sector will require contributions from all of these. In this section, we set out the combination of measures and their impacts that we assume in our scenarios for the Sixth Carbon Budget advice.

a) Abatement scenarios

Each of our scenarios is based on a combination of measures that will enable the surface transport sector to reach close to zero emissions by 2050, which will be critical in enabling the UK to deliver Net Zero.

i) Expectations for emissions without abatement action

Our analysis compares emissions under our decarbonisation scenarios against a baseline scenario, which represents the growth in emissions that we would expect to see if no action to reduce emissions were taken.

Our baseline scenario assumes that car demand continues to grow in line with population and GDP.

For road transport, we use DfT's National Transport Model (NTM), which generates forecasts of the total number of vehicle-kilometres and emissions that would be expected in the absence of abatement policy or action. For rail, we base our analysis on the Rail Delivery Group's forecasts of the number of passenger trains operating out to 2047[54] and the National Infrastructure Commission's expectations for freight demand out to 2050.[90] In both cases, we then assume no additional electrification or efficiency improvements. These assumptions lead to an 11% increase in road vehicle-kilometres and a 24% increase in train-kilometres by 2035, and result in a 13% increase in the sector's emissions to 128 $MtCO_2e$ by 2035.

ii) The Balanced Net Zero Pathway

The Balanced Net Zero Pathway represents our central scenario for how the transport sector will need to evolve towards delivery of Net Zero by 2050:

In the Balanced Pathway, sales of new petrol and diesel cars and vans are phased out by 2032.

- **ZEV uptake.** BEVs make up the majority of new car and van sales by 2030, while HDV sales of a mixture of BEVs and hydrogen vehicles ramp up during the 2030s.
    - We assume that sales of new petrol and diesel cars and vans are phased out by 2032. BEV ranges increase as shown in Table 2.2, while battery cost reduces from around £121/kWh today to £48/kWh by 2030 and £44/kWh by 2040 (see Box 2.5). As a result, BEVs make up 48% of all new sales in 2025, 97% in 2030 and 100% from 2032 onwards.
    - PHEV sales increase in the short term, reaching 25% in 2025, before falling to near zero by 2030.

- Commercial-scale zero-emission HDV trials take place from the early-2020s. Infrastructure development continues for the most cost-effective solutions, assumed to be batteries and hydrogen initially. Government subsidies ensure TCO parity between zero-emission and diesel options in 2035. As a result, BEVs make up 12% of new HGV sales and 25% of new bus sales in 2030, rising to 51% and 44% in 2040. Hydrogen fuel-cell vehicles make up 7% of new HGV sales and 44% of new bus sales in 2030, and 48% and 55% in 2040.*

- **Efficiency and biofuels.** New conventional vehicles become more fuel efficient. Biofuels have a role in reducing emissions from remaining petrol and diesel vehicles during the transition to ZEVs.
  - The carbon intensity of new conventional vehicles improves as in Table 2.1. HGVs realise operator efficiency savings, ranging from 13% for small rigid trucks to 22% for large articulated vehicles. Uptake of these measures reaches 80% of HGVs from 2025.
  - Following the introduction of E10 in 2021, biofuels makeup around 7% (by energy) of the conventional fuel used by cars and vans.
  - Among HDVs, the proportion of biofuels in the diesel consumed rises from 4% in 2030 to 12% by 2040.

Overall, we expect that 6% of baseline car demand can be avoided or switched to other modes by 2030, rising to 17% by 2050.

- **Demand reduction.** Demand for car travel is reduced by a combination of societal and technological changes reducing the need for travel and modal shift. Logistics and operational improvements reduce HGV demand.
  - Average car-kilometres decrease† by 6% by 2030, and this demand reduction increases gradually to 17% by 2050. Demand reduction for vans is lower, reaching 3% from 2030 onwards. Improved speed limit enforcement gives efficiency savings of 2% from 2025.
  - Factors including improved logistics mean that demand reductions for HGVs increase gradually to 10% for rigid HGVs and 11% for articulated HGVs by 2030, remaining at these levels thereafter.

- **Rail.** Electrification of the network continues steadily, including of key freight corridors. Battery-electric, hydrogen and hybrid trains are also introduced.
  - Total passenger rail traffic and total rail freight hauled grow linearly to 58% and 9% above today's levels by 2050, respectively.
  - The rail network is steadily electrified at a rate of 200 km/year. This takes the electrified proportion of the network to 55% by 2050.
  - All diesel trains are removed from category A passenger routes by 2035 and from all passenger routes by 2040. By 2040, most new passenger trains are electric (68%) or battery-electric (26%), with smaller roles for diesel-electric and hydrogen.

* These uptake percentages are similar to those shown in Table 2.4, but there is assumed to be no ERS provision, so those sales instead have to choose between battery-electric, hydrogen and diesel.

† Note that these reductions are relative to a baseline in which car ownership, and hence total car-kilometres, are assumed to be increasing. Overall vehicle-kilometres are expected to grow by 5% by 2030 and by 15% by 2050.

- Some diesel freight trains remain out to 2050, but the proportion drops from 87% today to 12% by 2050. In 2030, 84% of new freight trains are diesel-electric, but by 2050 almost half are pure electric.
- The efficiency of diesel trains improves linearly from 0.8 $kgCO_2/kWh$ today to 0.5 $kgCO_2/kWh$ by 2050.

The Balanced Net Zero Pathway delivers a reduction in surface transport emissions of over 70% by 2035, and 100%

Overall, these measures reduce surface transport emissions from 128 $MtCO_2e$ in the baseline to 32 $MtCO_2e$ in 2035 and 0.9 $MtCO_2e$ in 2050 and are cost-effective (Table 2.5; see also Figure 3.1.g in the Advice Report).

- The largest portion of this abatement is due to uptake of ZEVs (69 $MtCO_2e$).
- Other contributions come from demand-side measures in road transport (18 $MtCO_2e$), better efficiency of new conventional vehicles (5 $MtCO_2e$), uptake of PHEVs (2 $MtCO_2e$) and rail decarbonisation (2 $MtCO_2e$).

Table 2.5
Abatement costs for key surface transport sectors in 2035 in £/tCO_2e

	Average abatement cost across fleet	Marginal abatement costs for a new measure	
		Efficiency improvements to a new conventional vehicle	New electric vehicle (BEV in the case of road vehicles)
Cars	-10	Not on sale	-56
Vans	-34	Not on sale	-48
HGVs	106	-40	110
Buses	89	-78	-14
Motorcycles	384	51	331
Passenger rail	-1,690	-1,020	-2,880
Freight rail	288	-1,020	210

iii) Exploratory scenarios

Our exploratory scenarios explore alternative pathways by which the UK's Net Zero commitment can be achieved.* This section discusses the main differences between these scenarios and the Balanced Pathway.

In Headwinds, emissions reductions are lower due to slower zero-emission vehicle uptake and higher demand.

Headwinds. Remaining emissions in 2035 are higher at 38 $MtCO_2e$, compared with 32 $MtCO_2e$ in the Balanced Pathway. This is primarily due to slower uptake of ZEVs and lower levels of behavioural change.

- Sales of new petrol and diesel cars and vans continue to be allowed until 2035 and barriers to EV acceptance take longer to overcome. Therefore, BEVs make up only 24% of new car sales in 2025 and only begin to rise steeply towards the end of the 2020s.
- Battery technology does not become suitable for HDV use, and instead there is large-scale use of hydrogen in HDVs. Fewer low-carbon options mean diesel retains a higher proportion of HGV sales in 2030 (86%), and the transition occurs at higher cost.
- Slower transition to ZEVs means that total biofuel consumption is 26% higher in 2035 than in the Balanced Pathway.
- HGV uptake of operator efficiency measures is lower at 50%.

* To this end, each scenario delivers a very low level of emissions from the surface transport sector in 2050, ranging from a minimum of 0.6 $MtCO_2e$ in Tailwinds to a maximum of 1.4 $MtCO_2e$ in Widespread Engagement. Emissions in 2050 under the Balanced Pathway are 0.9 $MtCO_2e$.

- Car demand falls to only 12% below baseline levels by 2050.

Widespread Engagement demonstrates that enhanced behavioural change, through higher demand reduction and quicker electric vehicle uptake, can deliver deeper emissions reductions.

Widespread Engagement. Decarbonisation of the transport sector occurs more rapidly due to high levels of consumer engagement, which delivers higher demand reduction and quicker EV uptake. Emissions fall to 29 $MtCO_2e$ by 2035.

- Consumer biases against EVs are 30% lower, leading to faster uptake and sales of new petrol and diesel cars and vans end in 2030. 55% of all new cars sold in 2025 are BEVs.
- There is significant investment in a large-scale ERS network for HDVs, instead of investment in ultra-rapid public charging infrastructure. The maturity of this technology allows diesel sales to begin falling slightly faster than in any other scenario, but most HDVs (particularly small rigid HGVs) continue to choose BEVs, even with only depot-charging available. 14% of sales in 2040 are for ERS vehicles.
- Demand reduction among car users is at the upper end of what is possible, reaching 16% by 2030 and 34% by 2050. Speed limit reductions increase further efficiency gains to 7% from 2025.
- This demand reduction is partly accounted for by increased modal shift to rail, with passenger and freight demand 17% and 11% higher than in the Balanced Pathway. Rates of rail electrification are also higher, resulting in 60% of the railway being electrified by 2050 and allowing more electric passenger trains to be introduced. For freight, the need to travel across a wider portion of the network leads to more diesel-electrics being used.

If battery technology advances more rapidly, then electric vehicles could become cost-saving sooner, leading to quicker uptake. This is explored in Widespread Innovation.

Widespread Innovation. Battery technology improves rapidly, leading to more affordable BEVs which are adopted more quickly. CAV usage leads to increased demand, resulting in emissions of 35 $MtCO_2e$ in 2035.

- Sales of new petrol and diesel cars and vans end in 2030, while battery costs fall to £42/kWh, allowing typical BEV prices to be almost £200 lower and ranges to reach 400 km by 2030. This leads to faster EV uptake, with BEVs making up 56% of all new car sales in 2025.
- Battery innovation also enables BEVs to become more suitable for a variety of HDV operations more quickly. Therefore, infrastructure to support BEVs is the only area of investment to support HDV ZEV uptake. BEVs still take time to become suitable for the longest-range operations, so diesel vehicles still comprise 8% of new HDV sales by 2040. By 2045, however, BEVs (either charging only in-depot or using ultra-rapid public chargers) are suitable for all HDV operations.
- The introduction of CAVs largely offsets demand reduction in passenger vehicles until the mid-2030s, before leading to growth in overall demand by up to 5% by 2050.
- Advanced biofuels are developed exclusively for other sectors, so total biofuel use is 29% lower in 2035 than in the Balanced Pathway.
- Diesel train efficiency improves to 0.45 $kgCO_2/kWh$. Improved capability of battery-electric options means that the number of diesel-electric passenger trains operating in 2050 is 33% lower than in the Balanced Pathway. Further, two-thirds of all new freight trains are electric from the mid-2030s.

Tailwinds showcases how quickly transport emissions could be reduced within ambitious technological and societal contexts.

Tailwinds. Rapid technological development combined with widespread consumer engagement leads to swift adoption of EVs plus substantial reduction in demand. This results in emissions of 28 $MtCO_2e$ in 2035.

- For cars and vans, battery technology and EV uptake develop as in the Widespread Innovation scenario.
- Deployment of a range of HDV decarbonisation infrastructure occurs at an accelerated pace, supported by significant technological and market development. This leads to a ramp-up in supply and faster uptake of ZEVs. ZEVs comprise 96% of all new HDV sales by 2035, and diesel vehicles are removed from sale by 2040.
- 100% of HGV fleets adopt operator efficiency measures.
- Demand reduction is as in the Widespread Engagement scenario.
- Rail developments are as in the Widespread Innovation scenario.

b) Devolved administrations

The above scenarios cover surface transport emissions across the whole of the UK, but differences across Scotland, Wales or Northern Ireland could materially affect how the pathway is delivered. In some areas of our modelling, we have been able to give explicit consideration to each administration. The resulting decarbonisation pathways for surface transport in each devolved administration are similar:

- Our modelling of road transportation is calibrated against DfT's National Transport Model. This includes separate forecasts of travel demand and traffic growth for Scotland and Wales, but our analysis does not explicitly take account of differences in geography or journey types. For Northern Ireland, we assume that these totals grow in line with 4% of the Great Britain totals, based on historic vehicle-kilometres data.
- Our analysis assumes that infrastructure deployment and ZEV uptake in each nation are proportional to distance travelled and does not factor in any differences between nations in these factors. We will continue to monitor policy, deployment and uptake to understand if there are any geography-specific factors which should be accounted for.
- For rail, our analysis is conducted at a UK-wide level and then scaled by the proportion of track-kilometres in each nation. Again, we will continue to monitor for any geography-specific factors that should be considered.

c) Risks and uncertainties

The scenarios we set out illustrate the different choices and possible future contexts and the impacts that these could have on the decarbonisation pathway. We have also considered key uncertainties on car ownership, battery prices and fossil fuel prices, as well as the impact of COVID-19 on transport demand and consumer preferences (Box 2.8).

If car ownership growth can be avoided, then fewer electric vehicles will be needed and the transition will be achieved at lower cost.

Car ownership. Our baseline travel demand assumptions in the absence of climate policy are based on DfT's National Transport Model, which is largely driven by GDP and population growth. In the baseline, car ownership and demand grow by 19% to 2050. If car ownership (and demand) do not continue to increase, then overall emissions and the capital costs of the transition will be lower.

- All of our scenarios assume that car ownership continues to grow in line with population and GDP to 38 million by 2035 and that demand reduction is realised through a fall in kilometres driven by each car.
- If, instead, demand reduction were met through a reduction in the rate of car ownership (for instance through greater reliance on car-sharing and public transport), then the total number of cars by 2035 would be almost 4 million lower than this, and there would be correspondingly fewer EVs (Table 2.6).
- In this case, the capital cost of the transition would fall by £17 billion over the period to 2050, as fewer EVs need to be purchased.

Table 2.6
Number of battery-electric cars under three car ownership growth scenarios, in millions

Car ownership	2030	2035	2040
Increasing with population/GDP to 38m in 2035 (Balanced Pathway)	13	25	35
Central demand reduction through lower car ownership – growth to 35m in 2035	12	22	31
Higher demand reduction through lower car ownership – decline to 31m in 2035	11	20	26

- If it were possible to reduce both car ownership and kilometres per car, then total emissions over the five years of the Sixth Carbon Budget period would be 8 $MtCO_2e$ lower than in our Balanced Pathway. There are opportunities to deliver further emissions reduction, or to balance any barriers to EV uptake, through schemes to reduce car ownership.

Higher battery prices could inhibit electric vehicle uptake through higher prices. Nonetheless, they will still deliver cost savings by 2030.

Battery prices. If battery prices do not continue to decrease at the rate shown in Figure B2.5, then EV prices will remain higher for a longer period of time. EV uptake will be slower and emissions higher.

- If further reductions in battery prices from today are 25% below what is expected (see Box 2.5), then the upfront cost of a typical BEV in 2030 will be 6% higher than in our Balanced Pathway.
- A typical BEV would then begin to offer the purchaser cost savings – on a TCO basis – from 2027, which is 2 years later than in our Balanced Pathway.
- The ramp-up of BEV sales would be correspondingly slower, resulting in 570,000 fewer BEV cars and vans being sold by 2030. The resulting emissions would be almost 3 $MtCO_2e$ higher than in our Balanced Pathway over the Sixth Carbon Budget period.
- If there were no phase-out of conventional vehicles, then petrol and diesel cars would continue to make up a substantial portion of sales out to 2038.
- Battery development for HDVs is less certain. In the event that prices remain higher than expected, HDVs would likely see greater uptake of hydrogen, while larger subsidies may be required to incentivise BEV uptake.

Lower fossil fuel prices would also delay electric vehicle uptake. In addition, they could increase the mileage driven by conventional vehicles.

Fuel prices. If fossil fuel prices are lower than expected, then the operational cost benefits of BEVs will be reduced and so the financial incentive to adopt them will fall. This will lead to slower uptake and higher emissions.

- The lower cost of running a BEV than an ICE is a key factor in achieving TCO savings by the mid-2020s, and thereby in driving the wide uptake of BEVs.

- Similar to higher battery prices, this would lead to slower EV uptake. If the long-run variable costs of petrol and diesel follow their low forecasts, then retail fuel costs by 2030 would be around 10% lower than in our Balanced Pathway. This would reduce the lifetime cash fuel saving offered by a BEV purchased in 2030 by £1,000, potentially leading to 150,000 fewer BEV car and van purchases by 2030. In addition, cheaper fuel could lead to increased mileage among remaining conventional vehicles.
- Together, these impacts could lead to 3 $MtCO_2e$ higher emissions during the Sixth Carbon Budget period.
- For HGV fleets, lower diesel prices would further delay the point at which TCO parity is reached across all zero-emission options, increasing the level of subsidy that will be required during the 2030s to ensure timely switchover.

Through our exploratory scenarios and the above sensitivity tests, we have shown that our analysis is robust to a variety of alternative societal and technological contexts. However, while our scenarios attempt to capture the potential influence of a broad range of potential societal and technological developments, it remains possible that there could be unforeseen occurrences that cause demand and/or travel behaviour to change beyond the ranges considered within our scenarios.

This could include, for example, the advent of a new disruptive technology within the transport sector, whose impact goes beyond what we have considered in our Widespread Innovation scenario. In that case, Government would need to consider how best to make use of this new technology so as to deliver effective emissions reductions in parallel with enabling society to realise its wider benefits.

Box 2.8

Impact of COVID-19 on surface transport

The impact of COVID-19 has been felt across the transport sector, with an initial drop in both car and HGV usage followed by a slow recovery as lockdown restrictions eased. However, public transport continues to be affected with usage today at around a third of its pre-pandemic levels:

- In the immediate weeks following national lockdown, car usage was between 30-40% of pre-pandemic levels.[91] During that same period, HGV usage was between 60-75% of pre-pandemic levels, perhaps because of the increase in online food deliveries.[92]
- From May onwards, car usage began to gradually increase and in October reached 80-94% of pre-pandemic levels. By September, HGV usage surpassed pre-pandemic levels by between 2-25%. Total vehicle usage in September remained slightly lower than pre-pandemic levels, at around 85-97% on weekdays but 87-107% at weekends.
- National Rail use dropped to around 4-7% of pre-pandemic levels from March to May, with a gradual increase, from June, to around 40% in September. This demonstrates that public transport has not seen the same recovery that private transport has.
- Pre-pandemic demand for London buses and the London Underground were 6 million and 4 million journeys per day, respectively.[93] During lockdown, these figures fell to approximately 1.3 million bus journeys and 400,000 underground journeys per day. Following the easing of restrictions, the demand for public transport increased, but not to pre-pandemic levels. During September, at peak travel demand, there were approximately 3.8 million bus journeys and 1.5 million underground journeys per day.
- Cycling also increased significantly following the imposition of lockdown restrictions, with summer weekends seeing over three-times as many cyclists as pre-pandemic levels. Since the easing of lockdown restrictions, cycling levels have remained high. However, from late September onwards, although still mostly above pre-pandemic levels, the number of cyclists started to decrease.

The impacts of COVID-19 appear to be longer-lasting for public transport than for private transport. Our analysis assumes that this balance reverts to pre-pandemic levels, although we have considered the impact of alternative demand profiles through our exploratory scenarios. Government support and effective communications are likely to be required to support this recovery.

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Chapter 3

Buildings

Introduction and key messages

This chapter sets out the method for the buildings sector Sixth Carbon Budget pathways.

The scenario results of our costed pathways are set out in the accompanying Advice report. Policy implications are set out in the accompanying Policy report.

For ease, these sections covering pathways, method and policy advice for the Buildings sector are collated in The Sixth Carbon Budget - Buildings.

A full dataset including key charts is also available alongside this document.

The key messages are:

- **Background**. Direct greenhouse gas (GHG) emissions from buildings were 87 Mt CO_2e in 2019, accounting for 17% of UK GHG emissions. These emissions are mainly the result of burning fossil fuels for heating. Emissions from electricity use – known as indirect emissions – are caused primarily by the use of lighting and appliances, and are also covered in our assessment of the electricity sector.* Buildings emissions are primarily CO_2, with 1.4 Mt of methane and 0.8 Mt CO2e of emissions from fuel combustion processes and nitrous oxide in hospitals.
- **Options for reducing emissions**. Options for reducing emissions include: behavioural change, which can drive down or alter patterns in the consumption of energy; energy efficiency measures, which save energy; and fuel-switching away from fossil fuels to low-carbon alternatives.
- **Analytical approach**. Our starting point for this analysis has been the 2019 Net Zero report, which showed that the Net Zero target means eliminating buildings emissions by 2050. We have used bottom-up analysis to produce a set of pathways to deliver this, and use scenarios to explore a range of different futures. We include new evidence on: technical and economic potential for measures; the costs and savings associated with behaviour change, efficiency measures and low-carbon heat; as well incorporating updated evidence on deployment constraints and delivery feasibility.
- **Uncertainty.** We have used the scenario framework to test the impacts of uncertainties, and to inform our Balanced Net Zero Pathway. The key areas of uncertainty we test relate to: energy costs; behaviour change; energy efficiency uptake, costs and savings; heat supply; heat technology costs, lifetimes, sizing and efficiency; and the pace of action.

We set out our analysis in the following sections:

1. Current and historical emissions in buildings
2. Options to reduce emissions in buildings
3. Approach to analysis for the Sixth Carbon Budget

* We consider these emissions from an energy demand perspective in this chapter.

1. Current and historical emissions in buildings

Buildings emissions mainly stem from burning fossil fuels for heating.

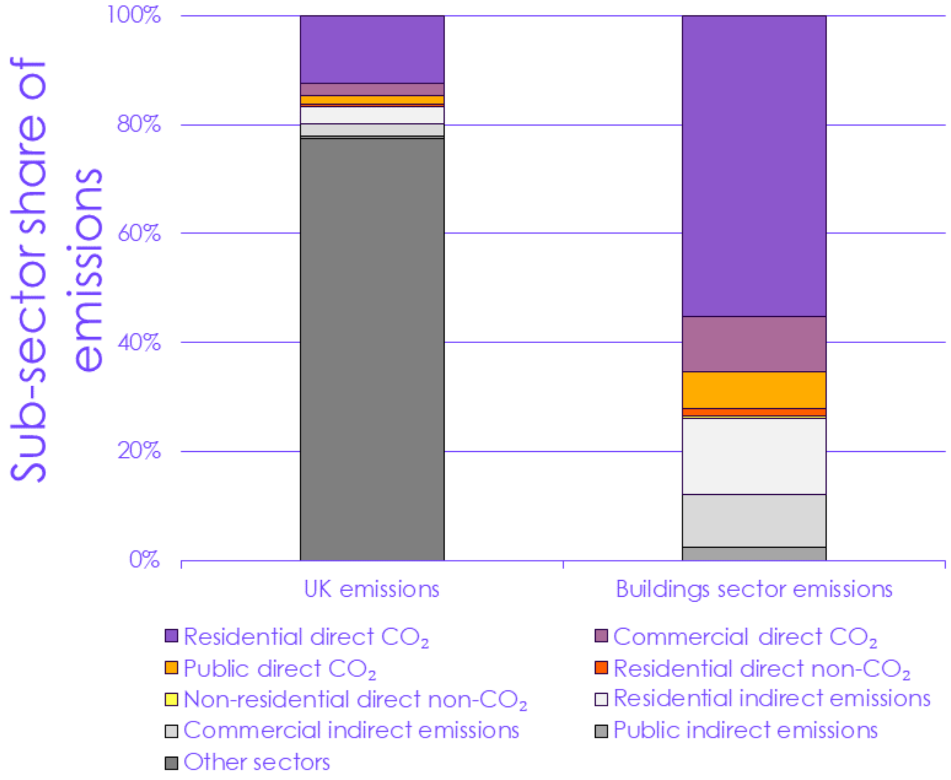
Direct greenhouse gas emissions from buildings were 87 $MtCO_2e$ in 2019, around 17% of the UK total.[1] Including indirect emissions, buildings account for 23% of the UK total (Figure 3.1):[2]

- **Direct building CO_2 emissions.** These were 85 $MtCO_2$ in 2019, split between homes (77%), commercial buildings (14%) and public buildings (9%).[3] Direct emissions in buildings result primarily from the use of fossil fuels for heating. Around 74% of the UK's heating and hot water demand in buildings is met by natural gas, and 10% by petroleum,[*] with smaller amounts of other fuels such as coal and biomass.[4]
- **Indirect building emissions**. Buildings are responsible for 59% of UK electricity consumption,[†] equivalent to a further 31 $MtCO_2e$ of indirect emissions.[5] Most electricity use (counted as indirect emissions) stems from appliances and lighting in homes, and cooling, catering and ICT equipment in non-residential buildings.
- **Non-CO_2**. Around 1.4 $MtCO_2e$ of methane and 0.8 $MtCO_2e$ of nitrous oxide emissions were associated with buildings in 2019.[6] The use of nitrous oxide as an anaesthetic accounts for just under 0.6 $MtCO_2e$ of these emissions. Other non-CO_2 emissions are produced by fuel combustion processes.

[*] Includes heating oil and LPG.

[†] Including a proportional share of intermediate consumption in the power sector.

Figure 3.1 Breakdown of buildings sector GHG emissions (2019)



Source: National Atmospheric Emissions Inventory (2020) *Breakdown of UK GHG emissions by source and greenhouse gas*; BEIS (2020) *DUKES, Electricity: commodity balances (DUKES 5.1)*.

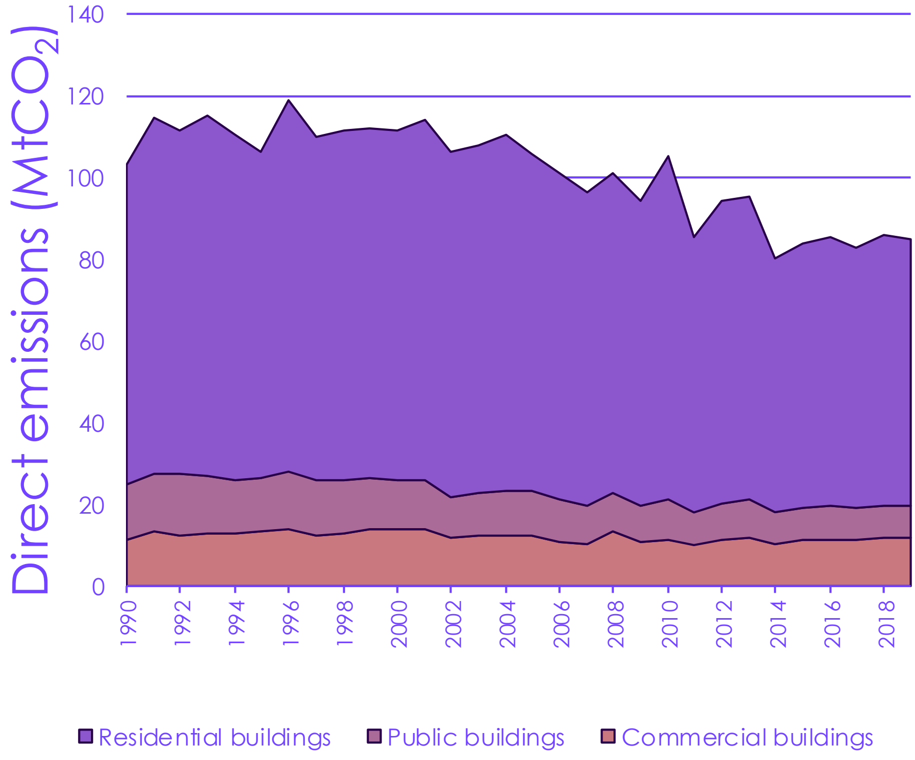
a) Trends and drivers

Direct emissions from buildings fell by 19% from 1990 to 2015 and have remained at a similar level since.

Direct emissions from buildings fell by 19% from 1990 to 2015 and (on a temperature adjusted basis) have remained at a similar level since then. Falls in emissions largely reflect energy efficiency improvements in buildings. Demand for gas and electricity has fallen by 16% and 14% since 2005 (Figure 3.2).[7,8] This means that despite energy price rises, household energy bills in 2016 were, on average, £115 cheaper (in real terms) than when the Climate Change Act was introduced in 2008.[9]

Indirect emissions from buildings have been falling at an average rate of 10% per year since 2009, due to both reductions in demand and the decarbonisation of electricity generation.[10]

Figure 3.2 Direct CO_2 emissions from the buildings sector since 1990



Source: National Atmospheric Emissions Inventory (2020) *Breakdown of UK GHG emissions by source and greenhouse gas.*

Opportunities to reduce emissions exist in four main areas: behaviour change, fabric energy efficiency, energy efficiency of lighting and appliances and switching away from fossil-fuel based heat.

In the buildings sector, there are opportunities for emission reductions in four main areas: behaviour change, increasing the energy efficiency of the building stock, improving the energy efficiency of lighting and electrical appliances, and switching away from fossil-fuel based heat.

In general, switching to efficient electric systems now delivers the largest readily available savings. These savings will grow steadily as the power sector continues to rapidly decarbonise.

a) Behaviour change

i) Residential buildings

There is significant potential to deliver emissions savings, just by changing the way we use our homes. Our Balanced Pathway for residential buildings finds that behaviour change can deliver operational cost savings in the region of £0.4 billion a year by 2050 (Box 3.1) and greater savings may well be possible.

Where homes are sufficiently well insulated, it is possible to pre-heat ahead of peak times, enabling access to cheaper tariffs which reflect the reduced costs associated with running networks and producing power during off-peak times. This means that pre-heating in particular can play an important role when switching to smart, flexible electric heating such as heat pumps with smart controls. If all homes with heat pumps pre-heated their homes, it would save an estimated £2 billion a year in a highly electrified scenario.[*]

Our analysis includes new evidence on pre-heating homes, smart heating management, hot water use and new business models such as heat-as-a-service propositions.

Box 3.1
Behaviour change evidence and assumptions in homes

There is a range of steps we can take to reduce and manage energy use in our homes, saving on both emissions and bills. We examine the following range of measures across our scenarios:

- **Turning off lights**: We assume that turning off lights when not in use can deliver annual electricity savings of 0.4 TWh by 2035. However this is dwarfed by the 5.4 TWh saved by deploying more energy efficient lighting in our scenarios relative to today.
- **Pre-heating**: Where homes are sufficiently well insulated, it is possible to pre-heat ahead of peak times. This enables access to cheaper tariffs which reflect the reduced costs associated with producing power off-peak and reducing requirements for network reinforcement to manage peak loads. Our scenarios assume that all new homes and between 25-50% of post-1952 homes can pre-heat, shifting their space heating consumption up to 4 hours ahead of peak and enabling access to cheaper energy prices as a result.[11]
- **Smarter heating management and use**: We assume a 3-6% reduction in heat demand can be achieved through more informed and smarter management of heating in existing homes. Smart meters and real time displays have been found to result in energy savings of around 3%, driven by associated actions such as turning the thermostat down or reducing the amount of time the heating is on.[12]

[*] CCC analysis drawing on Imperial (2018) *Analysis of alternative heat decarbonisation pathways* and based on the electrification scenario. We have made a conservative assumption in our Balanced Pathway and only assume that 25% of eligible existing homes (post-1952 homes) pre-heat. The number of homes with potential to pre-heat would be expected to be higher after insulation is applied.

- There is evidence that multizone control can drive higher savings – we make a conservative assumption that 6% heat demand savings can be realised through multizone control on the basis of analysis undertaken by the Energy System Catapult.*[13] However, there is evidence to suggest the savings could be much higher.†,[14] Public Health England recommend that homes should be heated to a minimum temperature of 18°C, with Age UK recommending the main living space in a home is heated to 21°C.[15]
- **Low-flow shower heads**: We assume widespread use of low flow shower heads across our scenarios, delivering a 5% reduction in heat demand.[16] These are also an important adaptation measure to prepare for the impacts of climate change, which will increase water stress in the UK.
- **Hot water temperature**: For the majority of our scenarios we assume a constant 60°C hot water temperature in existing homes. In our Widespread Engagement scenario, we assume a 50°C water temperature in homes with heat pumps, with allowance for a daily legionella cycle of one-hour duration. The Health and Safety Executive is currently undertaking work with the Chartered Institution of Building Services Engineers to look at guidance for low-temperature systems to manage legionella risk.
- **Water softening**: Build-up of limescale in a home's central heating system due to hard water can reduce the efficiency of heating systems. We therefore include measures for water softening in our scenarios.[17]
- **Heat as a service**: The Energy Systems Catapult has published evidence suggesting that guarantees around comfort levels and costs of heating could increase the consumer acceptability of low-carbon heat.[18] 'Heat as a service' delivery models can provide this, and involve consumers purchasing service bundles or 'outcomes' from providers (such as a certain number of warm hours) in place of kWhs of fuel. In our Widespread Innovation and Tailwinds scenarios, we assume that the heat-as-a-service delivery model proliferates in existing homes. Based on engagement with a range of stakeholders, we assume that this delivery model can be associated with 3% financial savings[19] and a 15% increase in heat pump efficiency resulting from better installation and operation. We also assume that it is associated with a 7.5% commercial cost of capital and a 5% increase in energy consumption (reflecting losses associated with shifting time of use).[20]

Source: CCC analysis; Element Energy for the CCC (2020) Development of trajectories for residential heat decarbonisation to inform the Sixth Carbon Budget.

ii) Public and commercial buildings

Evidence for both behaviour change and energy efficiency potential for non-residential buildings has been drawn from the Building Energy Efficiency Survey (BEES).[21] These two categories of measures have not explicitly been separated in our analysis. BEES includes a number of measures with a strong behavioural aspect, for example, improved energy management, awareness campaigns and training and procurement practices.

* The majority of UK homes rely on a single room thermostat, located in a hall or living room, to control the temperature in the home. This often overrides local control by thermostatic radiator valves, causing underheating or over-heating. Multi-zone control uses digital wireless technology to enable temperature to be controlled using a thermostat and managed radiator control in each individual room, facilitating improved temperature management.

† Research by the Energy Systems Catapult suggests gas usage reductions of up to 20% are possible, and research by Loughborough University suggests an aggregate saving of around 12% for the UK.

b) Efficiency

i) Residential buildings

Our scenarios examine the role a wide range of energy efficiency measures can play in reducing energy use in homes. We look at the potential for savings resulting from improving the efficiency of lighting in homes, and from the purchase of more efficient appliances.

For fabric energy efficiency in new homes, our scenarios build on the recommendations made by the CCC in our 2019 report *UK housing: Fit for the future?*, and assume ultra-high standards of energy efficiency in new homes from 2025 at the latest, delivered through measures such as triple glazing and high levels of airtightness.[22] We note that Government has signalled that they will bring forward the date of introduction to 2023, in line with our advice.[23]

For existing homes, we deploy measures such as loft, floor and wall insulation across our scenarios, as well as modelling low cost measures such as draught proofing and hot water tank insulation. Our Sixth Carbon Budget analysis is based on a comprehensive update of evidence, to underpin our modelling of energy efficiency retrofits (Box 3.2). This starts with the real-world performance of measures in homes, adjusted to reflect some closure of the performance gap.[*] Previously, our Fifth Carbon Budget analysis was based primarily on a modelled assessment of performance, with adjustment factors applied.[24]

Measures to address thermal efficiency, overheating, indoor air quality and moisture must be considered together when retrofitting or building new homes. We therefore also examine illustrative cost ranges for shading and ventilation measures in addition to our scenarios. See Chapter 3 of our Advice Report for further discussion.

[*] Regulations and monitoring metrics are focussed substantially on the modelled performance of dwellings as designed, rather than their actual performance 'as-built'. There is a large body of evidence which points to a substantial gap between the two. This is the 'performance gap'.

We also draw on new evidence of the technical potential, costs and performance of efficiency measures in the home. This is based on the National Energy Efficiency Database which looks at the impact of measures which have been installed to date.

Box 3.2
New evidence on fabric energy efficiency in existing homes

We have updated our energy efficiency assumptions in four key areas, relative to our previous work: technical potential, range of measures, costs, and savings. Our updated assumptions around costs and savings draw on a comprehensive assessment of the latest available evidence, undertaken by University College London.[25]

- **Technical and economic potential**: We have updated our assessment of the technical and economic potential for fabric energy efficiency measures in the UK housing stock, based on the latest Government statistical releases, data from housing surveys, and research on the prevalence of non-standard cavity walls and lofts.[*,26] Despite some progress having been made in insulation installations, the assessment has led to an overall increase in the assumed technical potential for lofts and cavities relative to the Fifth Carbon Budget. Amongst other changes, the latest assessment reflects new evidence from the National House Building Council that 72% of homes built from 1991-1995 were built with unfilled cavity walls (previously assumed to be insulated).[27] While technical potential for cavities and lofts has increased, our assessment of economic potential has remained broadly similar (Table B3.2). Our assessment of economic potential is informed by new evidence on the prevalence and cost of treating non-standard cavity walls and lofts.
- **Range of measures**: We have updated the range of energy efficiency measures modelled relative to our work for the Fifth Carbon Budget and Net Zero report. Key changes include the incorporation of new and emerging evidence on the costs and performance of thin internal wall insulation, and a first step in modelling deep whole house retrofits.[28]

We have also separately modelled ranges of costs which could be associated with delivering ventilation and overheating measures to accompany our scenarios, necessary as part of a holistic approach to retrofit (Box 3.2.a, Sixth Carbon Budget Advice Report).

- **Energy savings associated with measures**: UCL's assumptions for the savings associated with measures are drawn primarily from the Government's National Energy Efficiency Data (NEED) Framework.[29] The data framework matches gas and electricity annualised meter data, with data on energy efficiency measures installed in homes from the Homes Energy Efficiency Database (HEED), Green Deal, the Energy Company Obligation (ECO) and the Feed-in Tariff scheme. The results are then weighted to produce statistics representative of the whole housing stock. While real world performance data are expected to improve the accuracy of modelling, they are representative of past and current practice and therefore have the potential to underestimate the future performance of measures where improvements are delivered in installation practices and use. Our scenarios are predicated on best-practice delivery and we therefore assume some uplifts to savings associated with closing the performance gap, modelled as uplifts based on in-use factors.[30]
- **Costs associated with measures**: UCL's cost assumptions draw on the latest available evidence, including the 'What does it cost to retrofit homes?' research undertaken by Cambridge Architectural Research for BEIS, and research from the Energy Savings Trust on the costs of insulating non-standard cavities and lofts.[31] This has been supplemented with evidence on supplementary costs such as scaffolding and survey and design, and by additional evidence from field trials, case study data and discussions with retrofit professionals (Table B3.2).

While assumptions draw on the best available evidence, there remains uncertainty over the costs and savings associated with measures. Importantly, energy efficiency must be viewed in the context of the substantial wider benefits which can be delivered (discussed further in Chapter 3 of the Sixth Carbon Budget Advice Report).

[*] Technical potential represents the number of measures which could technically be applied across the UK stock. Economic potential represents a subset, examining only those measures deemed to be deliverable at reasonable cost. We generally excluded measures from our economic potential where costs came in above £700/tCO_2e for a typical home (assumed to be a medium semi-detached home, scaffolding and design costs not included in calculations for economic potential). Some non-standard lofts and cavities were excluded on this basis and our economic potential includes only the following non-standard categories: standard lofts with access issues, cavity walls in concrete dwellings, cavity walls with conservatories, narrow cavities, and high cavity walls. Glazing is not modelled, apart from in deep retrofits, but current rates of upgrade would be assumed to continue.

These factors have led us to model a range of energy efficiency uptake levels across our scenarios.

Table B3.2
Energy efficiency assumptions for key measures in existing homes

	Technical potential (millions of homes)	Economic potential (millions of homes)	Costs for a semi-detached home (£)	% reduction in space heat demand for a semi-detached home
External wall insulation	7.4	7.4	8590	18%
Internal wall insulation			7320	15%
Cavity wall insulation (easy to treat)	5.9	3.1	630	10%
Cavity wall insulation (hard to treat)			2480	
Loft insulation (easy to treat)	13.3	10.8	440	4%
Loft insulation (hard to treat)			740	

Notes: Economic potential represents measures modelled. Costs are in £2019 and rounded to the nearest 10. Costs do not include scaffolding (assumed to be incurred for external wall insulation) or design and planning costs (assumed to be incurred for all solid wall insulation). We assume costs of £986 and £1352 respectively in a semi-detached home. NEED savings have been adjusted to be set against a space heat demand baseline (after accounting for behavioural measures, but before any performance gap adjustment) and will differ from published percentage savings in NEED (which are calculated against total gas demand). Loft savings are based on the average savings in NEED, representing a combination of virgin loft insulation and top-ups. For a semi-detached dwelling with loft insulation of <100mm, savings are assumed to be 7.6%, while for a dwelling with 100-199mm of existing insulation a top-up is assumed to deliver 1.9% savings.

Source: CCC analysis; UCL (2020) Analysis work to refine fabric energy efficiency assumptions for use in developing the Sixth Carbon Budget; Element Energy for the CCC (2020) Development of trajectories for residential heat decarbonisation to inform the Sixth Carbon Budget.

ii) Public and commercial buildings

Evidence for energy efficiency potential in public and commercial buildings is drawn from BEES. This includes measures such as improved fabric efficiency, upgrades to lighting and cooling equipment, controls and metering. Our analysis excludes abatement potential in BEES from industrial buildings (which fall outside the scope of this sector) and abatement potential associated with upgrading space heating plant which we consider may overlap with our analysis of heat decarbonisation. We also exclude some of the highest cost measures (see Box 3.6).

c) Low-carbon heat

i) Residential buildings

There is broad scope for variation in the overall heat mix, and in the precise mix of technologies deployed.

Analysis for our 2018 report *Hydrogen in a low-carbon economy* found that a range of pathways for heat decarbonisation, based on low-carbon hydrogen and/or electrification, have similar costs. On this basis we model a range of pathways for decarbonising heat, with the key objective being to develop a balanced emissions trajectory which can be met in different ways, but which drives sufficient progress in the next decade to keep options open.

There is broad scope for variation in the overall heat mix, and in the precise mix of technologies deployed. Our scenarios include illustrative mixes of a wide range of technologies, including low-carbon district heat networks (Box 3.4), air source heat pumps (ASHPs) and ground source heat pumps (GSHPs), resistive and storage heating, solar thermal, and hydrogen technologies including hydrogen boilers and hydrogen hybrid heat pumps. We also model thermal storage in homes.

Our assessment of the economy-wide best use of biomass indicates that use in buildings should be minimised as far as possible.[32] Some scenarios exclude a role for biofuels. Others include a limited role, restricted to use in hybrid configurations alongside heat pumps in the hardest-to-heat off-gas homes, such that biofuels provide a back-up role in meeting peak demands on the coldest winter days.[*]

Our analysis for homes makes use of the latest available evidence to inform techno-economic assumptions, tested with experts from industry and Government.

We have used the latest available evidence, and input from BEIS and a range of industry stakeholders, to update our assumptions on technology sizing, costs and lifetimes (Table 3.1). We have expanded the range of technologies modelled relative to our previous work. We have refined our modelling of ground source heat pumps and included a greater variety of hybrid heating configurations (including solar thermal). We have also tested the impacts of widespread deployment of high temperature heat pumps in our Widespread Innovation scenario. Finally, we have extended the analysis to improve our representation of differing levels of flexibility in homes.

Table 3.1
Heat technology assumptions used in our residential analysis for existing homes in 2020

	Efficiency	**Lifetime (years)**	**Fixed cost (£)**	**Variable cost (£)**	**Opex (£/year)**
Air source heat pumps*	300%	15	4,430	370	100
Ground source heat pumps*	326%	20	9,070	530	100
Hybrid heat pumps**					
With hydrogen	See respective components		5,940	370	160
With biofuels			6,370	370	220
Hydrogen boiler	80%	15	2,960	N/A	100
Biofuel boiler	84%	15	3,130	N/A	100
Electrification (storage heater)	100%	15	N/A	780	100
Gas boiler	87%	15	2,860	N/A	100
Oil boiler	84%	15	3,130	N/A	100

Notes: Costs are in £2019 and rounded to the nearest 10. Boiler costs presented for a 24kW boiler. * Heat pump efficiencies represent the combined SPF assumed for 2020 at 40°C flow temperature (the weighted average flow temperature for heat pumps in our Balanced Pathway). ** While both GSHP and ASHP hybrids were tested in the modelling, ASHP hybrids were found to be more cost effective and are therefore the variant we present here.

ii) Public and commercial buildings

Our Sixth Carbon Budget scenarios explore a range of decarbonisation routes for public and commercial buildings, with a varying balance between electrification

[*] Our scenarios include a simplified representation and use liquid biofuels in place of solid biomass on the basis that the former is expected to be more conducive to functioning in a hybrid heat pump configuration. Solid biomass combustion can also have negative air quality impacts relative to biofuels.

and hydrogen. We see low-carbon district heat networks providing a significant share of public and commercial heat demand and serving as key anchor loads for networks. This is equivalent to around 22% by 2035 and 42% by 2050 in the majority of our scenarios. Our analysis of district heating is based on a refresh of evidence commissioned for our Fifth Carbon Budget analysis (Box 3.4). Our Widespread Innovation scenario explores lower district heat deployment, with a higher share of building level technologies.

Our analysis of building level heat is based on an illustrative selection of technologies including air-to-air heat pumps, low temperature air-to-water heat pumps, resistive electric heating and hydrogen boilers. Our energy and cost analysis uses air source heat pumps as an illustrative example, but in practice a wider range of technologies is available and could represent a part of the mix, for example ground source heat pumps, high temperature air-to-water heat pumps, hybrid heat pumps with biofuels, or in some limited cases, biomass boilers making use of local biomass sources or biogenic wastes. As a principle however, we have not included biomass boilers as a replacement technology for public or commercial buildings over the Sixth Carbon Budget period, based on our view that biomass resources could be better used as part of engineered removals or in other sectors where alternatives are limited. This is a slightly different approach than in homes, where there is a greater need for hybrid-based solutions, based on stakeholder feedback.

Our assumptions on heat technology technical potential, efficiencies, lifetimes and costs are primarily drawn from new research commissioned by BEIS for non-residential buildings in England and Wales (Box 3.3). We apply the evidence drawn from this study to UK heat demand in our analysis. Assumptions on capacity and load factors are mainly drawn from our Fifth Carbon Budget analysis.

We have drawn on new evidence commissioned by BEIS on the performance, cost and technical suitability of heating options in public and commercial buildings.

Box 3.3

New evidence on Heating, Ventilation and Air Conditioning (HVAC) technologies in non-domestic buildings

This study was commissioned by BEIS to determine the potential across England and Wales to reduce carbon emissions by implementing low-carbon space heating, hot water, ventilation and cooling (HVAC) technologies in non-domestic buildings. The study provides an evidence base on the applicability and cost effectiveness of low-carbon heat measures.

This study is based on data gathered in BEES on HVAC systems currently in the stock. A framework for reinterpreting the BEES data and predicting the HVAC servicing arrangements for each building within the BEES dataset was developed; resulting in the records being categorised into a set of building 'archetypes' with common HVAC characteristics.

Information on low-carbon HVAC system costs and performance was gathered through a literature review (involving detailed review of 52 sources) and industry engagement (including supply chain interviews and eight sub-sector deep dive interviews) to validate the data collected and fill gaps. The evidence gathered was used in modelling to quantify the potential to save carbon emissions from switching to low-carbon HVAC technologies, mapping potential options to archetypes.

A validation process tested the findings with external experts, including engaging a panel of experts through a project approach review workshop and commissioning an industry expert for a detailed review of the modelling inputs and outputs.

Our assumptions on technical potential are taken from data drawn from the study. This indicates the heat demand that can be met by each potential technology for each BEES sub-sector, split by whether the existing heating system is deemed 'abated', 'wet' or 'dry'. We use the BEES sub-sectors to map the technical potential against our public/commercial split of demand.

Table B3.3 shows the efficiency, lifetime and cost assumptions we have used in our analysis which are predominately drawn from the evidence base generated in this study. The main exception is that we have used a 15-year lifetime for hydrogen boilers, rather than 12 years as indicated in this study, for consistency with gas boilers and our view on hydrogen boilers in our residential analysis.

Table B3.3
Heat technology assumptions used in our analysis

	Efficiency*	Lifetime (years)	Capex (£/kW)	Opex: excluding fuel (£/kW)
Air-to-air heat pump	283%	20	772	9.6
Air-to-water heat pump (low temperature)	283%	20	1,530	6.2
Hydrogen boiler	86%	15	414	6.0
Electrification (direct heat)	100%	15	206	3.0
Biomass boiler	78%	20	666	12.9
Gas boiler	86%	15	200	6.0
Oil boiler	86%	20	238	6.1

Notes: * In situ performance coefficient. Evidence was taken from provisional assumptions of the forth coming study. The cost base year is 2019. Opex includes routine maintenance, but not fuel which is accounted for separately. The capex figures stated are used for 2020 and reductions are applied to some technologies from this point (see Section 1.3.c). Our capex assumption for biomass boilers is drawn from the renewal costs provided within the HVAC study, rather than for new installations, since we only include it as a counterfactual technology and there is a large difference between new and renewal costs in this study.

Sources: CCC analysis; Verco for BEIS (forthcoming) Low carbon Heating, Ventilation and Air Conditioning (HVAC) technologies in non-domestic buildings.

Box 3.4
Low-carbon district heat

In 2015 we commissioned a consortium led by Element Energy, and including Frontier Economics and Imperial College London, to undertake detailed analysis of the cost-effective potential of low-carbon heat networks in the UK to 2050.[33]

The work included a review of district heating, thermal storage and district cooling, along with considering the transition over time to both low-carbon and low-temperature heat networks. Scenarios were developed for our Fifth Carbon Budget advice based on detailed spatial analysis of supply options, combined with spatial analysis of demand.

These scenarios have been refreshed for the purposes of the Sixth Carbon Budget:

- We have updated the supply mixes to ensure they are Net Zero compatible. For the majority of scenarios, we model a fully electrified heat supply mix dominated by water- and sewage-source heat pumps and waste heat from industrial sources. Recent examples of large-scale heat pump solutions include London, Glasgow and the whole town of Drammen in Norway.[34] For our Headwinds scenario, we model an electrified supply mix which retains gas peaking capacity – transitioning to hydrogen over time.
- The majority of current district heat networks use gas Combined Heat and Power (CHP) to generate heat. These heat networks are expected to transition to low-carbon heat sources over time. Our deployment, energy and emissions scenarios take a simplified approach of modelling district heat deployment only at the point at which it becomes low-carbon. Heat network deployment in our scenarios is therefore more limited in early years than is expected in reality, with additional deployment being seen in later years to represent the point at which legacy CHP schemes convert to low carbon sources.
- For the purposes of calculating investment costs over time, we reapportion some network capex to reflect better the fact that a proportion of heat networks are expected to be built with gas CHP in the near-term. For the purposes of calculating costs, we have also updated the timeframe over which network capex is incurred from 20 years to 40 years. After this point, renewals would be expected.
- We assume that the pace of deployment over the next five years is slower than in our Fifth Carbon Budget scenarios. However, similar to the Fifth Carbon Budget, we assume that approximately 18% of homes are assigned to district heat by 2050 (representing the homes in areas of highest heat density). Public and commercial buildings have lower levels of uptake, reflecting new heat demand projections. We assume that from 2025 all new district heat connections are low-carbon, and that legacy gas CHP schemes convert to low-carbon sources between 2033 and 2040.
- In commercial and public buildings, we include a stylised scenario with lower deployment of district heat in our Widespread Innovation scenario; where district heat makes up 14% of heat demand by 2035 and 27% by 2050, compared to 22% by 2035 and 42% by 2050 in our Balanced Pathway.

Source: Element Energy, Frontier Economics, Imperial College for CCC (2015) *Research on district heating and local approaches to heat decarbonisation*; Element Energy for CCC (2020) *Development of trajectories for residential heat decarbonisation to inform the Sixth Carbon Budget.*

Our scenarios explore a range of future worlds, including ones with higher levels of innovation and behaviour change.

Our starting point for the analysis is the 2019 Net Zero report, which showed that the Net Zero target means eliminating buildings emissions by 2050.

We have used bottom-up analysis to produce a set of pathways to zero emissions from buildings in 2050.

Our starting point is current Government policy. We then look at the impacts of a range of additional policy levers, including phase-out dates for fossil fuel boilers.

We use the scenarios to explore a range of different futures, including ones with higher levels of innovation and behaviour change. We work on the basis of an underlying aim to minimise costs and disruption for households and businesses, working with technology lifetimes to minimise scrappage. In determining the pathways, we have also tested a range of regulatory policy levers as well as new business models. Our starting point is current Government policy. We then look at the impacts of a range of additional policy levers, including phase-out dates for fossil fuel boilers. Our scenarios aim to simulate what can be achieved under an ambitious and effective wide-ranging policy package that deals decisively with the various barriers to action.

Our analysis is split by residential and non-residential buildings, with low-carbon heat network pathways based on buildings-wide analysis produced for the Fifth Carbon Budget, which has been refreshed.

The following sections cover the analytical methodology behind our scenarios, our approach to deriving pathways for the devolved administrations and our approach to uncertainty (including impacts of COVID-19).

a) Analytical methodology

i) Residential buildings

Our 2019 analysis demonstrated that getting to very low levels of emissions in residential buildings is possible. For the purposes of the Sixth Carbon Budget, we have modelled paths which reach zero by 2050.*

We commissioned new modelling of pathways for existing homes, and produced in-house analysis covering new homes and electrical efficiency measures.

Our Sixth Carbon Budget scenarios for residential buildings are composed of five analytical workstreams, looking at decarbonisation pathways for heat in existing homes, heat in new homes, appliance efficiency, the decarbonisation of gas cooking, and the decarbonisation of household and garden machinery. The modelling for the decarbonisation of heat in existing homes draws on a project by Element Energy (Box 3.5), while the latter four analytical workstreams draw on in-house analysis.

For energy efficiency and heat in existing homes, we started by looking at different 2050 mixes, where we explored balances of behaviour change, fabric efficiency, and fuel-switching. We then determined pathways for decarbonisation, starting with current Government policy and considering additional levers on top of this. Our analysis was designed to respect the limits of feasibility and desirability for consumers (considering plausible ranges of behaviour change and technology uptake) and to allow time for supply chains and skills to ramp up (incorporating assumptions for deployment constraints amongst other things).

* There remain a very small volume of emissions in all of our scenarios (<1Mt) associated with limited use of biofuels, house fires, and non-aerosol household products.

Boiler lifetimes of around 15 years imply a need to scale up markets and supply chains for low-carbon heating to cover all new installations by the mid-2030s at the latest, if the Net Zero target is to be met. The pace of decarbonisation across our scenarios is therefore led by dates for regulated phase out of new fossil fuel boilers, in areas not designated for hydrogen or district heat conversion.

Box 3.5
The development of trajectories for residential heat decarbonisation in existing homes

We commissioned Element Energy to develop scenarios for the deployment of energy efficiency and decarbonised heat in existing homes, to inform our Sixth Carbon Budget advice. This work represents an update to, and extension of, the work they undertook for the CCC in 2019 to inform our advice on setting a Net Zero target.[35]

Element's modelling is based on an improved and updated building stock model of the UK, built around regional national housing survey data for England, Scotland, Wales and Northern Ireland, Energy Performance Certificate Data, and a range of other statistics and datasets.

As discussed in section 2, the modelling is underpinned by comprehensive updates to assumptions relating to energy efficiency and low-carbon heat, where new evidence has become available. It is aligned with Green Book assumptions on cost of capital and discount rates, with a 3.5% cost of capital applying for most scenarios, and 7.5% applying where heat-as-a-service is modelled.

The modelling uses a baseline calibrated to 2018 emissions and energy use data and takes into account improvements in boiler efficiency over time. The baseline has been adjusted to account for a 6.6% reduction in heat demand to 2030, in order to reflect near-term projections for the impacts of climate change in the UK (see Box 3.8 for further discussion).

The model was used to calculate end states for 2050 across scenarios, comprising of behavioural measures, energy efficiency measures and a low-carbon heating system for every home in the UK. The end states in our scenarios are informed by a number of considerations. These include:

- **Cost effectiveness.** We tested those mixes of energy efficiency and low-carbon heat which could deliver lowest lifetime costs, on a net present value basis, over a 20-year time horizon. This differs from the definition used for our Fifth Carbon Budget scenarios, which used target consistent carbon values to evaluate the point at which technologies would become 'cost-effective' relative to these carbon values.*
- **Wider benefits**. We considered wider benefits when determining what mix of measures and technologies to deploy. In particular, across all scenarios we deployed additional energy efficiency measures in order to help address fuel poverty, and in a number of our scenarios (including the Balanced Pathway) we deployed additional energy efficiency beyond this to reflect wider benefits including to comfort and health.
- **Consumer preferences.** We tested a range of behavioural measures, heating mixes and household flexibility levels across scenarios, reflecting variations in consumer and societal preferences.

Deployment trajectories were then developed. Uptake trajectories have been bounded by assumptions on deployment constraints for all key technologies. These constraints were developed using the latest available evidence and tested with industry experts.

Beyond these constraints, the trajectories are based around a regulated approach, reflecting feedback in our call for evidence that regulation is a key pillar for delivery. We took our starting point as current Government policy – in particular the plans to improve the energy efficiency of all buildings over the next 10-15 years, and the plans to phase-out the installation of new high-carbon fossil fuels in the 2020s.

* Carbon values represent a cost of carbon to the economy, and are used as part of HMT Green Book appraisal. The CCC Fifth Carbon Budget carbon values are based on a rising cost of carbon over the next decades, increasing to over £200/tCO2e by 2050. For further detail, see CCC (2015) *The Fifth Carbon Budget*.

We then modelled additional levers on top of this, testing a range of phase-out dates for the installation of fossil fuel boilers. These phase-out dates drive uptake of electrified technologies on and off the gas grid.

Separate trajectories were developed for uptake of hydrogen and low-carbon district heating. For hydrogen, an uptake trajectory was developed to reflect hydrogen grid conversion, led by use of hydrogen in industrial clusters. For low-carbon district heat, our Fifth Carbon Budget scenarios were used as a basis, and updated to reflect slower progress in the early years, with CHP phase out for new low-carbon heat networks in 2025, and conversion of all legacy schemes to low-carbon sources by 2040 (Box 3.4).

Source: CCC analysis; Element Energy for the CCC (2020) *Development of trajectories for residential heat decarbonisation to inform the Sixth Carbon Budget*.

Our scenarios for the decarbonisation of heat and energy efficiency measures in new homes build on the recommendations made in our 2019 report *UK housing: Fit for the future?*, and assume that from the mid-2020s at the latest, no new homes are connected to the gas grid and instead are built with ultra-high energy efficiency standards and heated through low-carbon sources (either heat pumps or district heat). Our scenarios draw heavily on analysis undertaken for the CCC by Currie Brown and Aecom in 2019.[36] The following key assumptions underpin the new build analysis:

- We assume that build rates profile up to meet Government new build commitments of 300,000 homes per year by the mid-2020s in England, with rates held constant for the devolved administrations. Projections thereafter follow a profile developed by Element Energy for the Fifth Carbon Budget.
- We assume that any homes built between now, and the date at which regulations on low-carbon heat come into force, must be retrofitted with low-carbon heat at the point of heating system renewal.
- All new build homes are assumed to pre-heat and therefore be capable of accessing lower electricity costs.
- We model costs on the basis of modelling undertaken by Currie & Brown which uses a 7.5% cost of capital for one year.[37] We take a simplified approach of modelling costs in representative years for ten different house types, including homes and flats using different low-carbon heating systems and at different levels of energy efficiency.

Our Sixth Carbon Budget scenarios for lighting and appliance efficiency in homes draw on analysis undertaken for the Fifth Carbon Budget, updated to better align with evidence on the heat replacement effect and to reflect updated assumptions on electricity costs and the rate of decarbonisation.*

We separately model the decarbonisation of gas cooking appliances (2.1% of residential direct emissions), and household and garden machinery (0.6% of residential direct emissions).

We assume that gas cooking appliances are replaced with electric appliances in most scenarios. Our calculations conservatively assume the efficiency levels of conventional electric hobs, although induction hobs are increasingly popular, and provide superior performance and greater efficiency savings where suitable. In Headwinds we assume that gas cooking appliances are mainly replaced by hydrogen appliances.

* The heat replacement effect occurs because as lighting and other electricity products become more efficient, they produce less waste heat. Our assessment allows for a small amount of additional heating requirement.

Hydrogen cooking appliances are expected to provide similar performance to gas cookers and could be used wherever the gas grid is converted. The timeframes for cooking decarbonisation are aligned with the dates of phase out for new gas boiler sales and with hydrogen switchover trajectories in the Headwinds scenario.

We assume that the phase out of petrol and diesel household and garden machinery (such as lawnmowers, garden tractors, and hedge trimmers) is aligned with the phase out of petrol vehicles in the transport sector (i.e. all new sales are zero-carbon from 2032 at the latest in our Balanced Pathway).

ii) Public and commercial buildings

All our non-residential scenarios are based on buildings reaching near-zero emissions ahead of 2050.

All our scenarios are based on non-residential buildings reaching near-zero emissions ahead of 2050. As in our Net Zero analysis, the main source of remaining emissions in 2050 is N_2O used for anaesthesia, which seems relatively costly to abate by replacement. We note the NHS now has a target to reduce these emissions by 40% by 2050 as part of its strategy for delivering a Net Zero emission health service.[38] We plan to undertake further work in this area in the future.

Our baseline energy demand is primarily based on BEIS' Energy and Emission Projections.[39]. These are stylised and do not take account of any potential changes in trends associated with increased home-working resulting from the COVID-19 pandemic (see Box 3.7).

As in our Net Zero analysis, the main source of remaining emissions in 2050 is N_2O used for anaesthesia, which seems relatively costly to abate by replacement.

Our scenarios are grounded in current policy. For example, we use expected dates for the phase out of high-carbon fossil fuel heating such as oil, based on policy. We assess our rollout profile of energy efficiency against relevant commitments such as the Government's goal to enable businesses and industry to improve energy efficiency by at least 20% by 2030 and its aim to reduce public sector emissions by 50% by 2032 against 2017 levels.

We then develop a pathway based on the pace of hydrogen conversion of the grid, district heat development and boiler stock turn over for buildings assumed not to convert to hydrogen or district heat. We apply different dates where no new gas boilers would be installed across our scenarios reflecting the potential for regulated phase out of fossil fuels. Each of these ensures that gas is fully phased out before 2050 through natural replacement cycles.

The non-residential buildings analysis was approached by reducing baseline emissions in the following sequence: subtracting energy savings from behavioural measures and energy efficiency, allocating a share of remaining heat demand to district heating, then analysing fuel-switching and improved system efficiency for remaining building-level heat and catering and other fossil fuel demands.

The level of energy savings reached at maximum deployment from behavioural measures and energy efficiency is held constant across scenarios. We vary the profile over which the savings develop according to scenario and the value of the savings varies across scenarios according to different energy prices. Our method of deriving energy savings from BEES and our cost methodology for energy efficiency is described in Box 3.6.

Hydrogen rollout aligns to the pace in homes and is informed by our industrial analysis.

After accounting for reduced heat demand following energy efficiency and uptake of district heating, we consider the mix of technologies for the remaining heat demand.

- We align the uptake of hydrogen boilers in public and commercial buildings to the share of on-gas homes (excluding district heat) that convert to hydrogen in the residential analysis. We assume that grid conversions radiate out from industrial clusters.

- For the share of remaining buildings not assigned to convert to hydrogen, we model uptake of heat pumps and resistive electric heating based on turnover from our assumed phase-out dates.

- Our interpretation of the HVAC study technical potential implies all wet-based systems (gas, oil and biomass boilers) convert to air-to-water heat pumps, while dry systems (resistive electric heating) convert to air-to-air heat pumps, and localised gas heating systems such as found in storage facilities convert to a mixture of air-to-air heat pumps and resistive elective heating.[40]

- The costs of providing heat output with each technology are shown in Table 3.2. This is the smoothed cost over the technology lifetime for an installation in a given year, incorporating our assumptions on capex, opex, fuel costs and efficiencies of each technology.

Table 3.2
Levelised cost of energy for heat technologies installed each year

	Public (£/MWh)		Commercial (£/MWh)	
	2030	2050	2030	2050
Air-to-air heat pump	42	39	48	44
Air-to-water heat pump (low temperature)	77	69	95	85
Hydrogen boiler	85	85	90	90
Electrification (direct heat)	80	74	82	76
Biomass boiler	57	57	64	64
Gas boiler	42	42	44	44
Oil boiler	63	64	66	68

Notes: Cost of capital of 3.5% assumed for public sector and 7.5% assumed for commercial.

After applying energy efficiency, we model the gradual replacement of fossil fuels for catering and other uses.

- We assume that fossil-fuel appliances are replaced with alternatives on reaching the end of their life. Assuming a 15-year lifetime, fossil-fuel appliances are therefore phased out at a linear rate over 15 years following the phase-out date for each fuel.

- Natural gas is replaced by a mix of electricity and hydrogen, which varies between scenarios. Other fossil fuels are assumed to be replaced by electrification.

- We assume that the efficiency of hydrogen and gas appliances is identical. We apply an efficiency saving for converting to electric catering equipment, based on the efficiencies of different types of appliance, weighted by their current aggregate annual consumption.

- Other uses mainly involve the heating of water (e.g. for swimming pools and hospital steam systems). We make the conservative assumption that these are replaced by resistive electric heating (in practice, heat pumps are used increasingly as a source for swimming pools globally).
- Cost estimates for converting catering and other fossil fuel uses are based on fuel costs alone. We assume that other running costs and capital expenditure are identical to fossil fuel equipment.

We use evidence from BEES to assess the potential energy savings and costs associated with behavioural and energy efficiency measures.

Box 3.6
Using the Building Energy Efficiency Survey

The Building Energy Efficiency Survey (BEES), commissioned by BEIS, reports on the energy use and potential for reduction in energy use in non-residential buildings in England and Wales in 2014-15. Abatement potential for a 39% reduction from current energy consumption was identified.

Our analysis excludes abatement potential in BEES from industrial buildings (which fall outside the scope of this sector) and abatement potential associated with upgrading space heating plant which we consider may overlap with our analysis of heat decarbonisation.

Since the BEES data are for England and Wales only, we scale the abatement potential and baseline energy consumption in BEES upwards to reflect inclusion of Scotland and Northern Ireland in our analysis. We do so with a scaling factor derived from sub-national energy consumption data for electricity and gas (which is applied to non-electric energy).

We compared the adjusted baseline energy demands from BEES with the baseline energy developed for our analysis which is based on BEIS' *Energy and Emission Projections (EEP)*: [41]

- This showed the adjusted BEES baseline energy demand was significantly lower that our baseline for 2018, particularly for non-electric energy consumption.
- The disparity grows through time with static BEES data and generally an upward trend to EEP, so the difference would be larger by the time we assume the savings are delivered (some point in the early 2030s).*
- We have applied uplifts of 35% and 20% to commercial and public non-electric abatement potential respectively. This makes up for only a share of the baseline discrepancy which we judge to be a conservative approach reflecting that not all the abatement potential identified might be representative of all non-residential energy demands (e.g. in other locations) and that growth in baseline demand over time will be driven by a range of factors (including new build).

We have excluded some of the most expensive measure categories in BEES from our analysis based on cost:

- We have excluded humidification, small appliances, ventilation, air conditioning and cooling, and building services distribution systems. This reduces non-electrical energy savings marginally and electrical energy savings by around 23%.
- We consider that where electrical energy savings would have a high abatement cost over the carbon values, this may be better dealt with through the electricity supply side where electricity will be very low carbon in later years.
- We have made exclusions based on cost only at the category level, so we may be excluding some measures within this that would not be prohibitively expensive (i.e. over around £150/tCO_2e in 2030).

We include 51.6 TWh of energy savings per year from the date when energy efficiency measures are fully deployed in our modelling.

* The projections show strong growth in commercial electricity consumption and public gas consumption, slight growth in commercial gas consumption and declining public electricity consumption.

This represents a 27% reduction compared to our 2018 baseline. In our Balanced Pathway this translates to a reduction in commercial energy consumption of 26% in 2030 relative to 2018. This exceeds the overall commercial and industry goal of 20%, since we understand the commercial sector is likely to take on a larger share of this effort due to greater abatement potential. The level of savings drawn from different measure categories is shown in Table B3.6.

We estimate capex and opex associated with energy efficiency measures at BEES measure category level (e.g. building fabric, lighting) and use a representative lifetime for each category informed by the BEES data, weighted by category of measure (Table B3.6). We then estimate abatement costs for each of the segments of energy efficiency abatement in our analysis by using the measure category costs weighted by the share of energy savings it contributes to our abatement segment. Investment costs are based on the total capex for each measure category spread across its assumed lifetime and assigned across relevant abatement chunks. We make the conservative assumption that annual investment costs associated with energy efficiency continue throughout the period of our analysis to reflect renewals.

Table B3.6
Energy efficiency savings and costs using our analysis

	Annual electricity savings (GWh/year)	Annual non-electric savings (GWh/year)	Capex for initial deployment (£ million)	Opex for initial deployment (£ million)	Lifetime (years)
Building instrumentation and control	1,800	10,360	3,000	100	6
Building fabric	1,160	7,840	7,630	-	20
Carbon and energy management	5,100	8,110	1,820	60	3
Lighting	9,500	-	4,550	190	10
Refrigeration	2,390	-	1,410	-	7
Swimming pools	130	780	430	1	5
Space heating	400	3,890	1,070	15	7
Hot water	60	140	110	-	10
Total	**20,520**	**31,120**	**20,020**	**365**	

Notes: Figures may not sum to totals due to rounding.
Sources: CCC analysis; BEIS (2016) *Building Energy Efficiency Survey*.

b) Deriving the paths for the devolved administrations

The pathways for the devolved administrations have been derived using a combination of top down approaches with a detailed bottom-up assessment for heat and energy efficiency in existing homes.

The pathways for the devolved administrations have been derived using a combination of top-down approaches based on key metrics, and some more detailed workings for existing homes. Northern Ireland sees a faster decarbonisation pathway as a result of the higher proportion of homes off the gas grid (Figure 3.3).

For heat decarbonisation in existing homes, our analysis is based on a building stock model of the UK which incorporates regional national housing survey data for England, Scotland, Wales, and Northern Ireland providing an estimate of the breakdown of physical attributes and existing heating systems across each of those three administrations.

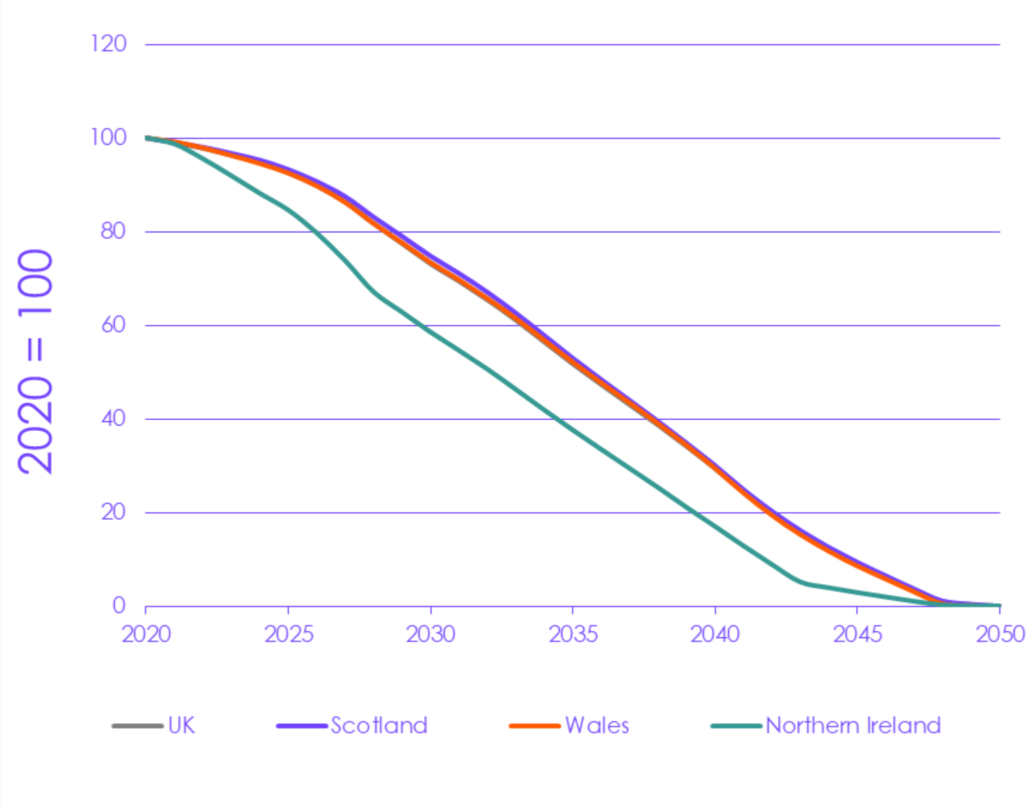
Our scenarios do not differentiate between the devolved administrations in terms of the regulatory levers applied, although it remains the case that there is scope for higher levels of ambition to be pursued.

The remainder of our modelling for homes uses 2018 statistics on the number of dwellings to infer a split of decarbonisation across the devolved administrations.

For non-residential buildings, the emissions and energy baselines and pathways for the devolved administrations are based on current shares of non-residential direct emissions. At the level of individual measures and fuels the method is a simplification since the current shares for individual fuels may deviate from aggregate emissions for a sector.

- Differing shares were applied for the public and commercial sectors.
- Emissions, energy demand, direct and indirect abatement, and investment costs are split across the devolved administrations using the same method.
- Costs per tonne of abatement are assumed to be identical across devolved administrations.

Figure 3.3 Comparison of residential buildings emissions pathways for the UK, Scotland, Wales and Northern Ireland



Source: CCC analysis; Element Energy for the CCC (2020) Development of trajectories for residential heat decarbonisation to inform the Sixth Carbon Budget.

c) Approach to uncertainty

We use our exploratory scenarios to test a range of uncertainties.

In developing our advice, we have sought to consider the key uncertainties which could influence the path for buildings decarbonisation in the UK. We explore these uncertainties primarily through our use of scenario analysis:

- The exploratory scenarios reach Net Zero emissions by 2050 in quite different ways, illustrating the range of ways in which it can be achieved. We use these scenarios to guide judgements on the achievable and sensible pace of decarbonisation in the face of uncertainty, and to understand how less success in one area can be compensated for elsewhere.
- The Tailwinds scenario assumes considerable success on both innovation and societal/behavioural change and goes beyond the Sixth Carbon Budget Pathway to achieve Net Zero before 2050. This scenario is intended to be at the limits of feasibility.
- Our Balanced Pathway is designed to drive progress through the 2020s, while creating options in a way that seeks to keep the three 'exploratory' scenarios open.

The key sources of uncertainty we test through our Buildings scenarios include:

This includes uncertainties around energy costs, levels of behaviour change, techno-economic assumptions for energy efficiency, heat mixes, techno-economic assumptions for heating, and the pace of action.

- **Energy costs**. We use differing assumptions for economy-wide changes in grid carbon intensity and energy costs across scenarios. We additionally explore the impacts of higher bound hydrogen prices in our residential Headwinds scenario for the purposes of determining energy efficiency uptake in homes. For further discussion on uncertainties in energy costs, see Chapter 1.
- **Behaviour change.** We test varying levels of behaviour change across our scenarios for homes. For existing homes, this includes varying levels of pre-heating and demand reduction, as well as considering the heat-as-a-service delivery model in some scenarios (Table 3.3).
- **Energy efficiency.** We explore a wide range of energy efficiency uptake levels across our scenarios for homes. We also vary our assumptions on costs of different low-carbon measures, and the level of closure of the performance gap which might be achieved across scenarios. For public and commercial buildings, we vary the rates at which measures are rolled out (Table 3.3).
- **Heat mixes**. We explore a range of routes to decarbonising heat across our scenarios, ranging from a fully electrified heating mix in our Widespread Engagement scenario, to a hydrogen-heavy heating mix in our Headwinds scenario. A number of our scenarios, including the Balanced Pathway, represent a hybrid system (Table 3.3).
- **Heating technology costs, lifetimes and sizing**. We explore different levels of technology cost reductions across our scenarios. We also vary the assumed technology lifetimes and sizing for heat pumps across scenarios for homes (Table 3.3).
- **Heat technology efficiency.** In line with our Fifth Carbon Budget analysis, we assume improvements in heat pump Seasonal Performance Factors (SPF) of 0.5 between 2020 and 2030. For the Widespread Innovation and Tailwinds scenarios, we assume a further 15% efficiency uplift for all years. For homes, this is based on a heat-as-a-service delivery model.

- **Pace of action.** We vary the dates of regulatory levers across scenarios, and the pace of uptake within deployment constraints, to test varying rates of progress (Chapter 3, Table 3.2.c).

Table 3.3
Assumption ranges tested through our scenarios

	Balanced Pathway	Range
Residential buildings		
Pre-heating	**25% of eligible existing homes, and all new homes**	25-50% of eligible existing homes, and all new homes
Reduction in space heat from smarter heating management and use*	**3%**	3%-6%
Hot water temperature in homes*	**60°C**	50°C (with daily legionella cycle) to 60°C
Cost of capital for building scale investment	**3.5% for existing homes, 7.5% for new build**	3.5%-7.5% for existing homes (where heat-as-a-service assumed), 7.5% for new build
Degree of closure of the performance gap*	**Uplift equivalent to one third closure of in-use factors**	Uplift equivalent to between one third and one half closure of in-use factors
Heat demand savings as a result of energy efficiency and behaviour change*	**12%**	11%-22%
Percentage of homes using hydrogen by 2050	**11%**	0%-71%
Heat pump efficiencies in 2020*,**		
Air source heat pump combined SPF	**2.54 at 50°C flow, 3 at 40°C flow**	2.92 at 50°C flow, 3.45 at 40°C flow
Ground source heat pump combined SPF	**2.84 at 50°C flow, 3.26 at 40°C flow**	3.27 at 50°C flow, 3.75 at 40°C flow
Heat pump cost reductions*		
Unit and installation	**20% reduction to 2030, 30% reduction to 2050**	20-30% reduction to 2030, 30-40% reduction to 2050
Ground source heat pump groundworks	**30% reduction to 2030**	30-40% reduction to 2030
Heat pump lifetime assumptions*		
Air source heat pump	**15 years**	15-17 years
Ground source heat pump***	**20 years**	20-22 years
Non-residential buildings		
Energy efficiency fully deployed by		
Public buildings	**2032**	2030-2032
Commercial buildings	**2030**	2030-2035
Percentage of non-residential heat demand using hydrogen by 2050	**5%**	0%-46%
Heat pump efficiency in 2020**	**283%**	283%-325%
Heat pump cost reduction (unit and installation)	**20% reduction to 2030, 30% reduction to 2050**	20-30% reduction to 2030, 30-40% reduction to 2050

Notes: This table represents a non-comprehensive list of the metrics varied between scenarios. * Assumptions relevant to existing homes only. ** An improvement of 0.5 in the combined SPF is assumed by 2030 across scenarios. Heat pump efficiencies at 50°C flow temperature are aligned with our Fifth Carbon Budget assumptions, with higher efficiencies assumed where radiators are upgraded to facilitate lower flow temperatures on average. Efficiency variations between flow temperatures based on MCS emitter guide. Further research is needed to improve the evidence base for these assumptions. *** Ground source heat pump ground works are modelled with a separate lifetime, assumed to be 100yrs across scenarios based on consultation with stakeholders. Evidence on the lifetime of ground loops remains limited and would benefit from further research.

We have not explicitly modelled the impacts of COVID-19 on demand and note that the longevity of any impacts remains highly uncertain. Any long-term shift to home working would lead to a shift in emissions from non-residential to residential buildings, particularly during the heating season. This could imply an increase in emissions in aggregate due to the loss in efficiency of having people working in a greater number of spaces which all need heating during working hours. Research undertaken by the International Energy Agency suggests there may be some net gains from a shift to homeworking where this displaces a commute by private car. However, the net impacts remain highly uncertain (Box 3.7).

Box 3.7
Modelling of the impacts on building emissions of a shift to homeworking

The COVID-19 pandemic has driven a substantial increase in homeworking. In April 2020, 46.6% of the labour force did some work at home.[42] It is currently unknown to what extent this may lead to a long-term shift.

The aggregate impacts on emissions from an increase in homeworking are uncertain and complex.

At a household level, working from home results in increased residential energy demand, and reduced transport energy demand. According to analysis undertaken by the IEA, the net impact of these changes is a reduction in energy demand where private vehicles are the main means of commuting.

However, a shift to homeworking would have wider effects on energy consumption:

- Reduced demand for office space would reduce energy consumption and emissions from non-residential buildings. However, offices may be more efficient workspaces than households (i.e. due to greater concentrations of people; newer buildings). In the UK, offices include a greater share of electric heating suggesting they could also be lower emission.
- Changes to where people live may result in increased travel distances or shifts away from public transport.

The impact on emissions depends on the net effects of increases in energy consumption in residential buildings and decreases in non-residential buildings, their relative efficiency, as well as secondary impacts on patterns of living and travel.

Source: IEA (2020) *Working from home can save energy and reduce emissions. But how much?*; O'Brien, W. and Aliabadi, F. (2020) Does telecommuting save energy? A critical review of quantitative studies and their research methods, *Energy and Buildings, 15 October 2020.*

i) Residential buildings

Remaining uncertainties specific to our residential modelling include projections for electricity use from lighting and appliances and for new build, energy savings associated with solid wall insulation, heat pump efficiencies, the performance of hybrids and the performance gap.

While it has been possible to test a range of uncertainties through the scenarios, with sensitivities undertaken alongside, the analysis is necessarily limited by the number of scenarios developed, and by the availability of evidence to inform assumptions. In particular, updated evidence or analysis in the following areas could be expected to impact aspects of the results:

- **Projections of fuel use and new homes.** Projections of baseline fuel use to 2050 remain highly uncertain. This includes projections for electricity use in homes (and achievable savings from lighting and appliance efficiency) where we have conservative assumptions leading to high levels of modelled electricity consumption in 2050. Long-term new build projections are also uncertain and would impact overall energy demand. Finally, we make assumptions about the impact of climate change on future heat demand, and the demand for cooling which remain uncertain (Box 3.8).

- **Solid wall insulation.** While the evidence base on the potential energy savings associated with fabric energy efficiency measures has improved relative to previous work, achievable savings remain highly uncertain in some cases. In particular, evidence used to inform our assumptions indicates lower cost effectiveness for solid wall insulation than has been suggested by previous work. This could in part be a function of U-values of solid uninsulated walls being lower than has been assumed historically, leading to lower observed savings from insulation in the NEED data.[43] However, there are also known uncertainties in the NEED data in relation to the number of partial wall installations in the sample (which would be expected to suppress savings). On this basis the savings we assume are expected to be an underestimate to some degree.

- **Heat pump efficiency.** Our Fifth Carbon Budget assumptions on heat pump efficiency were informed by field trials and monitoring for the Renewable Heat Premium Payment (RHPP) scheme, leading to conservative assumptions in the near term. While deficiencies in this data are widely acknowledged, in the absence of large-scale new published evidence, our Sixth Carbon Budget assumptions have used these conservative assumptions as a starting point. Our assumptions have then been updated to seek to reflect the higher efficiencies that might be achieved at lower flow temperatures, where radiators are replaced. The evidence for these assumptions remains limited and subject to uncertainty.[44] The Metering and Monitoring Service Package data is expected to provide an updated and expanded evidence base on in-situ heat pump performance which will support future analysis.

- **Hybrid heat pumps.** There remains uncertainty over how hybrid technologies will perform in-situ. Based on work undertaken by Imperial College London our base assumption is that hybrid heat pumps can operate in heat pump mode up to 80% of the time.[45] Other trial data (e.g. from Passiv Systems, when combined with smart controls) supports the Imperial assumptions. Trials undertaken by the Energy Systems Catapult have shown that performance can be highly variable and dependent on household heating behaviours.[46] We test the impacts of this through sensitivities on our scenarios.

- **The performance gap**. Our new-build modelling does not include a representation of the performance gap and is therefore likely to underestimate near-term fuel consumption to some degree. We include a representation of some closure of the performance gap for retrofit energy efficiency measures in existing homes. In both cases there is a high level of uncertainty over the precise scale of the performance gap, although a large body of evidence points to it being substantial.

Box 3.8
The impacts of climate warming

Changes in the UK's climate will impact on the energy demand of buildings between now and 2050. Our scenarios for homes have been designed to reflect a number of expected dynamics resulting from the changing climate:

- We assume that increasing winter temperatures result in reduced demand for heating. Based on the average from an ensemble of UK regional climate projections, we assume that increases in average winter temperatures to 2030 result in a 6.6% reduction in heat demand. We hold this reduction constant from 2030 to 2050.[*, †]
- We assume that increasing summer temperatures result in additional demand for cooling. We allow for an additional energy demand of 5TWh annually by 2050. This is aligned with the Energy Systems Catapult's projections, based on an increase in energy demand for cooling calibrated to levels for households in EU countries which currently experience similar levels of Cooling Degree Days to those predicted for the UK in 2050.[47]
- We have separately examined the costs associated with retrofitting shading and ventilation measures in homes to manage overheating risk. This is discussed further in Chapter 3, Box 3.2.a.

The precise impacts of the changing climate on energy demand are uncertain, as they depend on behavioural responses to changes in summer and winter temperatures. We do not model the impacts for public and commercial buildings on the basis that these buildings are expected to be subject to more complex trade-offs between heating and cooling demand that it has not been possible to capture through our Sixth Carbon Budget analysis. Further analysis on energy demand will be covered in the next UK Climate Change Risk Assessment Evidence Report, due to be published by the Adaptation Committee in summer 2021.

Sources: Met Office analysis; CCC analysis; Element Energy for the CCC (2020) *Development of trajectories for residential heat decarbonisation to inform the Sixth Carbon Budget;* Robert Sansom for Energy Systems Catapult (2020) *Domestic heat demand study.*

ii) Public and commercial buildings

Remaining uncertainties specific to our non-residential modelling include energy efficiency costs, heat technology costs and baseline projections.

There are a number of further uncertainties and limitations associated with the non-residential analysis that could impact results:

- **Energy efficiency costs**. We have taken a conservative approach to the estimation of energy efficiency abatement and investment costs, which is likely to overestimate costs.
  - We have used the full capex value derived from BEES (for the scope of abatement that we have included). This would mean that all the cost is additional to what would have been incurred in the baseline, whereas in practice we anticipate that a share of the measures would be in place of business-as-usual investment (e.g. replacing lighting or refrigeration equipment). If replacements take place near the end of a product's natural life then there may be no additional capital cost, or possibly even some cost saving.

[*] Our residential heat analysis is based on an assessment of end state technology mixes in 2050, which are then deployed over the trajectory to 2050. While further warming after 2030 is expected, we hold the heat demand reduction constant to ensure that the technologies deployed in our modelling are able to meet the heat demands expected from 2030 onwards.

[†] Based on Met Office analysis of Heating Degree Day data derived from the 2018 UK Climate Projections, calculated for a 15.5 degree threshold and based on the RCP8.5 pathway – note that the outputs are similar for any emissions scenarios before 2050 (Riahi et al 2007).

- We also assume renewal costs continue throughout the appraisal period. With some very short measure lifetimes (e.g. less than five years), this means the costs are repeated several times. If the benefits of some measures could be maintained (e.g. the impact of training or procurement practice) without reinvesting, then costs could be considerably lower than our estimates.

We have taken a simplified approach to modelling both hot water and heat technology mixes in the analysis and note modelled potential for abating emissions resulting from the use of anaesthetics in health care.

- **Heat and hot water.** We have taken a simplified approach of modelling heat and hot water demands together which is likely to slightly underestimate demand and costs.
  - Suitability and uptake are driven by space heating demand, which are applied to hot water demands. This is an oversimplification. For example, hot water makes up 7% of baseline electrical heat and hot water demand that is converted to air-to-air heat pumps, whereas a supplementary technology would be necessary for the hot water.
  - Our costs for delivering all heat and hot water demands are based on costs for generating heat which is likely to lead to an underestimation of costs.
- **Heat technology mixes.** We have modelled all 'wet' based systems that convert to heat pumps using low temperature air-to-water heat pumps, and 'dry' systems converting to air-to-air heat pumps. A wider range of technologies are available which would have different energy requirements and costs. It may also be feasible for buildings with 'wet' systems to convert to lower cost air-to-air heat pumps instead of air-to-water heat pumps and take on additional work in converting distribution systems.
- **Heat technology costs.** Our cost inputs (£/kW) are drawn from the HVAC study commissioned by BEIS. Our cost methodology pairs these with capacity and load factor assumptions drawn primarily from our Fifth Carbon Budget analysis. Capacity and load factors are difficult to assess. We believe we have based our analysis on the best information available but recognise the potential for incompatibility between these data sources and the relatively large impact changing any of these assumptions can have on heat costs.
- **Baseline projections.** There are discrepancies between data sources on commercial and public energy consumption for 2018. We understand a revision to reallocate 18TWh of oil from industry to other final users has resulted in higher energy consumption for public and commercial buildings in Energy Consumption in the UK (ECUK) than is reflected in inventory data or BEIS Energy and Emission Projections (EEP). [*,48,49] Due to a closer mapping to inventory data, we have grounded our analysis on EEP data for 2018 and scaled this slightly to align fully to inventory data. The balance between public and commercial sub-sectors and fuel types varies by data source, so introduces a few elements of uncertainty. Projections of energy use to 2050 are clearly uncertain. Our baseline projections are generally based on BEIS' EEP which shows a strong growth in commercial electricity consumption to 2035, which leads to a 77% increase in commercial electricity from 2018 - 2050 in our analysis. Taking this baseline is a cautious approach which may be leading to more low-carbon electricity generation requirements than may be necessary.

[*] Other final users include the public sector, commercial buildings and agriculture.

- **N_2O emissions from anaesthetics.** In line with our Net Zero analysis, we have not modelled the potential for abating 0.6MtCO_2e of N_2O emissions arising through use in anaesthesia. A recent NHS report suggests these emissions can be reduced by up to 75% by 2050. [50] This abatement and associated costs are not included in our analysis.

Our scenarios and analytical approach have been deliberately designed to explore and test the implications of uncertainties, allowing us to develop a balanced assessment of achievable carbon savings which might be met in a range of ways. While uncertainties will inevitably remain, the analysis undertaken provides a solid basis on which to proceed.

Endnotes

[1] National Atmospheric Emissions Inventory (NAEI) (2020) *Breakdown of UK GHG emissions by source and greenhouse gas*.

[2] Department for Business, Energy & Industrial Strategy (BEIS) (2020) *DUKES, Electricity: commodity balances (DUKES 5.1)*.

[3] NAEI (2020) *Breakdown of UK GHG emissions by source and greenhouse gas*.

[4] BEIS (2020) *Energy Consumption in the UK (ECUK, End uses data tables*, Table U2.

[5] BEIS (2020) *DUKES, Electricity: commodity balances (DUKES 5.1)*.

[6] NAEI (2020) *Breakdown of UK GHG emissions by source and greenhouse gas*.

[7] BEIS (2020) *DUKES*, Natural gas: commodity balances (DUKES 4.1).

[8] BEIS (2020) *DUKES, Electricity: commodity balances (DUKES 5.1)*.

[9] CCC (2017) *Energy Prices and Bills – impacts of meeting carbon budgets*.

[10] BEIS (2020) *DUKES, Electricity: commodity balances (DUKES 5.1)*.

[11] See Figure 4-5: Imperial College London for the CCC (2018) *Analysis of Alternative UK Heat Decarbonisation Pathways*.

[12] Aecom (2011) *Energy Demand Research Project: Final Analysis*.

[13] Energy Systems Catapult (2019) *Pathways to Low Carbon Heating: Dynamic Modelling of Five UK Homes*.

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[16] Based on difference between standard shower head (18l/min) vs low flow (6l/min). Element Energy for the CCC (2020) *Development of trajectories for residential heat decarbonisation to inform the Sixth Carbon Budget*.

[17] Battelle Memorial Institute (2009) *Final report study on benefits of removal of water hardness (calcium and magnesium ions) from a water supply*; Element Energy for the CCC (2020) *Development of trajectories for residential heat decarbonisation to inform the Sixth Carbon Budget*.

[18] Energy Systems Catapult (2019) *Smart Energy Services for Low Carbon Heat*; Energy Technologies Institute (2018) *How can people get the heat they want at home, without the carbon?*

[19] Energy Systems Catapult (2019) *Heat as a Service Case Study*.

[20] Values for financial savings and energy consumption increase were taken from nominal results by Energy Systems Catapult: Energy Systems Catapult (2019) *Smart Systems and Heat Phase 2 D10 - D14: Market Transformations Report*. These findings are sensitive to assumptions regarding future market structures and service propositions. Assumptions on cost of capital in scenarios using heat-as-a-service are conservative, on the basis that the 7.5% cost of capital is applied to all low-carbon heat and energy efficiency in existing homes.

[21] BEIS (2016) *Building Energy Efficiency Survey*.

[22] CCC (2019) *UK housing: Fit for the future;* Currie & Brown and Aecom for the CCC (2019) *The costs and benefits of tighter standards for new buildings*.

[23] CCC (2020) *Letter: Future Homes Standard and proposals for tightening Part L in 2020*.

[24] SAP methodology was used to calculate energy savings from measures, and in-use factors applied to correlate better the modelled data with real-world performance. For further detail see Element Energy and the Energy Saving Trust for the CCC (2013) *Review of potential for carbon savings from residential energy efficiency*.

[25] UCL (2020) *Analysis work to refine fabric energy efficiency assumptions for use in developing the Sixth Carbon Budget.*

[26] Energy Saving Trust (2016) *Quantification of non-standard cavity walls and lofts in Great Britain*; Energy Saving Trust (2019) *Determining the costs of insulating non-standard cavity walls and lofts.*

[27] Referenced in Energy Saving Trust for DECC (2016) *Quantification of non-standard cavity walls and lofts in Great Britain.*

[28] Assumptions for thin internal wall insulation based on forthcoming research by Leeds Beckett University for BEIS, Thin Internal Wall Insulation (TIWI) Project. Assumptions for deep whole house retrofits informed by evidence provided by Energiesprong. It should be noted that our modelling of deep retrofits differs from the Energiesprong model in a number of important ways; notably we do not model onsite generation or counterfactual maintenance costs which are core to the Energiesprong business case. For further discussion of the benefits of the Energiesprong retrofit model see CCC (2018) *UK housing: Fit for the future?*

[29] BEIS (2019) *National Energy Efficiency Data Framework (NEED): impact of measures data tables 2019.*

[30] For further discussion see Element Energy for the CCC (2020) *Development of trajectories for residential heat decarbonisation to inform the Sixth Carbon Budget.*

[31] Cambridge Architectural Research for BEIS (2017) *What does it cost to retrofit homes;* EST for BEIS (2019) *Determining the costs of insulating non-standard cavity walls and lofts.*

[32] CCC (2018) *Biomass in a low-carbon economy*.

[33] Element Energy, Frontier Economics and Imperial College London (2015) *Research on district heating and local approaches to heat decarbonisation*.

[34] Euroheat and Power (2020) 100% RE District – Drammen, Norway, https://www.euroheat.org/knowledge-hub/case-studies/100-re-district-drammen-norway/.

[35] Element Energy for the CCC (2020) *Development of trajectories for residential heat decarbonisation to inform the Sixth Carbon Budget.*

[36] CCC (2019) *UK housing: Fit for the future?*; Currie & Brown and Aecom for the CCC (2019) *The costs and benefits of tighter standards for new buildings*.

[37] Currie & Brown and Aecom for the CCC (2019) *The costs and benefits of tighter standards for new buildings.*

[38] NHS (2020) *Delivering a 'Net Zero' National Health Service*.

[39] BEIS (2019) *2018 Updated Energy and Emission Projections.*

[40] Verco for BEIS (forthcoming) *Low carbon Heating, Ventilation and Air Conditioning (HVAC) technologies in non-domestic buildings.*

[41] BEIS (2019) *2018 Updated Energy and Emission Projections.*

[42] ONS (2020) *Coronavirus and homeworking in the UK: April 2020*. Office for National Statistics. https://www.ons.gov.uk/employmentandlabourmarket/peopleinwork/employmentandemployeetypes/bulletins/coronavirusandhomeworkingintheuk/april2020.

[43] BRE (2016) *Solid wall heat losses and the potential for energy saving*.

[44] Based on the MCS Emitter Guide, for further detail see Element Energy for the CCC (2020) *Development of trajectories for residential heat decarbonisation to inform the Sixth Carbon Budget*.

[45] CCC calculations based on Imperial College (2018) *Analysis of alternative heat decarbonisation pathways* (Hybrid heat pump 10 Mt scenario).

[46] Energy Systems Catapult for BEIS (2019) *D8 Decarbonising Heat: Understanding how to increase the appeal and performance of heat pumps.*

[47] Robert Sansom for Energy Systems Catapult (2020) *Domestic heat demand study.*

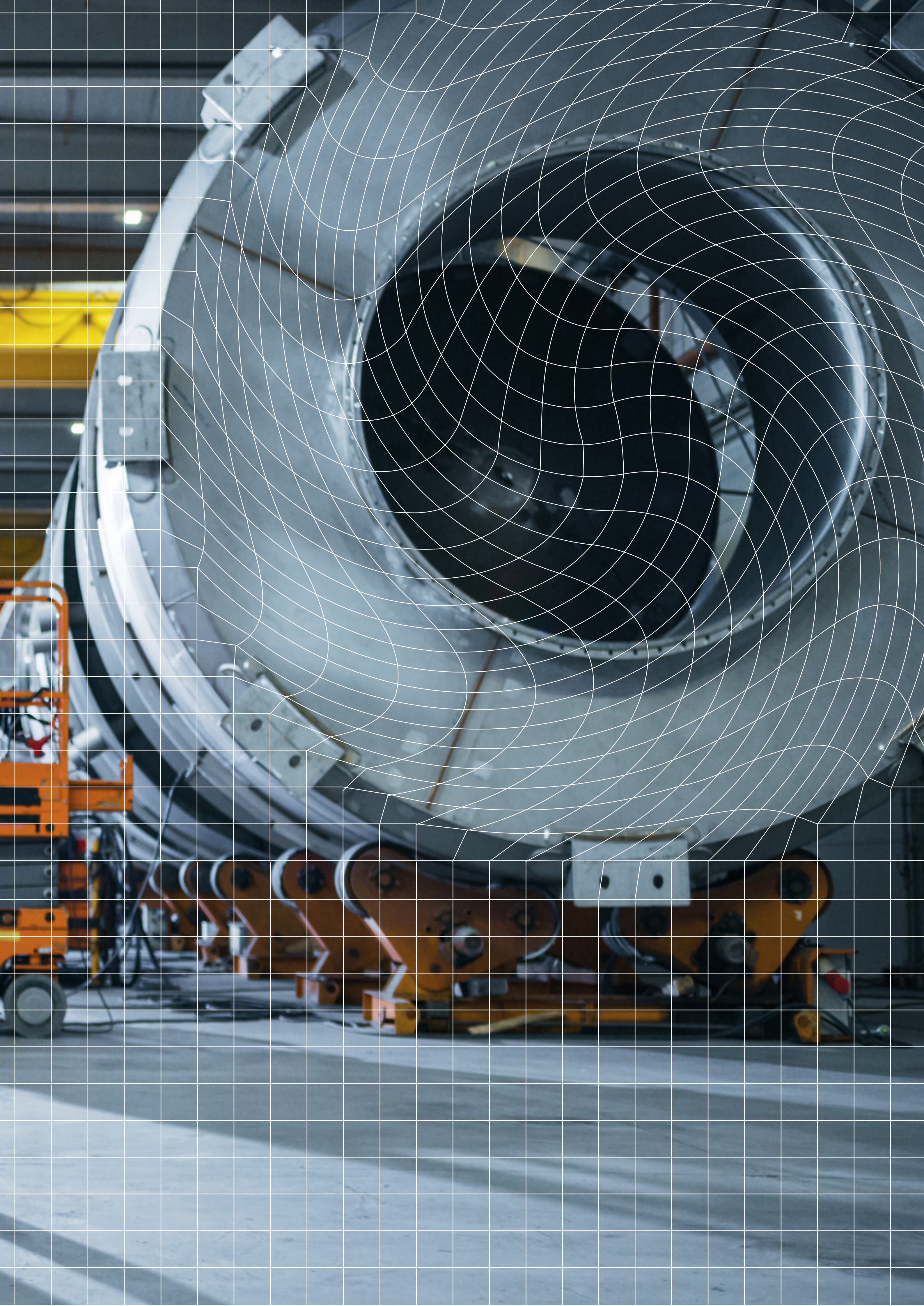
[48] BEIS (2019) *Energy Trends: June 2019, special feature article - Change to method of estimating sector demand for oil products*.

[49] BEIS (2019) *Energy Consumption in the UK (ECUK)*.

[50] NHS (2020) *Delivering a ' Net Zero' National Health Service*

Chapter 4

Manufacturing and construction



Introduction and approach

This chapter sets out the method for the manufacturing and construction sector Sixth Carbon Budget pathways.

The scenario results of our costed pathways are set out in the accompanying *Advice report*. Policy implications are set out in the accompanying *Policy report*.

For ease, these sections covering pathways, method and policy advice for the manufacturing and construction sector are collated in *The Sixth Carbon Budget – Manufacturing and Construction*. A full dataset including key charts is also available alongside this document.

We set out our analysis in the following sections.

1. Background
2. Options for reducing emissions
3. Analytical approach

a) Current emissions

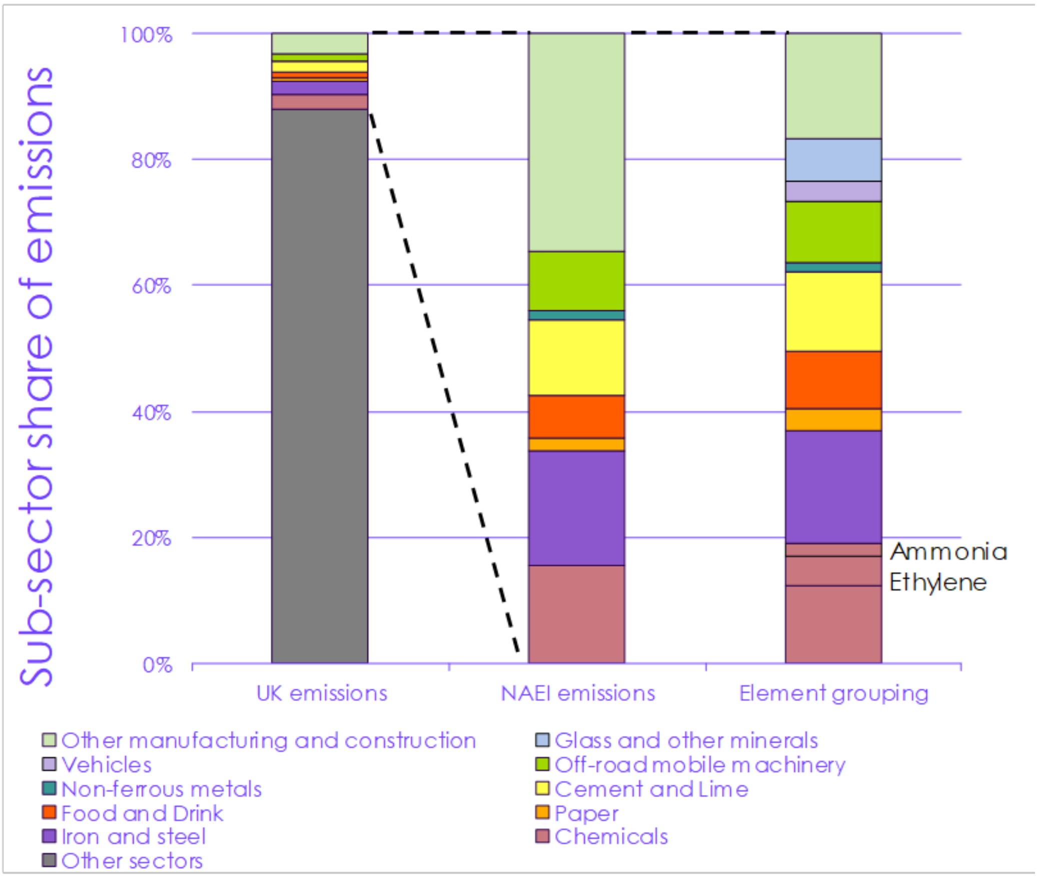
Greenhouse gas emissions from manufacturing and construction were 66 $MtCO_2e$ in 2018, 12% of the UK total (Figure 4.1):

- Manufacturing represents 90% (60 $MtCO_2e$) of this sector's emissions. Of these, 86% were from fuel combustion (for high- and low-grade heat, drying/separation, space heating and on-site electricity generation) and 14% were process emissions (which arise from a range of chemical reactions e.g. from the calcination of limestone for cement). Manufacturing emissions are spread across a wide variety of subsectors (e.g. cement, iron and steel, chemicals).

- The remaining 10% (6 $MtCO_2e$) of emissions were from off-road mobile machinery (ORMM). Off-road mobile machinery is 77% construction and 12% mining equipment. An additional 3% of emissions come from ORMM use in transport infrastructure (e.g. harbours, tunnels, bridges) with a wide variety of applications making up the rest of this subsector. Emissions in this sector come from the combustion of diesel, which is used as a fuel.

- Most (98.6%, 65.4 $MtCO_2e$) emissions were of CO_2, 0.6% (0.4 $MtCO_2e$) were of CH_4 and 0.8% (0.5 $MtCO_2e$) of N_2O.

Figure 4.1 Breakdown of manufacturing and construction emissions (2018, 66 $MtCO_2e$)



Source: National Atmospheric Emissions Inventory (2020) *Breakdown of UK GHG emissions by source and greenhouse gas;* CCC analysis.

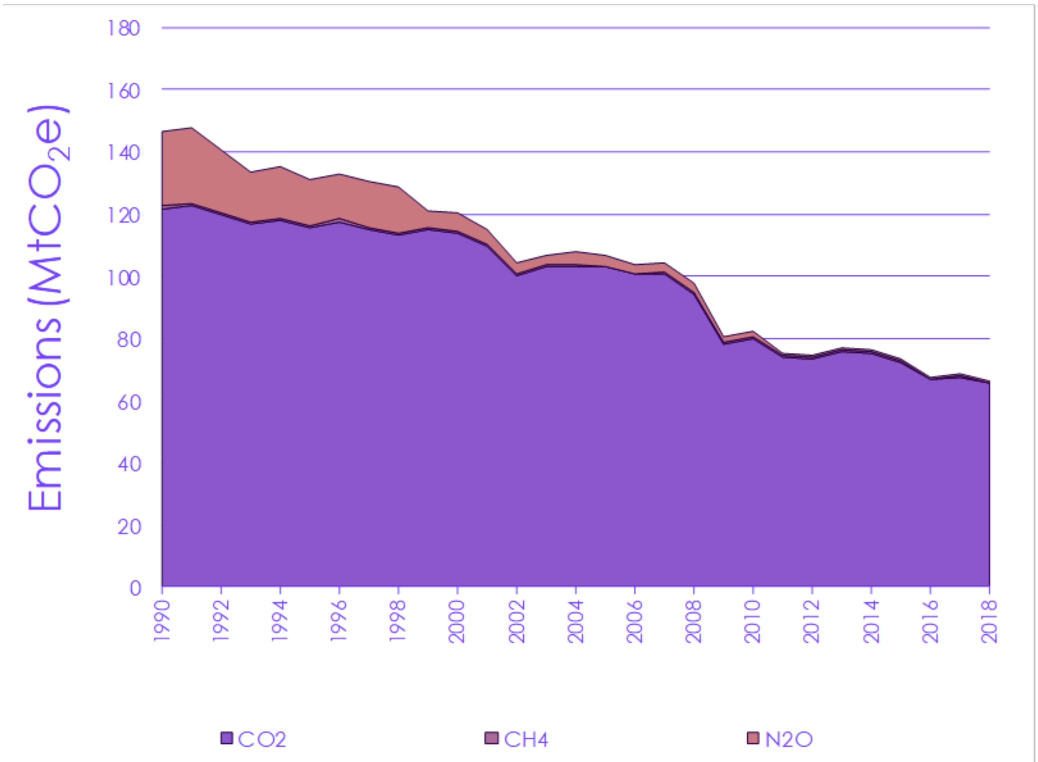
Direct emissions from manufacturing and construction fell by 2% in 2019. Emissions were 56% below the 1990 baseline (Figure 4.2). More detailed sectoral data are produced with a one-year lag. The 1% rise in emissions in 2017 was largely due to rises in chemical process emissions, as well as process emissions from food, drink and tobacco. This followed a drop in 2016 from a reduction in iron and steel production, following the closure of Redcar steelworks in Teesside.

We also analyse factors that contribute to a change in emissions, attributing changes to:

- Output effects (e.g. recession-related emissions reduction);
- Structural effects (e.g. manufacturing output moving towards less carbon-intensive sectors);
- Switching to fuels with higher or lower direct emissions (e.g. fossil fuel to electricity); and
- Energy intensity (e.g. due to energy efficiency, changes in plant utilisation or product mix).

Our decomposition analysis* suggests that over the period 2009-2017 industrial output grew 10%, and the 25% fall in direct CO_2 emissions can be attributed to a structural movement towards a less carbon intensive mix of industrial output (accounting for 25% of the change), improvements in energy intensity (50%) and changes in fuel mix (25%).†

Figure 4.2 Trends in manufacturing and construction emissions



Source: National Atmospheric Emissions Inventory (2020) *Breakdown of UK GHG emissions by source and greenhouse gas;* CCC analysis.

* Data supplied by Ricardo Energy and Environment

† Numbers rounded to nearest 5%.

This section sets out the different options for reducing emissions from manufacturing and construction in the UK.

a) Resource efficiency

Reducing the flow of materials through the economy and using products more efficiently (and for longer) can reduce manufacturing emissions, as part of a shift towards a more circular economy. A range of different measures are detailed in Box 4.1 in section 3, and fall into two categories: reduced end-user consumption of resources, and more efficient use of resources in production. Some of these measures involve behaviour change on the part of the consumer. These typically involve increased recycling, using products for longer, and sharing resources (e.g. car clubs).

b) Material substitution

Material substitution can reduce manufacturing emissions by switching from high-embodied-carbon materials to low-embodied-carbon materials. Measures include using wood in construction and using replacements to clinker (e.g. fly ash) in cement.

c) Energy efficiency

Using energy more efficiently reduces operating costs while cutting emissions. The energy efficiency measures that we include are 'low-regret' measures that often save significant fuel costs. Measures include process and equipment upgrades, installing/improving heat recovery systems, and clustering/networking with other sites and businesses to efficiently utilise waste heat and other by-products.

d) Fuel-switching

Fuel switching in manufacturing

Hydrogen, electricity and bioenergy can all be used to meet heat, motion (and electrical) demands, thus replacing the use of fossil fuels and reducing GHG emissions.

- There are a range of hydrogen, electrical and bioenergy heating technologies, which are designed to provide different types of heat demand.
- Some fuels or heating technologies have wider potential than others. For example, biomass is not always suited to replacing natural gas for direct high-temperature heating because the resulting combustion gases have a less desirable composition than those from natural gas.
- Biomass should only be used in applications with CCS in the long-term, based on the assessment of best uses in our Biomass Review.[1] This combination is referred to as Bioenergy Carbon Capture and Storage (BECCS) and has the net effect of removing CO_2 emissions from the atmosphere. These removals are counted in our Greenhouse Gas Removals sector (see Chapter 12).

- Each of these fuels is already used in the manufacturing and construction sector although sometimes they are not low-carbon and/or not used for energy. In 2018, 26% of energy demand in manufacturing and construction was met through electricity, with a further 12% from biomass and waste.
    - Electricity is currently used to meet a variety of energy demands in manufacturing and construction, including driving motors and to produce process heat. The largest electricity-using sectors are other manufacturing, chemicals, and food and drink.
    - Biomass and waste are currently used to produce electricity and heat in the cement and paper industries. Waste includes the use of waste solvents, wood, scrap tyres, and municipal solid waste.
    - Hydrogen is currently used in ammonia production, as an input to the Haber-Bosch process. This hydrogen is produced from fossil gas without CCS, so it is not low-carbon. Hydrogen production for fuel use is covered separately (Chapter 6).

We group a couple of other technologies in with fuel-switching, that may be regarded as a process change, rather than fuel-switching.

- In most existing primary steel production, coke (made from coal) is used as a reductant in blast furnaces. Hydrogen-based direct reduction of iron (DRI), can replace coke as the reductant with hydrogen (so, in part, the reductant is switched rather than the fuel). This process change leads to water vapour being produced, instead of CO_2.
- Electric arc furnaces (EAF) use different materials (e.g. recycled or scrap steel) to blast furnaces, so may be considered a different process, rather than fuel switching, although in this case the fuel is switched.

Fuel switching in off-road mobile machinery (ORMM)

Off-road mobile machinery (e.g. forklifts, generators) typically use diesel as a fuel. Multiple options are available to decarbonise ORMM, including electricity, hydrogen, and biodiesel. The sector will likely require a mix of these abatement options, given the wide range of equipment that aims to meet specific needs for construction and mining.

- Hydrogen and electricity are likely to provide long-term solutions for abatement. Not only would they reduce emissions, but they could lead to fuel cost savings that would benefit the sector, as both technologies are more efficient than burning diesel.
- However, the adoption of hydrogen depends on the development of a wider hydrogen infrastructure to reduce costs and ensure fuel availability for construction sites.
- There could similarly be barriers in the uptake of electricity, as construction sites will need to accommodate space for battery swapping or connections to the electricity grid.
- Biodiesel could play a role as a transition fuel to start decarbonising the sector, provided sufficient bioenergy is available.

e) Carbon Capture and Storage (CCS)

CCS can be used to capture CO_2 produced by larger industrial point-sources, and transport it to a CO_2 storage site, thus reducing emissions to the atmosphere. The captured CO_2 may alternatively be used in Carbon Capture and Use (CCU), although the potential amount that could be used is expected to be substantially smaller than that which could be stored.

CCS is particularly important in the manufacturing sector, as it can abate emissions that cannot be addressed simply by switching to low- or zero-carbon energy. This includes capturing non-combustion process CO_2 emissions (from chemical reactions such as the calcination of limestone in cement production) and combustion emissions, including those arising from the combustion of internal fuels (gases that are produced as part of the industrial process).

When capturing emissions from biomass combustion, reduction or fermentation, this results in BECCS.

f) Other

Greenhouse gas emissions from flaring in iron and steel production and leakage from processes in the manufacture of chemicals can also be addressed. Flaring emissions can be reduced by capturing methane and selling it. Leakage of methane in the chemicals subsector can be reduced through periodic leakage detection and repair or continuous monitoring, to find the leaks as early as possible and limit the volume of methane released.

The Balanced Net Zero Pathway and the four exploratory scenarios in this sector vary in several ways, including their energy mix, levels of resource efficiency and rates of decarbonisation. More information on this is in Chapter 3, Table 3.3a of the *Advice report*, and the dataset that accompanies the report.

These pathways and scenarios are underpinned by new analysis in several areas, as well as some of the evidence and analysis used for our 2019 *Net Zero* advice[2] and the accompanying *Net Zero technical report*.[3]

New analysis includes work commissioned from Element Energy on deep-decarbonisation pathways for UK industry and internal analysis of options for decarbonising off-road mobile machinery. We have also updated our synthesis of evidence on resource- and energy-efficiency options, and our baselines.

The structure of our analysis follows the following steps:

- It starts by considering a baseline world where there is no new climate change mitigation policy beyond 2019.
- From this emissions baseline we deduct, in sequence, abatement from resource efficiency, material substitution and energy efficiency.
- We then deduct abatement from 'deep decarbonisation' options: fuel-switching, CCS and measures to reduce methane flaring, venting and leakage.[*]

We set out the approaches we have taken for each of these steps, below.

a) Baseline projections

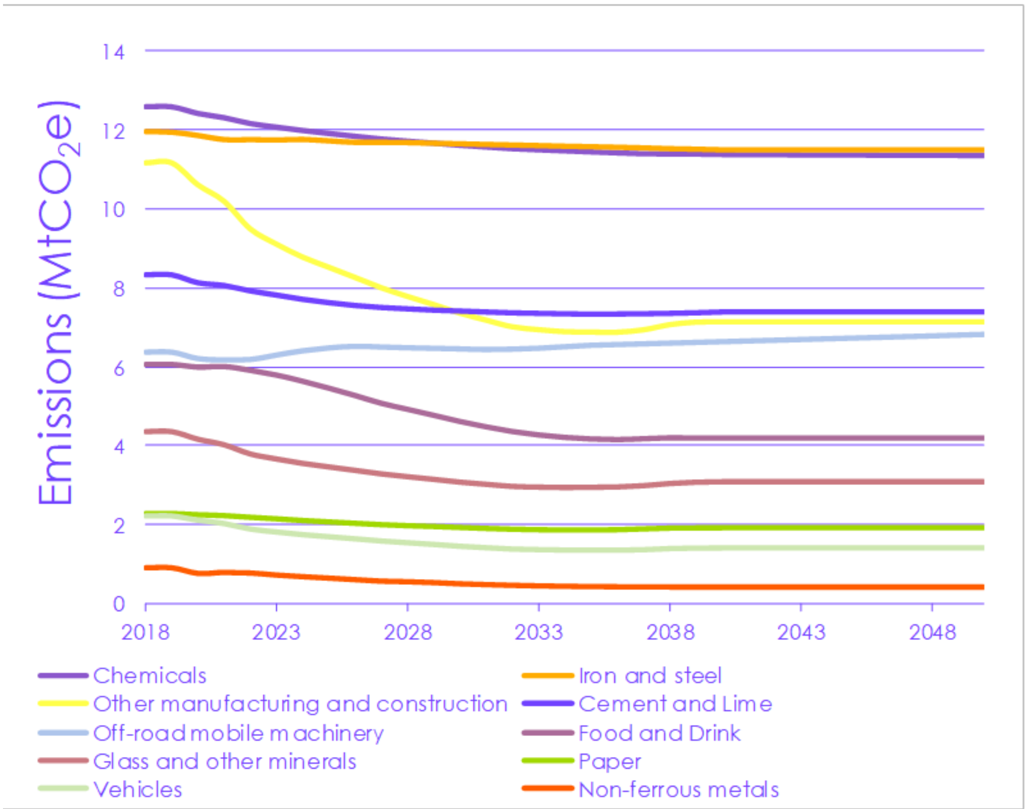
Our emissions baseline (Figure 4.3) starts aligned to historical emissions for 2018, the latest year with fully reported data, based on the National Atmospheric Emissions Inventory (NAEI).[4] For combustion emissions, corresponding energy data are drawn from a mix of the NAEI and DUKES,[5] allowing for the inclusion of existing electricity and bioenergy use (which are not reported in the Inventory).

Future energy and emissions are projected from the historical 2018 data using the scaling (% change from 2018) of the BEIS Energy and Emissions Projections 2019 reference case.[6] This reference case accounts for a small amount of projected abatement from existing 'firm' policies. We made several bespoke assumptions in the use of these projections, in particular:

- We do not use the BEIS energy and emissions projections to project the change from 2018 to 2019. This reflects that the BEIS econometric methodology results in large jumps in emissions from the last historical year (2018) to the first projected year (2019), which we know from provisional data have not happened.
- We do not use the projections for the chemicals sector, for which the econometric method projects a very large decline in emissions, instead assuming that baseline emissions stay constant for most of the subsector.

[*] There is only a small amount of the methane reduction measures required in this sector.

Figure 4.3 Baseline projections for subsectors in manufacturing and construction



Source: National Atmospheric Emissions Inventory (2020) *Breakdown of UK GHG emissions by source and greenhouse gas;* BEIS (2020) *Updated energy and emissions projections: 2019*; Element Energy (2020) *Deep-decarbonisation pathways for UK Industry, report for the Climate Change Committee*; CCC analysis.

b) Resource efficiency, energy efficiency and material substitution

To establish pathways for abatement from resource efficiency, energy efficiency and material substitution, we refreshed our synthesis of evidence on the abatement potential in these areas.

Resource efficiency

Resource efficiency measures are divided into two categories: more efficient use of resources in production and lower end-user consumption of resources. Box 4.1 sets out the evidence we used on resource efficiency and how we constructed our scenarios using this evidence. Table 4.1 summarises the resource efficiency measures included.

Measures that reduce consumption of resources (a third of the resource efficiency abatement) are assumed to result in lower industrial output, as we assume similar measures are applied by trading partners – for example as a result of the EU's work on the Circular Economy. For the purpose of our geographical analysis, where this reduced consumption, combined with baseline change, results in a reduction of a subsector's output, we assume that 80% of this reduction is achieved by site closures, while 20% comes from reduced output of the remaining sites.

Abatement from these resource efficiency measures is applied to the baseline before material substitution and energy efficiency.

Box 4.1:
Summary of latest evidence on resource efficiency and material substitution

Using a study from the University of Leeds and University of Manchester, and engaging with industry stakeholders, we have considered where resource efficiency can reduce UK greenhouse gas emissions. The measures we have considered are summarised in Table 4.1.

From the baseline, first we accounted for significant changes across the economy that would affect demand: the move away from petroleum for transport and other uses leading to big reductions in demand from oil refineries, and changes to the amount of waste arising.

We then included specific resource efficiency measures. The study produced three scenarios for material productivity (low, medium and high), reflecting different levels of ambition in changing production and consumption practices.

- The medium scenario leads to a 6% reduction in UK industrial emissions in 2050 and is implemented for our Headwinds scenario. The high scenario leads to an 13% reduction in UK manufacturing and construction emissions in 2050 and is implemented for our Balanced Net Zero Pathway, Widespread Engagement and Tailwinds.
- In the Widespread Innovation scenario, we anticipate lower consumer engagement on the consumption of resources savings compared to Widespread Engagement, although further potential for improvements in resource use in production may be realised through new innovations. Therefore, the Widespread Innovation scenario uses a medium-high material productivity scenario, slightly lower ambition than Widespread Engagement, resulting in an emissions reduction of 11% in 2050 across the manufacturing and construction sector.
- The Balanced Net Zero Pathway follows the high scenario, which is an ambitious set of measures requiring changes to many people's lifestyles and industrial practices. However, there is evidence that even larger emissions savings are possible, with the Energy Transition Commission estimating that 40% of emissions from heavy industry can be avoided through circular economy strategies.

The study does not include financial savings and costs associated with the measures. We were also not able to find a wider evidence base on savings and costs of resource efficiency measures. Resource efficiency could lead to cost savings. However, these are dependent on structural changes in the economy for which there is little evidence available to date. It is unclear whether these would offset any costs associated with the uptake of resource efficiency measures. We have assumed that the savings balance the costs. We seek to improve our evidence base in this area in future, which would necessitate understanding how savings and costs flow through the economy.

Source: Scott, K., Giesekam, J., Barrett, J. and Owen, A. (2018) *Bridging the climate mitigation gap with economy-wide material productivity*, Journal of Industrial Ecology, https://doi.org/10.1111/jiec.1283, Energy Transitions Commission (2018) *Mission Possible*, http://www.energy-transitions.org/mission-possible
Notes: Scott et. al. scenarios have been adjusted to include CCC analysis on clinker substitution in cement, wood in construction, increase in use of recycled glass, and analysis from the Government's Industrial Decarbonisation and Energy Efficiency Roadmaps to 2050 for yield improvements in steel production.

Table 4.1 Summary of resource efficiency and material substitution strategies		
Sector	**Measures to reduce resource use in production**	**Measures to reduce end-user consumption of resources**
Clothing and Textiles	• Efficiency improvements in fibre and yarn production, dyeing and finishing	• Disposing of less and reusing and recycling more • Using clothes for longer
Food and Drink	• Reducing food waste in food services and hospitality sectors	• Reducing household food waste
Packaging	• Eliminating or reducing weight of packaging (metal, plastic, paper, glass) • Increasing use of recycled glass	
Vehicles	• Reducing steel, aluminium and additional weight without material or alloy changes • Yield improvement (metals) in car structures through cutting techniques • Steel fabrication yield improvement • Reusing discarded steel products	• Shifting from recycling to refurbishing • Using car clubs • Using cars for longer
Electronics, Appliances, Machinery and Furniture	• Reducing steel without material or alloy changes • Steel fabrication yield improvement • Reusing discarded steel products in industrial equipment	• Sharing less-frequently used electrical appliances, power tools and leisure equipment • Longer use of products • Remanufacturing instead of throwing away • Disposing of less and reusing and recycling more
Construction	• Design optimisation to reduce material inputs • Increasing use of wood in construction • Increasing clinker substitution in cement • Reusing materials	

Material substitution

Next, we applied material substitution from high-embodied-carbon to low-embodied-carbon materials. This accounts for a decrease in cement, mortar and brick production and an increase in timber production for increased wood in construction. There is also an increase in substitution of high-carbon clinker for either waste products such as fly ash, or ground granulated blast furnace slag or innovative new types of lower-carbon cementitious materials. In addition, some raw material is replaced with cullet (from recycled glass) in glass production.

Energy efficiency

Our energy efficiency abatement pathways are primarily based on the 'Max Tech' scenarios from the '2015 BIS Industrial Decarbonisation and Energy Efficiency Roadmaps to 2050',[7], but also assume some additional abatement from sectors not covered by the Roadmaps.

- We have evaluated the abatement costs for all of the measures in the Max Tech pathways and included all of those that are cheaper than 350 £/tCO2e (consistent with our approach to carbon valuation – see Chapter 1), as well as the majority of measures which are overall cost negative.

- There are likely to be energy efficiency opportunities in the less-energy-intensive sectors, where energy efficiency opportunities may be less salient to decision makers. We assume a 12 TWh overall energy demand reduction across the less-energy-intense sectors based on BEIS analysis.[8]

The energy efficiency measures covered by the roadmaps are generally cost-saving, so we have applied these measures across scenarios. We have updated the savings and costs from the 2015 roadmaps to reflect our updated energy costs.

c) Deep decarbonisation measures

To establish our pathways for abatement from deep decarbonisation measures we commissioned Element Energy to substantially extend previous analysis produced for the CCC and BEIS and develop pathways for the CCC (Box 4.2). This involved gathering new evidence and using this within a new Net Zero Industrial Pathways (N-ZIP) model. We also undertook new analysis internally on abatement pathways for off-road mobile machinery (Box 4.3).

The Element Energy evidence gathering, N-ZIP modelling and our subsequent pathways and scenarios have several key features. In particular, the results on the pace of deep decarbonisation were carefully considered and account for considerable new evidence.

- The pathway results account for time for supply chains to scale up and new low-carbon technologies to scale up, based on consultation with industry about what is possible if policy is put in place.
- The results allow time for infrastructure to be rolled out, for example for CO_2 and hydrogen networks and consider the interaction of the location of sites with when hydrogen or carbon capture and storage (CCS) options may become cost-effective.
- The results allow time for effective policy to be developed and implemented, before deployment.
- The modelling includes a broad set of technology options, with updated cost data.
- The pace of decarbonisation is established to reflect a level of effort that is consistent with that in other sectors of the economy, Net Zero ambition overall and the UK's commitments under the Paris Agreement. This is partly achieved through placing a value on carbon abatement to drive action (see Chapter 1). Accounting for this value of carbon, the N-ZIP model is used to identify when sites should decarbonise processes in order to maximise the net present value of their overall operations. It simultaneously accounts for the supply chain, infrastructure and policy considerations outlined above. This approach balances the value of action with waiting for a substantially cheaper technology.
- The scenarios account for non-cost factors, such as low salience of energy costs for very small sites and the potential for a preference towards retrofit over refitting.
- Our pathways of abatement from resource efficiency, energy efficiency and material substitution were input into the N-ZIP model as assumptions. This meant that deep decarbonisation measures were considered only for adjusted energy and emissions 'baselines' that account for the efficiency measures. Our analysis of fuel switching in off-road mobile machinery was also passed through the N-ZIP model for completeness.

- In the Balanced Pathway some deep decarbonisation actions are included in the early years to ensure that options for further deployment remain open in later years, reflecting real-life uncertainty about which technologies will prevail. This also helps to bring down costs of technologies.

A few small amendments were applied to the deep decarbonisation abatement measures coming from the manufacturing and construction pathways and scenarios from the Element Energy analysis, resulting in a difference between the results reported in the Element Energy report and our results.

In particular, CCS capture rates were adjusted in the period pre-2040 to 90%, from higher rates. A final version of our off-road mobile machinery analysis was also included at this stage.

Box 4.2

Summary of Element Energy analysis and report on Deep Decarbonisation Pathways for UK Industry

We commissioned Element Energy to improve our evidence base and develop pathways for deep decarbonisation from UK industry emissions – currently 110.6 $MtCO_2e$ in total of which 66.2 $MtCO_2e$ is manufacturing and construction, 39.2 $MtCO_2e$ is fossil fuel supply (see Chapter 6) and 5.1 $MtCO_2e$ is energy from waste (see Chapter 10).

The deep decarbonisation abatement technologies considered for each sector are detailed in the 'options to reduce emissions' section of the relevant chapter of this report (e.g. Chapter 4, section 2 for manufacturing and construction).

The research included four key components (a) advancing our evidence on the constraints on the pace of technology and infrastructure deployment (b) improving our evidence on technology availability, costs and non-cost factors determining technology choice (c) considering geographical resolution within both these aspects (d) combining these evidence bases in a net-zero industry pathways (N-ZIP) model to produce socially-optimal industry decarbonisation pathways.

Given (a) – (c), the N-ZIP model accounted for:

- absolute constraints on pace relating to technology availability, supply chain capacity, CO_2 and hydrogen infrastructure availability, biomass availability and time to develop policy;
- cost model of all relevant decarbonisation options, accounting for the location of a site relative to abatement options (e.g. hydrogen or CO_2 transportation), the levels of hydrogen and CCS use elsewhere in the economy, and the costs of scrappage; and
- salience of energy costs to the smallest energy users and the potential for a preference towards retrofit over refit.

These factors fed into criteria for deciding when and which abatement measure (if any) was socially-optimal to mitigate each emitting-process at each site:

- Net Present Value (NPV) at the site-level was used to make decisions. This considers the difference between the cost and benefits of abatement and the counterfactual. It accounts for the discounting and the value of emissions that are abated.
- The model ranks the available decarbonisation options for each site for each year by their NPV.
- The highest ranked option is initially chosen for each process on each site, providing the NPV is positive. This was then checked against the model constraints. If a model constraint was exceeded, the model switched to the next ranked option. Where multiple options exceed a model constraint, those with the highest NPV were prioritised.

Figure 4.4 sets out a schematic of the N-ZIP model methodology.

Key model assumptions included:

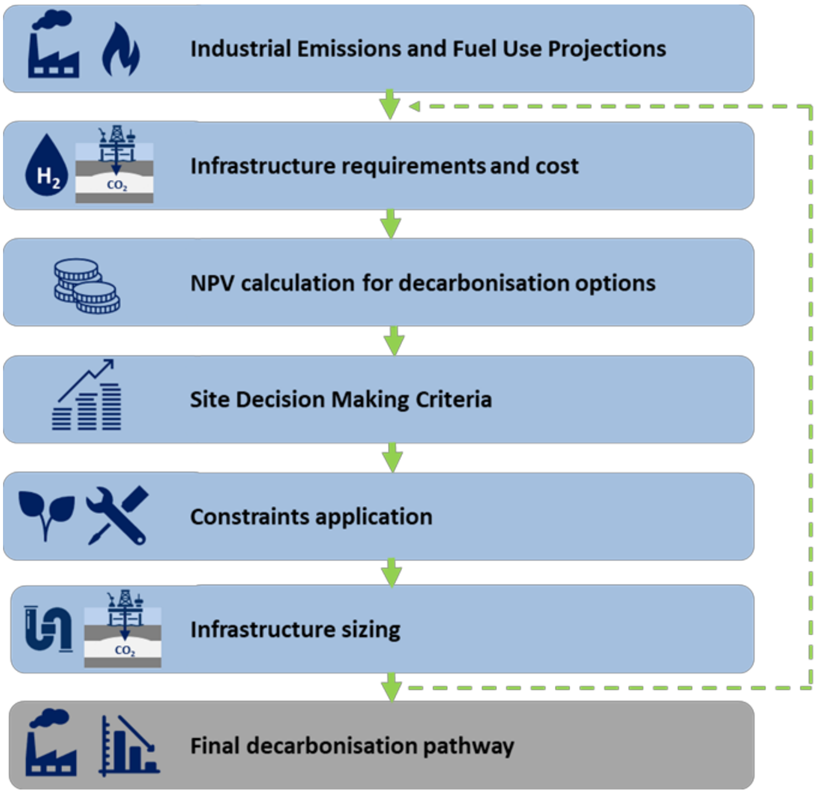
- Long-run variable costs for energy (i.e. excluding profit and policy costs), were used. These costs are consistent with fuel costs in the Sixth Carbon Budget analysis for other CCC sectors (see Chapter 1). Element Energy analysis informed the costs of CO_2 transport and hydrogen infrastructure.
- The capacity of supply chains limits the proportion of a subsector that can decarbonise each year through deep decarbonisation measures. Following a dedicated consultation, under the Balanced Net Zero Pathway the constraint was set at 5%/year of baseline emissions in 2025, and increased annually by 0.5%/year until reaching 10%/year, at which it was fixed from 2035 onwards. This constraint applied independently to other constraints, such as technology availability.
- Target consistent carbon values are as set out in Chapter 1 for the Balanced Net Zero Pathway, Headwinds, Widespread Engagement and Widespread Innovation scenarios. Tailwinds uses a higher carbon value path of £450/tCO_2e in 2050, discounted backwards by 3.5% per year.
- Where hydrogen can be used for fuel-switching, the existing appliance can be retrofitted to used hydrogen. It is assumed that existing appliances cannot be retrofitted to use electricity and that if conversion is applied before the lifetime end of the counterfactual technology, then a cost of scrappage is incurred.
- Biomass is only used in subsectors that are already using significant amounts of biomass and is allocated according to the CCC hierarchy for biomass use (see Chapter 6).
- The type of processes within industrial subsectors do not change in the period to 2050.
- The model used CO_2 capture rate of 95% for CCS in the Balanced Net Zero Pathway, Headwinds, and Widespread Engagement scenarios and a capture rate of 99% in the Widespread Innovation and Tailwinds scenarios. The CCC final results assume capture rates of 90% up until 2040.

Nearly all emissions were allocated at least one suitable abatement technology. Remaining emissions fell into two categories:

- Processes where no abatement was applied. This occurred where the abatement was too expensive or no suitable abatement technology was identified.
- Residual emissions from abatement technologies that do not remove 100% of emissions (e.g. CCS, reductions in flaring, venting and leakage).

Further details can be found in the Element Energy report published alongside this report: 'Deep-decarbonisation pathways for UK Industry'.

Figure B4.2 Schematic of the N-ZIP model methodology



Source: Element Energy Element Energy (2020) *Deep-decarbonisation pathways for UK Industry, report for the Climate Change Committee.*

Source: Element Energy (2020) Deep-decarbonisation pathways for UK Industry, report for the Climate Change Committee.

Box 4.3:
Summary of new research on decarbonising off-road mobile machinery

The analysis for off-road mobile machinery (ORMM) decarbonisation was carried out internally by the CCC.

- For electric or hydrogen machinery, we assumed that they are linearly deployed and displace conventional ORMM to reduce emissions.
- The composition of the fleet is based on the 2004 Department of Transport survey. For the purposes of our work, we created categories of ORMM to encompass the wider range of equipment that exists in the sector. These categories considered the power and usage to estimate the contribution to emissions of different types of off-road mobile machinery.
- Thereafter, we were able to cost the low-carbon ORMM in each category. We assume that the costs of electric and fuel cell batteries are the same in ORMM as in transport at £65/kWh and £174/kW in 2050, respectively. In addition, CCC analysis provided us with electricity and hydrogen fuel costs.
- The core of our analysis evaluated hydrogen, electricity and biodiesel as potential abatement options. In each of our scenarios, the option with the lowest NPV was selected to decarbonise each category of off-road. This varied for each category in the different pathways. In the Balanced Net Zero Pathway, deployment by 2050 is mostly hydrogen for large machinery and electricity for small and medium machinery.

Source: Department for Transport (2004) *Non-Road Mobile Machinery, Usage, Life, and Correction Factors*, CCC analysis

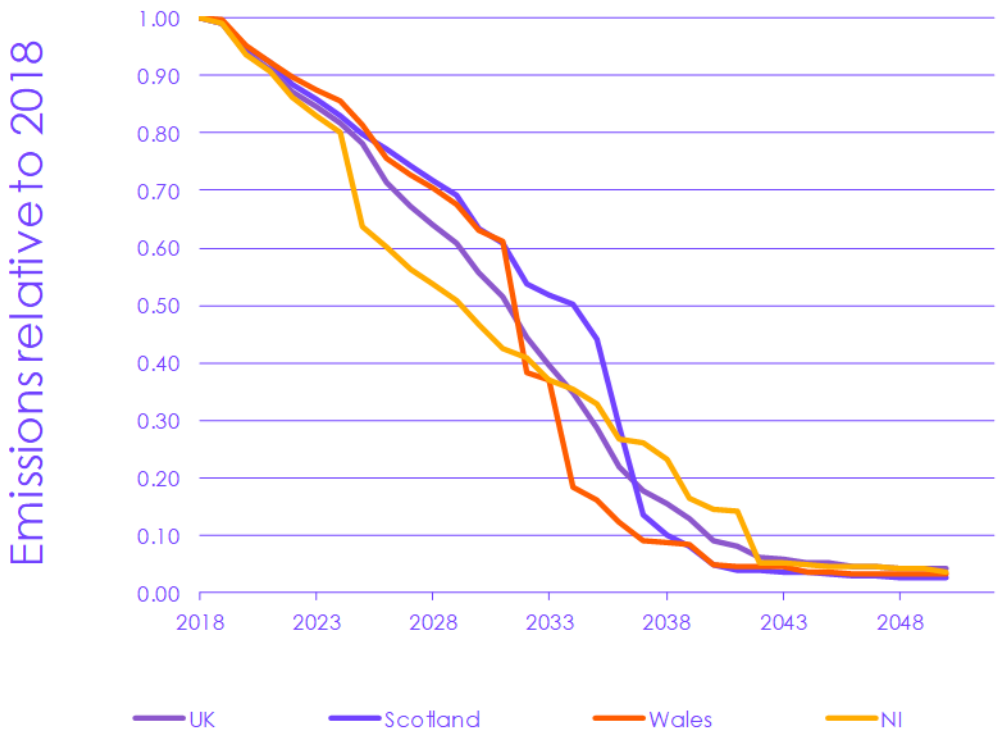
d) Deriving the emissions paths for the devolved administrations

The use of site-level (and for small sites and regionally assigned data) in the N-ZIP model provided emissions, abatement and costs data that could be attributed to the devolved administrations (DA). For off-road mobile machinery, we did not have regionally assigned data, so we assume the historical distribution of emissions across DAs remain the same over time.

We used this data to produce a pathway for each DA for each scenario. The Balanced Net Zero Pathway for manufacturing and construction in the devolved administrations is shown in Figure 4.4.

The steep decline in Welsh emissions in the early 2030s reflects the conversion to low-carbon production of Port Talbot Steelworks.

Figure 4.4 Balanced Net Zero Pathway emissions for manufacturing and construction in devolved administrations



Source: CCC analysis.

e) Uncertainty

We have used the results of our analysis to inform our recommendations around future deployment of industrial decarbonisation measures. However, there is much uncertainty about many of the assumptions that we have used in our analysis.

Therefore, we have considered a range of sensitivities to the assumptions, to form different pathways, with the purpose of identifying a range of different futures and the most – and least – robust conclusions of the analysis.

More detail on the model sensitivities relating to deep decarbonisation measures is given in the accompanying report by Element Energy.[9] Sensitivities we explored included varying the following assumptions:

- **CO_2 and hydrogen demand from other sectors** did not result in significant changes to the amount of abatement or the options chosen.
- **Biomass availability** had a limited effect, but primarily because we constrained the sectors for which biomass could be used. If relaxed, we would expect a higher level of biomass uptake. However, even when using this bioenergy with carbon capture and storage (i.e. BECCS), this would not result in overall lower emissions across the economy, as this would divert biomass from other BECCS applications.
- **Carbon values.** We tested a higher carbon value in the Tailwinds scenario, which increased abatement, and brought forward the dates at which some abatement occurs.
- **Supply chain constraints** had an impact on the pace of roll-out of abatement technologies. As a result, Element Energy conducted additional research with stakeholders to inform this constraint.
- **Electricity network upgrade costs** had an impact on decision making. As a result, higher connection costs were explored in the Headwinds scenario.
- **Fuel costs** influenced the abatement measure where a site had multiple decarbonisation options, but only had a modest effect on the level and pace of abatement as can be seen from our Headwinds scenario.
- **Scrappage** was included in the cost of electrification. When scrappage was not allowed, this constrained the rate of electrification as an abatement option. To explore this, scrappage was not allowed in the Headwinds exploratory scenario.

We have used the results of these sensitivities to identify low-regrets options for the decarbonisation of manufacturing and construction, as well as low-regrets approaches to deploying hydrogen and CO_2 infrastructure. We have used the scenarios to identify important near-term actions required to keep important alternative pathways open.

Analysis on off-road machinery remains uncertain mainly due to the scarcity of data. Indeed, the latest survey on fleet composition dates to 2004. As a result, it is unclear how the fleet has and might continue to evolve in the future. In addition, decarbonising ORMM with hydrogen will require the development of a hydrogen infrastructure. Without hydrogen, reducing emissions would be possible, however access to electricity on construction and mining sites would need to improve.

Endnotes

[1] Committee on Climate Change (2018) *Biomass in a low-carbon economy*. https://www.theccc.org.uk/publication/biomass-in-a-low-carbon-economy/

[2] CCC (2019) *Net Zero – The UK'S contribution to stopping global warming*

[3] CCC (2019) *Net Zero – Technical Report*

[4] National Atmospheric Emissions Inventory (2020) *Breakdown of UK GHG emissions by source and greenhouse gas*

[5] BEIS (2019) *Digest of UK Energy Statistics*

[6] BEIS (2020) *Updated energy and emissions projections: 2019*. https://www.gov.uk/government/publications/updated-energy-and-emissions-projections-2019

[7] DECC & BIS (2015) *Industrial Decarbonisation and Energy Efficiency Roadmaps to 2050*. https://www.gov.uk/government/publications/industrial-decarbonisation-and-energy-efficiency-roadmaps-to-2050

[8] BEIS (2019) *Leading on clean growth: government response to the Committee on Climate Change 2019 progress report to Parliament – Reducing UK emissions*

[9] Element Energy (2020) *Deep-decarbonisation pathways for UK Industry, report for the Climate Change Committee*

Chapter 5

Electricity generation

Introduction and key messages

This chapter sets out the methodology applied for the electricity generation sector analysis that informs the Committee's advice on the level of the Sixth Carbon Budget.

The scenario results of our costed pathways are set out in the accompanying Advice Report. Policy implications are set out in the accompanying Policy Report. For ease, sections covering pathways, method and policy advice for electricity generation are collated in the Sixth Carbon Budget – Electricity Generation. A full dataset including key charts is also available alongside this document.

The key messages for electricity generation are:

- **Emissions from electricity generation have already fallen by 68% since 1990.** The majority of these emissions reductions happened in the last decade. Emissions fell by 62% between 2008 and 2018, reflecting a move away from coal towards gas and low-carbon generation. The sector was responsible for 15% of UK emissions in 2018.
- **Options for reducing emissions.** Reducing power emissions further will entail increasing the role of renewables and possibly nuclear, and decarbonising dispatchable generation via carbon capture and storage (CCS) and/or hydrogen. In order to accommodate high levels of renewables, demand will also need to become increasingly flexible, which will require improvements in system flexibility from storage, interconnection, and demand-side response.
- **Analytical approach.** The analysis undertaken to develop scenarios for the Sixth Carbon Budget was based on power modelling that explored varying roles for generation technologies given electricity demand from other sectors. Finding least-cost systems that are optimal across hydrogen and electricity supply required complementary off-model analysis that informed the development of our scenarios. We find that it is possible to phase out unabated gas by 2035 and build a power system with 75% to 90% share of variable renewable generation by 2050.
- **Uncertainty.** Our scenarios to 2050 include uncertainties that will need to be resolved. This includes uncertainty over the achievable CO_2 capture rates of CCS; the level of flexibility that smart charging, pre-heating, and storage can provide; the carbon intensity of imported electricity; the ability to ensure security of supply as unabated gas-fired generation is phased out; the future costs of low-carbon technologies; and the implications of a growing electricity system for water use.

We set out our analysis in the following three sections:

1. Current and historical emissions in power
2. Options to reduce emissions and ensure security of supply
3. Approach to analysis for the Sixth Carbon Budget

1. Current and historical emissions in power

Burning of coal and gas are the contributions from electricity generation to the UK's greenhouse gas emissions.

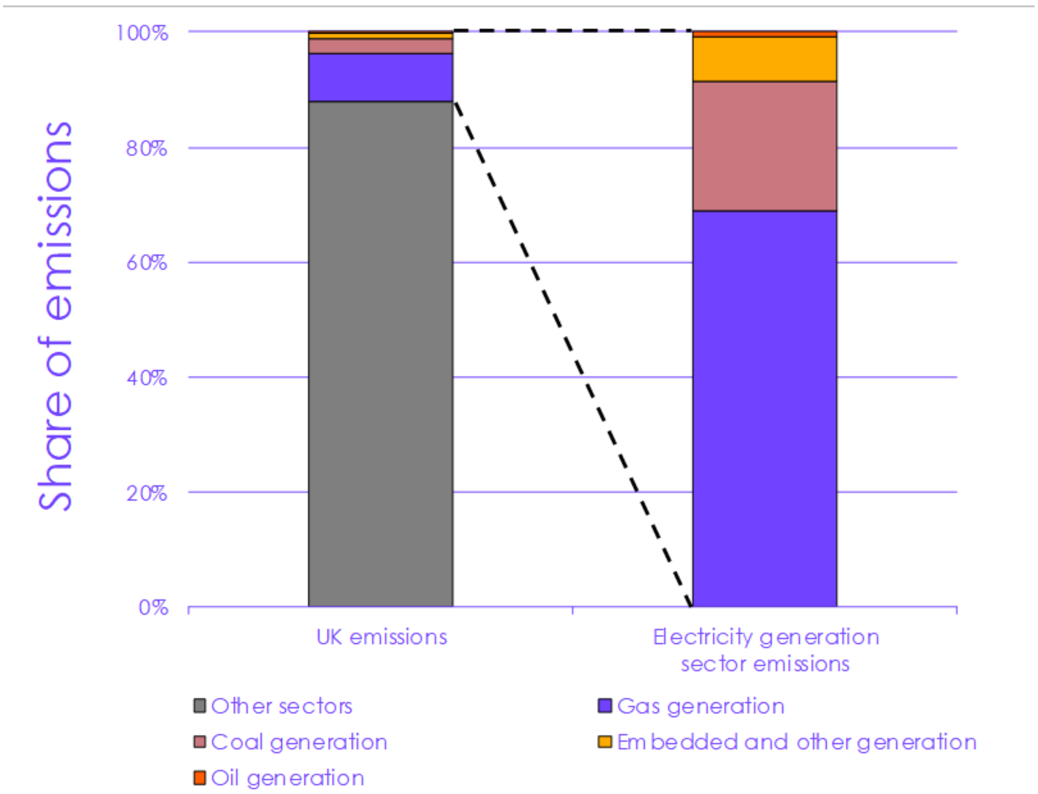
Greenhouse gas (GHG) emissions from the power sector were 65 $MtCO_2$ in 2018, which is 15% of the UK total (Figure 5.1).*

These emissions come from the burning of coal and gas for electricity, with a small proportion from oil and other small-scale embedded generation:

- Gas plants contribute to 70% of power emissions. They provide 40% of total electricity generation.
- Coal accounts for 23% of emissions but only 5% of generation.
- The remaining 7% of emissions come from oil and a variety of other small generation sources.

70% of emissions from electricity generation come from burning natural gas.

Figure 5.1 Breakdown of emissions from electricity generation (2019)



Source: BEIS (2019) *UK Greenhouse Gas Emissions 1990-2017,* and BEIS (2019) *Energy trends: Table 5.1*; CCC analysis.
Notes: Estimates of emissions from coal and gas generation are based on generation from major power producers. Embedded and other generation includes municipal solid waste plants.

Emissions from electricity generation have fallen by 70% since 1990, as the UK has switched from coal to gas and low-carbon generation.

Emissions from electricity generation in 2018 were 68% below 1990 levels (Figure 5.2). Most of these emissions reductions occurred between 2012 and 2018, when emissions fell by 58%.

* Biomass, municipal waste, and coal power emit nitrous oxide (N2O) and methane (CH4). However, these are less than 1% of power emissions, which is why this chapter will focus on CO_2.

This was driven by reductions in electricity demand and a reduction in carbon intensity of generation as coal was replaced by gas and renewables.

Electricity demand has fallen as lighting and appliances have become more energy-efficient (50% of all installed lightbulbs are now low-energy).

- **Lower electricity demand.** In 2018, electricity demand was around 300 TWh. This represents a decline of 12% compared to 2008 levels, and has led to lower generation and hence lower emissions. There was a reduction in both residential and industrial electricity consumption.
  - Residential electricity consumption fell by 12% between 2008 and 2018, even as the UK population grew by 7%. This is due to improvements in energy efficiency of lighting and appliances.
    - Households have seen efficiency improvements in lighting and appliances (e.g. low-energy lightbulbs now account for half of all installed lightbulbs, compared to around 15% in 2009).[1]
    - These trends should continue, as consumers continue to move towards more-efficient technologies. For example, the use of LEDs can contribute to energy savings as they are seven times more efficient than incandescent bulbs.
  - Industrial electricity consumption fell by 20% between 2008 and 2018, despite an increase in industrial output of 10% (see Chapter 4). This reflects structural changes in manufacturing and construction, away from more carbon-intensive sectors in addition to improvements in energy efficiency, particularly in the manufacturing of iron and steel, chemicals, and car manufacturing.[2]

Coal is the most polluting form of electricity generation. In 1990 coal generated 80% of UK electricity. Now it generates less than 5%.

- **Reduction in carbon intensity.** Carbon intensity of electricity generation decreased by 55% between 2008 and 2018, from 535 gCO_2/kWh to 245 gCO_2/kWh. That reflects a shift away from coal towards gas and renewable generation (Figure 5.3). Nuclear also contributes to low-carbon electricity generation.
  - In 1990, coal generated 80% of UK electricity. Following the 'dash-for-gas', that share dropped to 30% where it remained stable until the early 2010s. The introduction of the carbon price floor in 2013, alongside air quality legislation, initiated the phase-out of coal-fired generation. This has contributed to sustained emissions reductions in the sector of 14 $MtCO_2$ per year on average since 2013.
  - Carbon pricing also favoured the uptake of gas generation, which has provided around 40% of total generation since 2000. While emissions of gas-fired electricity are 60% lower than coal, this source of generation contributes to power emissions.
  - Deployment of variable renewables* has also displaced coal generation.
    - Variable renewables now account for 22% of electricity generation, up from 3% in 2008.
    - This increase has been driven by Government commitments to support renewable deployment through Contracts for Difference (CfDs), of which 16 GW of capacity has been auctioned since 2015.

* Wind and solar generation.

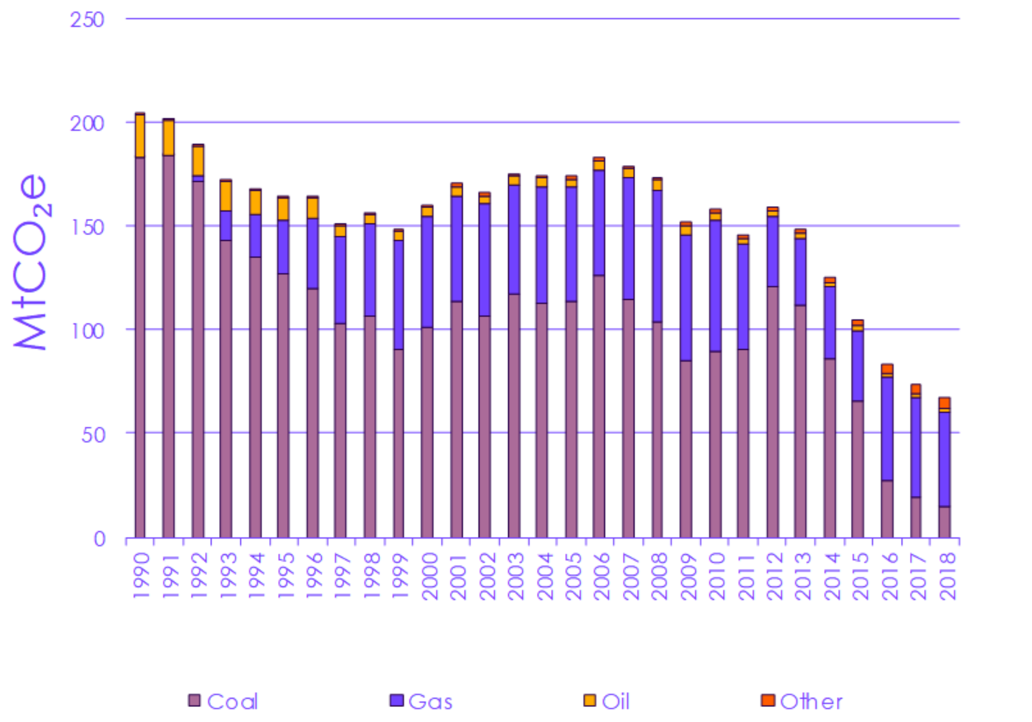
- Since the first contracts where allocated to projects, renewable costs have halved (see Variable Renewables section).

– Nuclear has consistently provided around 20% of UK electricity generation since 2000, with zero emissions.

UK emissions from electricity generation have fallen by 68% since 1990, reflecting a reduction in coal use.

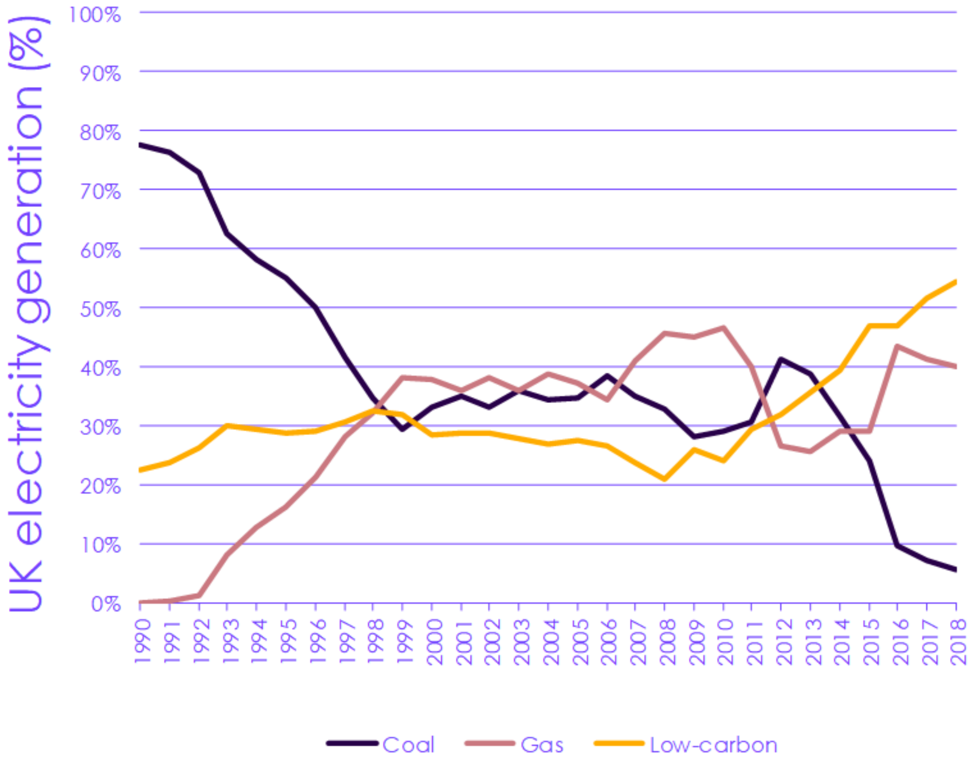
The success of phasing out coal means this now only accounts for less than 5% of electricity generation. The Government has committed to ending the use of coal by 2024. In future, this means efforts to decarbonise electricity generation will need to focus on displacing unabated gas, the remaining source of emissions to which we now turn.

Figure 5.2 Breakdown of emissions from electricity generation (1990-2018)



Source: BEIS (2019) *UK Greenhouse Gas Emissions 1990-2017,* and BEIS (2019) *Energy trends;* CCC analysis.
Notes: 'Other' includes emissions from municipal solid waste.

Figure 5.3 Share of electricity generation by Source (1990-2018)



Source: BEIS (2020) *Energy trends: table 5.1,* and BEIS (2020) *Energy trends: Table 6.1*; CCC analysis.
Notes: 'Other' includes emissions from municipal solid waste.

Continuing to reduce emissions from electricity generation while meeting new demands from the electrification of heat and transport will require a portfolio of generation technologies. That includes variable renewables and other low-carbon options (e.g. nuclear, gas CCS, hydrogen), as well as flexible demand and storage.

We set out the options for reducing emissions in the following five sections:

a) Demand and energy efficiency

b) Variable renewables

c) Firm power

d) Dispatchable generation

e) Flexibility and storage

a) Demand and energy efficiency

The overall strategic approach is to decarbonise electricity and then use low-carbon electricity to power as much of the economy as possible.

Electrification represents a key abatement option to reduce emissions in other sectors.

Given potential limits to the pace of deployment of low-carbon capacity, it will be important to focus on sectors which have the most efficient use of low-carbon electricity (Figure 5.4).

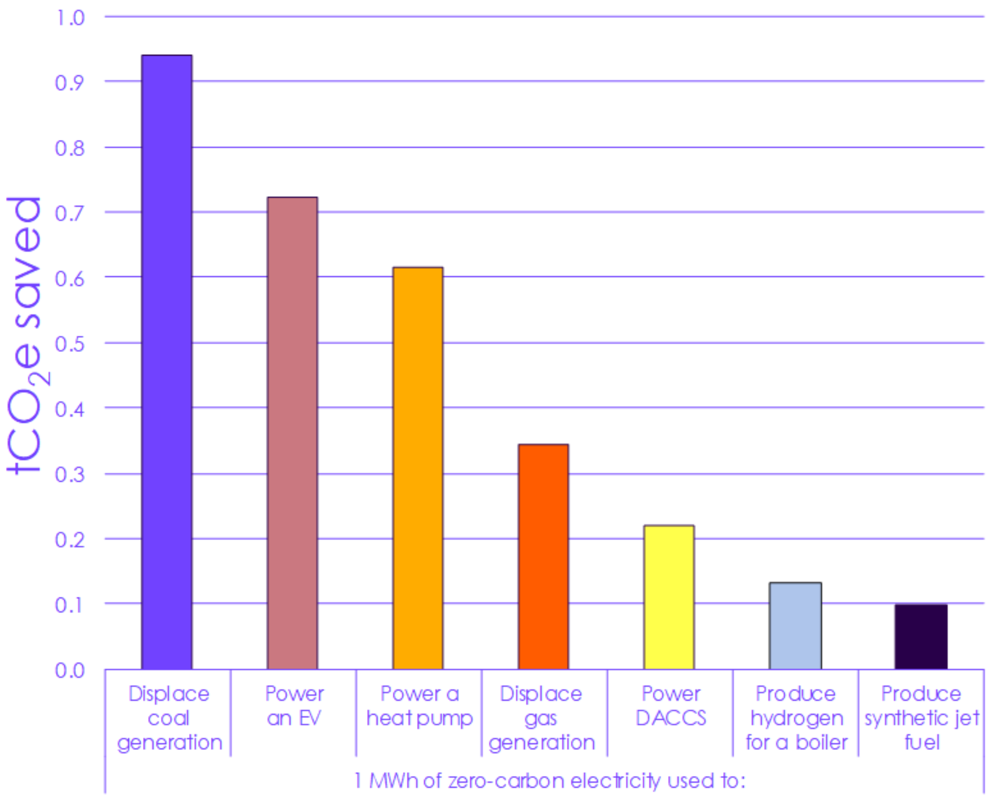
Electrification should be targeted where it has the most impact (e.g. electric vehicles, heat pumps rather than hydrogen production).

Across our scenarios new demands therefore come primarily from the electrification of transport, heat, and industry. Hydrogen production, Direct Air Capture, and synthetic fuels are relatively inefficient uses of electricity and should be lower priority than direct use of electricity for decarbonisation.

The range for demand across our scenarios is 550-680 TWh in 2050, compared to around 300 TWh in 2018. Demand in the Balanced Pathway is 610 TWh.

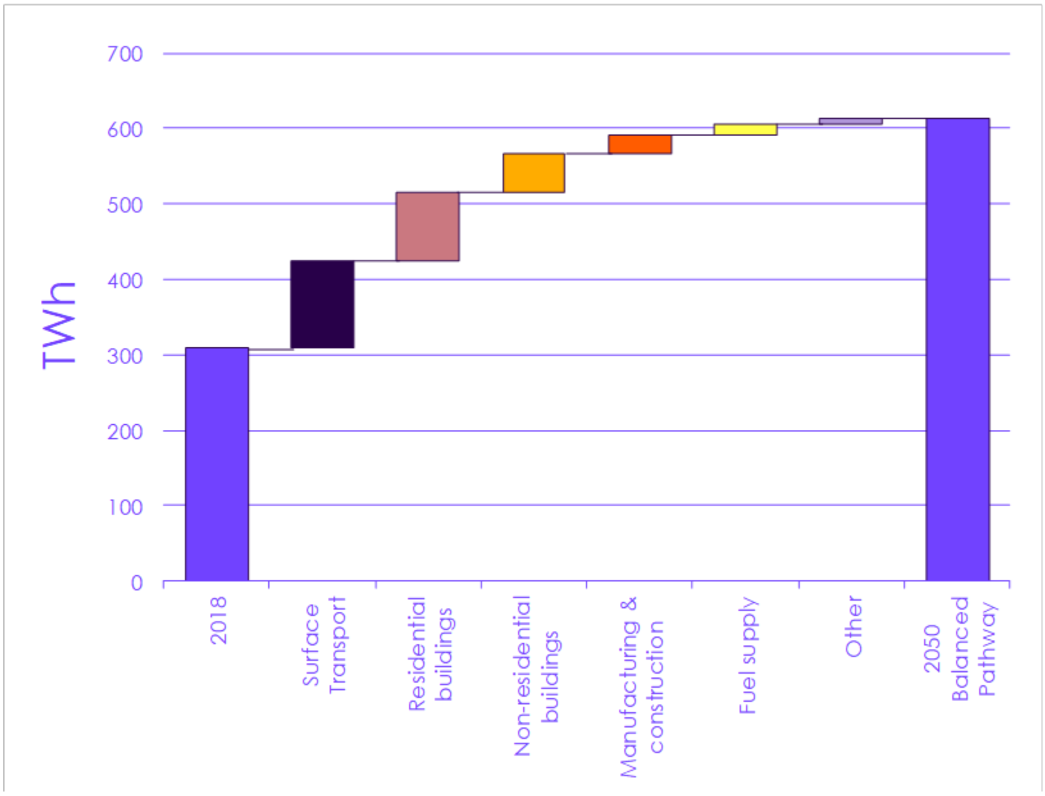
Figure 5.5 shows how each sector contributes to the increase in demand out to 2050. This shows that the majority (85%) of the increase in electricity demand is a result of the electrification of surface transport and buildings.

Figure 5.4 Emissions saved with 1 MWh of zero-carbon electricity across sectors



Source: CCC analysis.

Figure 5.5 Contribution by sectors to increased Electricity demand in the Balanced Pathway (2018-50)



Source: CCC analysis.
Notes: 'Other' category includes agriculture, aviation, direct air capture, shipping and F-gases.

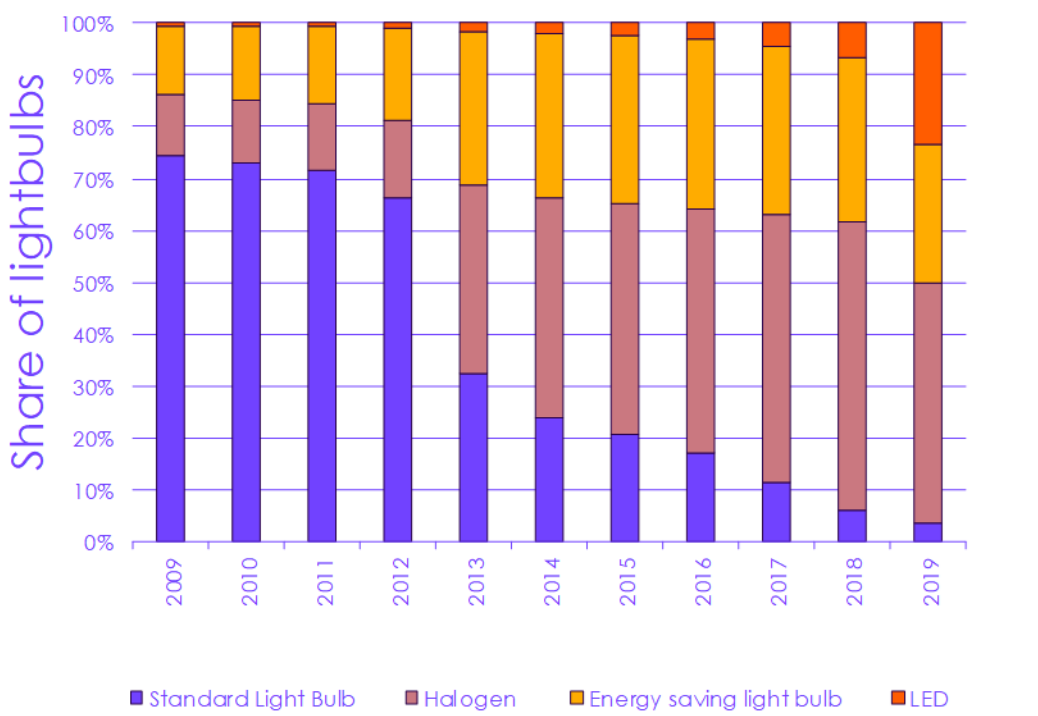
Energy efficiency improvements will limit the increase in demand.

These demand scenarios incorporate efficiency measures that limit the increase in electricity demand:

- **Lighting and appliances.** Energy efficiency in households has already led to lower demand in recent years. Low-energy lightbulbs now account for half of all lightbulbs in use (compared to around 15% in 2009). Lighting and appliances could continue to improve their efficiency and reduce electricity demand. However, the scope for further improvements will decrease over time as the stock becomes increasingly converted to energy-efficient options (Figure 5.6).
- **Heating.** Although deployment of heat pumps will lead to an increase in electricity demand, their use requires energy-efficient buildings in order to optimise performance. Heat pumps are also much more efficient than boilers, by a factor of three to four. These factors naturally help limit the increase in electricity demand from heating.
- **Manufacturing.** The uptake of energy efficiency (e.g. heat recovery) across a wide range of manufacturing sectors coupled with resource efficiency (e.g. lower demand for manufacturing products) could have a significant effect on electricity demand.
- **Transport.** Structural changes such as a transition away from car use towards public transportation and/or active travel could reduce electricity demand from transport. In addition, electric vehicles are around three times more efficient than internal combustion engine vehicles.

Low energy lightbulbs now make up 50% of all installed lightbulbs, compared to around 15% in 2009.

Figure 5.6 Share of energy-efficient light bulbs in UK homes (2009-2019)



Source: BEIS (2020) *Energy Consumption in the UK.*
Notes: Standard light bulb is an incandescent type. Energy saving lightbulb is a CFL type.

b) Variable renewables

The UK has extensive renewables resources which can generate electricity at low cost.

Variable renewables (i.e. wind and solar) have a key role to play in the decarbonisation of electricity generation, as they can provide zero-carbon electricity generation at low cost.

- **The UK benefits from extensive wind and solar resources.**
  - Previous analysis undertaken for the Committee suggests the UK has the potential to deploy capacity to generate 415-1075 TWh (95-245 GW) of offshore wind, 100-335 TWh (29-96 GW) of onshore wind, and 130-540 TWh (145-615 GW) of solar power.[3]
  - In 2018, 65 TWh came from variable renewable generation, which provided 22% of total UK generation. That represents an increase of 6 TWh every year since 2012.

Costs of renewables have fallen significantly over the last decade, and offshore wind is now among the cheapest forms of electricity generation.

- **Variable renewables are a low-cost source of generation.**
  - Costs of renewables have fallen significantly, with offshore wind costs falling from £150/MWh to £45/MWh over the last decade.
  - That compares to £50/MWh for gas generation, meaning renewables are now the cheapest generation technology on a levelised cost basis.

– Variable renewables will need to be accompanied by changes to the electricity system to accommodate intermittency (Section 2.e).

– Our modelling considers both the levelised costs and the wider system changes required to accommodate generation from different sources (Section 3).

There is enough space for offshore wind, but it will need to co-exist with other uses of the sea.

- **Maximising the potential of variable renewables in the UK will have wider implications for the land and seabed (Box 5.1).**

  – Offshore wind deployment must take into account a range of constraints, including seabed availability, wildlife and radar interference.

  – The Crown Estate for England and Wales has already leased seabed rights for 45 GW of offshore wind. Crown Estate Scotland could lease an additional 10 GW.

  – Existing leasing is sufficient to meet the Government target of reaching 40 GW of offshore wind by 2030. This would require around 4,000 turbines of 10 MW, which would cover 5,700 to 8000 km^2 of the seabed. Less than 1% of the seabed should therefore be used by offshore wind to meet the target.

  – In addition, we expect some offshore wind to be floating rather than fixed to the seabed. This means turbines could be deployed in deeper waters where there are likely to be fewer constraints.

  – We are therefore confident that offshore wind, planned strategically, should be deployable at significant levels.

  – With 14 GW, onshore wind currently takes up 2,700 km^2 of land.[*] To deploy 30 GW of onshore wind could need an additional 3,300 km^2 of land.

  – Large-scale solar currently has 13 GW installed capacity in the UK, which requires 290 km^2.[†] Maximising the potential of solar generation might entail using an additional 1,500 km^2.

Box 5.1
Challenges to deploying offshore wind

In less than a decade, the UK has been able to increase offshore wind capacity to 10 GW in 2019. Around a third of that capacity was deployed between 2017 and 2020, doubling build rates to 1.7 GW of offshore wind per year. Another 10 GW has already been contracted and will start generating in the 2020s. In order to achieve the Government target of 40 GW by 2030, an additional 20 GW of capacity will need to be delivered, which are likely to be commissioned from the mid-2020s (Figure B5.1).

- As a result, deployment rates could increase to about 4 GW/year. Our analysis suggests that the UK would need to maintain this pace of deployment past 2030 to reach 95 GW of offshore wind, as in our Balanced Pathway scenario.
- An additional 2 GW/year might be needed in the 2030s and 2040s to repower the existing fleet at the end of its lifetime. This will create an opportunity to replace existing turbines with better-performing ones, thus limiting the need for new capacity. This would increase offshore wind capacity at lower costs, as development and transmission costs would not need to be incurred again.

[*] Assuming 5 MW/km^2.

[†] Assuming 45 MW/km^2.

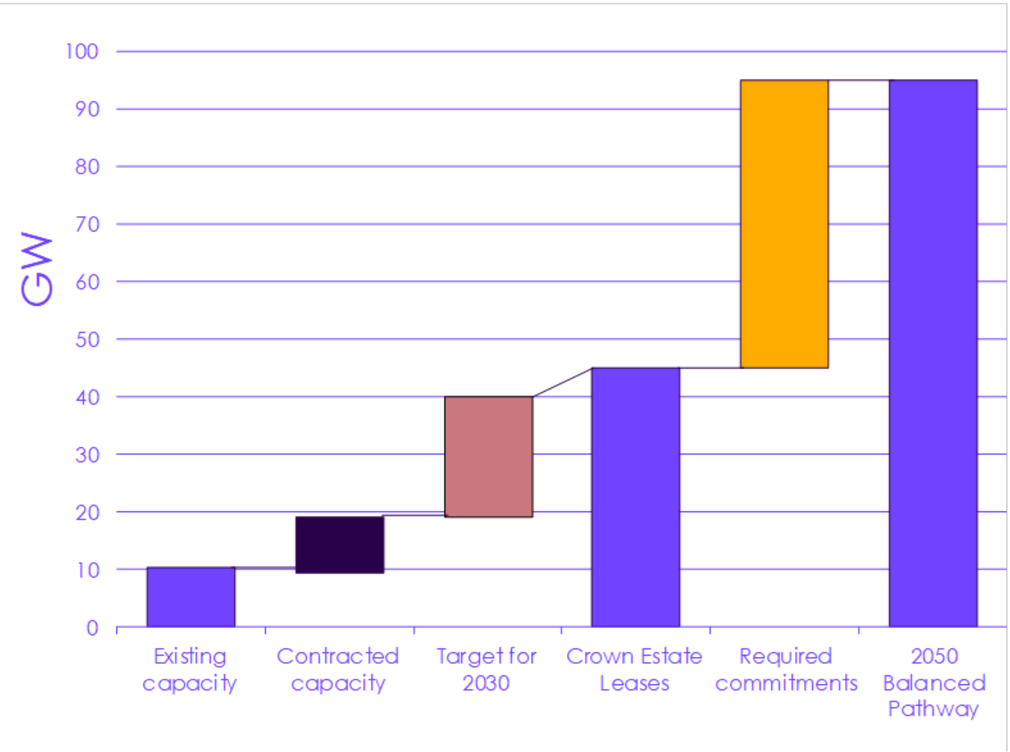
An expansion of offshore wind beyond the 2030 commitment for 40 GW will be required by 2050 for Net Zero.

These levels of deployment will bring about different challenges:

- **Supply chains.** Maximising the potential of offshore wind to meet the 2030 Government target already represents a challenge for supply chains, as they will have to increase the pace of deployment. That level of ambition might need to be sustained and possibly increased past 2030 to help meet Net Zero by 2050.
  - Supply chains will require long-term signals over capacity needs to provide a predictable environment to investors and developers. This includes certainty on offshore wind consenting and support mechanisms in order to avoid stop/start of supply chain investment.
  - However, there could also be opportunities for UK supply chains to meet new demand for offshore wind capacity. A recent study suggests that 3,500 jobs could be created across the supply chain in the North East alone, if offshore wind were to be developed further.[4]
- **Leasing.** Crown Estate England and Wales has unlocked a total of 45 GW of offshore wind in the seabed. In addition, the first round of ScotWind leasing could lead to leasing seabed in Scottish waters for an additional 10 GW. This is more than sufficient for the 2030 Government target. Nonetheless, securing new seabed leases requires several years as projects need to do pre-development planning, consenting applications, and construction. Accordingly, the UK will need to hold new leasing rounds to provide clarity to developers.
- **Networks.** With high renewable deployment, the governance of networks for offshore wind will need to be increasingly coordinated.
  - To date, Offshore Transmission Owners (OFTOs), offshore wind developers and operators have taken responsibility for developing connections between offshore wind farms and the onshore network. This reduced reliance on third parties and the possibility of delays.
  - The result has been a lack of coordination, as offshore wind farms planned connection routes independently. This represents a lost opportunity to optimise the existing network design, but it is also affecting coastal communities.
  - Better governance will ensure we can maximise the potential of offshore wind, minimise total costs and reduce the possibility of delays.
- **Cumulative impacts.** Deploying offshore wind at very high levels could entail putting pressure on areas sensitive to wildlife.
  - Activities in the seabed, including existing offshore wind farms could lead to cumulative environmental impacts on birdlife and marine mammals. In addition to the environmental cost, this could lead to direct costs for developers, as compensation might be required.
  - Nevertheless, these impacts can be avoided with a planning and consenting regime that allocates seabed locations with low risks for wildlife. Wider coordination between the Crown Estates, Government, industry, and conservation bodies could ensure wider monitoring of these impacts beyond that of project operators.
  - In addition, floating wind turbines could be deployed in deeper waters, which is less sensitive to wildlife.

Further detail on the policy implications of these challenges is set out in Chapter 5 of the accompanying Policy Report.

Figure B5.1 Delivering offshore wind to 2050 in the Balanced Pathway



Source: BEIS (2019) Energy trends: Table 5.1, The Crown Estate (2019) *Offshore wind operational report*, Low Carbon Contracts Company (2020) *CfD Register*; CCC analysis.

c) Firm power

'Firm power' refers to sources of predictable electricity generation. In this report, this mainly refers to nuclear generation, which is designed to run continuously.

Nuclear provides a source of zero-carbon generation.

- **Nuclear has consistently provided 20% of generation in the UK. As nuclear plants retire, there is potential for new projects to maintain or possibly increase that contribution.**
    - There is currently 9 GW of nuclear capacity in the UK, which provides around 60 TWh (20%) of UK electricity generation. However, 8 GW is set to retire in the 2020s. Without new nuclear projects, nuclear generation would therefore fall to 2-3% of total electricity generation by 2030.
    - Analysis undertaken by the Energy Technologies Institute (ETI) suggests that the UK could deploy up to 35 GW of nuclear capacity. That could provide 275 TWh of generation, which is 90% of current electricity demand. Nonetheless, maximising nuclear capacity is contingent on costs.[5]
    - Three projects are underway to replace retiring nuclear plants. One is under construction and two are awaiting approval for their reactor designs.

– Hinkley Point C (HPC) should provide 3 GW of capacity in the second half of the 2020s, backed by a 35-year Contract for Difference with a £105/MWh strike price.*

– Plants at Sizewell C and Bradwell could provide an additional 5 GW of nuclear capacity. That would lead to a total 10 GW of nuclear capacity in the UK, despite planned retirements. The nuclear sector deal has committed to bringing costs down by 20-30% (at £85-75/MWh) by replicating the design of Hinkley Point C.[6]

– Small Modular Reactors (SMR) could further increase the potential for nuclear in the UK, given that they could be deployed on a wider range of sites. However, they may face similar barriers to large nuclear plants regarding costs in addition to new challenges around public acceptability.

Nuclear is higher-cost than renewables, but provides predictable generation.

- **In a system driven by variable renewables, nuclear can play an important role to provide predictable low-carbon power.**

– Despite higher levelised costs than renewables, the predictability of nuclear power and its high capacity factor can make it an important part of the generation mix.

– However, the relative inflexibility of nuclear power production can lead to excess generation when demand is low. This surplus of electricity could be used to produce hydrogen via electrolysis, albeit at a higher energy cost than from renewables.

d) Dispatchable low-carbon generation

Dispatchable low-carbon generation is needed to complement variable renewables generation.

To complement variable renewable generation, other low-carbon sources are able to provide dispatchable low-carbon electricity generation. This generation can be planned with a high degree of confidence for hours, days and, normally, weeks ahead and relied on to be able to run continuously if required. These include gas with carbon capture and storage (CCS), bioenergy with carbon capture and storage (BECCS), and hydrogen plants.

i) Gas CCS and BECCS

Gas CCS and BECCS are two main sources of flexible dispatchable generation.

Gas CCS and BECCS plants are expected to be able to deliver relatively flexible low-carbon output, at medium cost. BECCS plants also offer the additional benefit of removing carbon emissions from the atmosphere.

- **The UK is well placed to deploy gas CCS and BECCS plants, given the CO_2 storage potential in the North Sea and other areas.**

– The UK has vast resources in CO_2 storage. Indeed, studies suggest that the UK has 78 Gt of CO_2 storage available.[7] This would be the equivalent to storing over 150 $MtCO_2$ per year, which could support 50 GW of gas CCS plant running all year, for 500 years.

– In addition, the cost of storage and transport should be limited to £15-19/tCO_2.

– CO_2 storage should not therefore be a limiting factor to developing gas CCS and BECCS.

* £2019 prices.

Although more expensive than renewables, gas CCS and BECCS provide valuable flexibility.

- **Gas CCS and BECCS are projected to be more expensive than renewables, but could bring value to a system dominated by variable generation.**
  - Gas CCS costs are expected to be higher than renewables, but competitive with nuclear at £85/MWh if running baseload.[8]
  - BECCS could play a similar role to gas CCS, albeit at higher costs that we estimate would be closer to £130/MWh based on analysis by the Wood Group.[9]
  - Despite higher costs than renewables, this form of dispatchable generation would be bring value to a generation mix driven by renewables, helping meet demand when renewable output is low.
- **The value of gas CCS and BECCS is dependent on the ability to efficiently capture CO_2.** Our analysis assumes capture rates ranging from 90% to 95%. If those rates were to be lower, the value of gas CCS as an abatement option would decrease.
  - A system based on renewables might require gas CCS and BECCS plants to run fewer hours in the year, making them more flexible. This could result in lower capture rates at start-up and shut-down, which would increase residual emissions.
  - A recent study by AECOM suggests capture rates of 95% could be maintained at low additional costs (Box 5.2).
- **By removing carbon from the atmosphere,* BECCS offers significant benefits as an abatement option.** However, the development of BECCS is contingent on sourcing sustainable biomass, given concerns over the associated lifecycle emissions.[10]

ii) Hydrogen plants

Hydrogen can also play a role as dispatchable low-carbon generation.

Hydrogen or ammonia† in electricity generation could play a crucial role in delivering flexible generation. By adjusting their output in a short period of time, hydrogen plants can ensure security of supply with low-carbon generation. These could be burnt in dedicated plants, or in retrofitted natural gas plants.

- Our 2018 *Hydrogen Review* suggested that hydrogen burned in gas turbines or engines was technically possible for electricity generation.[11] Further research and testing will nonetheless be required to better understand the performance of hydrogen plants.
- Existing and new gas turbines could run on hydrogen without significant increases in capital costs.[12] The cost of hydrogen as a fuel will be the main driver of total costs, which will depend on how this is produced.
  - Hydrogen burned in gas plants can be produced via electrolysis, which uses electricity as an energy input, or methane reformation that relies on CCS. Electrolysis supplies hydrogen without producing direct emissions, however electricity costs tend to be higher than those of gas, which is used for methane reformation.

* We refer to negative emissions to indicate the sequestering of avoided carbon.

† In this report, references to hydrogen include hydrogen carriers such as ammonia.

- In the 2020s, methane reformers with CCS are more likely to play a role in providing hydrogen. That is because the cost of electricity would need to be as low as £10/MWh to be cost competitive with methane reformers that could cost £40/MWh of hydrogen. In this case, a hydrogen plant burning blue hydrogen to produce electricity could be £80/MWh.
- However, as renewables become a larger share of the generation mix, there could be surplus generation when demand is low but renewable output is high. This surplus electricity could be used to produce hydrogen at costs competitive with methane reformation with CCS, albeit at volumes constrained by availability of these surpluses.
- We therefore expect to see a transition towards green hydrogen as the share of renewables on the electricity system grows (see Chapter 6).

To fully utilise the potential for hydrogen a transportation and storage network will be required.

- The development of hydrogen plants will be contingent on development of transportation and storage for low-carbon fuels such as ammonia or hydrogen.
- To maximise the potential of hydrogen, gas networks would need to be converted to hydrogen. Alternatively, gas plants could be located in conjunction with hydrogen production sites, thereby facilitating the transport of the fuel.

Box 5.2
New evidence informing our analysis

A number of new publications have supplemented the evidence base used for this report:

- A report published by AECOM[13] explored potential solutions to improve capture rates of gas CCS plants at start-up and shut-down periods. This analysis suggests gas CCS could run more flexibly to accommodate more renewables without increasing residual emissions. However, this would lead to additional costs that could make gas CCS less competitive than generation technologies with flexible outputs such as hydrogen plants.
- A study by Jacobs investigated the costs of long-term storage technologies.[14] The analysis shows that pumped hydro could provide the cheapest form of one-week duration storage at £70/MWh. Other forms of storage such as Compressed Air Energy Storage (CAES) could have higher costs at £160/MWh for the same storage duration. In comparison, hydrogen storage could cost £100/MWh. Nevertheless, this analysis does not consider seasonal storage that could offer months of storage. Our analysis relies more heavily on this form of hydrogen storage, given that medium-term storage technologies could not be modelled directly within our analysis using the Dynamic Dispatch Model (see section 3). However, a combination of these technologies might be required to meet storage requirements in a renewable-driven generation mix.

e) Managing the system

i) Integration of variable renewables

Variable renewables are weather dependent and therefore generate intermittently.

The increase in renewable generation in the electricity system will come hand-in-hand with higher intermittency. This will lead to additional system requirements, particularly to ensure security of supply.

- **Historically, coal and gas generation have been able to increase or decrease their output rapidly, which has been essential to meet periods of peak demand.**
  - Peaking plants currently run on gas or oil. Despite low levels of fuel efficiency, their contributions to emissions are relatively low given that they run 10% of hours in the year, on average.
  - However, these emissions could increase substantially in a year when wind is scarce, even after flexibility of demand and storage have been fully utilised. Decarbonising peak generation will therefore be an important part of running a Net Zero electricity system.
- **Variable renewables are different to conventional generation technologies as they are dependent on the weather to generate and therefore cannot vary their output on demand.**
  - The output of wind farms varies according to wind patterns, while solar plants are dependent on solar irradiance.
  - These weather patterns can change within hours on the same day, and can vary seasonally or even year-by-year for wind. As a result, renewable generation cannot be relied on to meet demand at all times, even if it can provide a very high proportion of generation on average across the year.

Costs of additional services to address intermittency are likely to be low.

- **As a result, the electricity system as a whole needs to provide additional system services to ensure security of supply.** These services incur additional costs to integrate a larger share of renewables into the system.
  - The Committee's Net Zero Technical Annex on integrating variable renewables into the UK electricity system reviewed the evidence on integration costs.[15] These range from £10/MWh to £25/MWh for generation mixes with 50% to 65% of renewables.
  - As the deployment of renewables increases, integration costs will increase. Modelling undertaken for this report shows that these integration costs could be £25-30/MWh for a system with 75% to 90% of variable renewables.
  - Increases in integration costs would be partly offset by reductions in the cost of renewable generation. With sufficient flexibility, a system based on renewables could be cheaper than one running on fossil fuels (see Chapter 3 in the accompanying Advice Report).

Surplus generation could be stored or used to make hydrogen.

- **Surplus generation (i.e. when renewable output is greater than electricity demand) would reduce the marginal value of renewables and nuclear, but this could be captured through storage.**
  - Surplus electricity could be used for short to medium-term storage, exports, or hydrogen production.
  - In turn these services could help support security of supply in a daily or seasonal capacity when renewable output is low.
- **As electricity generation is increasingly decarbonised and demand grows, network requirements will also rise.**
  - Investments in transmissions networks will be key to accommodate higher levels of generation that are located far from demand, like offshore wind.
  - The uptake of electric vehicles and heat pumps will also lead to an increase in electricity demand in most areas. As a result, upgrades in distribution networks might be necessary.

ii) Flexibility

In addition to low-carbon dispatchable generation, demand flexibility can help address the intermittency of renewable generation.

An increasingly flexible electricity system could help offset the intermittency impacts, and associated system costs, of variable renewables generation,

That flexibility could be provided by a range of options, including demand, storage, and interconnection.

- **Consumers that use electric vehicles and/or heat pumps could provide flexibility by allowing their demand to be shifted.**
  - That would require incentives to consume electricity outside periods of peak demand, for example through lower prices in those periods. That would reduce energy bills.
  - That will require some degree of behavioural change, as consumers will need to engage with their own demand, but it will also require the deployment of smart technology to send and manage price signals (see Section 3).

There are a range of storage options, able to cover a variety of duration lengths from daily to seasonal.

- **In an electricity system based on renewables, storage will be important to manage variable output.**
  - Battery storage can provide within-day flexibility when renewable output falls rapidly.
  - Hydrogen could be used as a form of medium-term storage as electricity is converted into this energy vector.
  - Other forms of medium-term storage such as pumped hydro, Compressed Air Energy Storage (CAES), could play a similar role to hydrogen. A study by Jacobs suggests pumped hydro and hydrogen could be used at similar costs of £70-100/kWh.[16]
- **Interconnectors**. Interconnections between the UK and neighbouring countries have a total current capacity of 6 GW.[17] These allow the sale of surplus energy to neighbouring markets and provide access to resources in other countries. Planned projects with 5 GW of capacity are expected to be delivered in the early 2020s. However, until the power systems in the rest of Europe become fully decarbonised, there is uncertainty around the carbon intensity of imported electricity.

a) Analytical methodology

i) Modelling and analytical processes

In this section, we set out the approach used to develop the emission scenarios for electricity generation that informed the level of the Sixth Carbon Budget. This covers the modelling approach and the approach taken for selecting scenarios.

We undertook detailed modelling of the electricity system out to 2050.

For the analysis underpinning this report we used the Department of Business, Energy, and Industrial Strategy's (BEIS) Dynamic Dispatch Model (DDM). We supplemented this with additional analysis to reflect the use of evidence and analyses that were not supported by the model.

BEIS Dynamic Dispatch Model

The DDM is an electricity market model that considers electricity demand and supply in Great Britain on a half-hourly basis. The model estimates the merit order of plants, which is then matched to demand.

The DDM does not have perfect foresight. Hundreds of possible generation mixes were modelled for each year and scenario.

- The model takes into account demand profiles of different end users as well as weather patterns for sample days. The model does not have perfect foresight in order to reflect investor decision-making, but rather generates many different capacity mixes and resulting mixes of generation.
- We used the model to identify a range of optimal pathways for emissions reflecting different input factor combinations, each of which had to meet security of supply constraints. That range of solutions included capacity deployment of different technologies and associated costs, provided by the CCC. This resulted in hundreds of possible generation mixes for each year modelled and each scenario.
- The modelling provided us with results on generation, capacity, costs, security of supply, and emissions.[18]

The CCC provided external inputs that covered demand, flexibility assumptions, capacity ranges, costs, and carbon values. As a result, our analysis does not share the same assumptions - or results - as other analyses undertaken by BEIS.

Scenario modelling

For each year, we provided inputs on demand levels and demand-side flexibility, ranges of possible capacity levels for different generation technologies, costs, and carbon prices.

- For each scenario, we provided assumptions on electricity demand (Figure 5.7). These inputs reflect the use of electrification to decarbonise other sectors. This, in turn, was predominantly determined by the modelling carried out in those sectors, including surface transport, manufacturing, buildings, fuel supply, greenhouse gas removals, aviation and shipping.

Flexible demand will be important for managing the future electricity system.

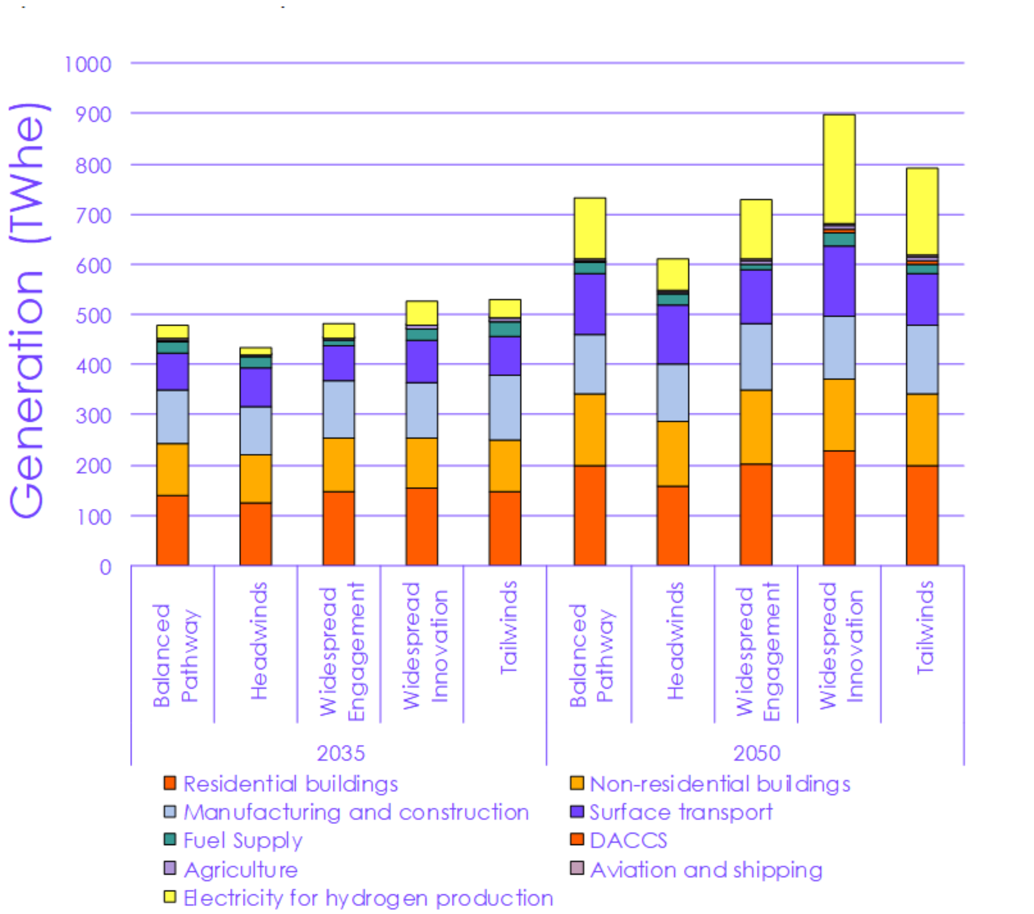
– Demand inputs included assumptions on flexibility provided by heat and transport (Box 1.11 in Chapter 1). We assumed that pre-heating and hot water tanks enable certain homes to shift their electricity demand four hours away from peak, while homes with storage heaters can shift their demand at all times. In transport, we assume that 80% of charging demand can be shifted up to eight hours outside of peak.

– These demands already consider energy efficiency measures in buildings and industry, thus avoiding 40 TWh of new demand and helping to limit total demand to 610 TWh (Figure 5.8).

- Capacity ranges were another key modelling input. For each scenario and each year, the model could select from a range of possible capacity levels of different generation technologies, including wind, solar, gas CCS and nuclear. This range was informed by existing capacity that represented a lower bound while historical build rates provided the basis to estimate an upper limit.
- We provided estimates for cost assumptions, including costs associated with capital, operation and maintenance as well as fuel. We assumed costs remained the same across scenarios, except in the Widespread Innovation and Tailwinds scenarios where variable renewables experience further cost reductions. Cost assumptions are set out in further detail in Table 5.1.

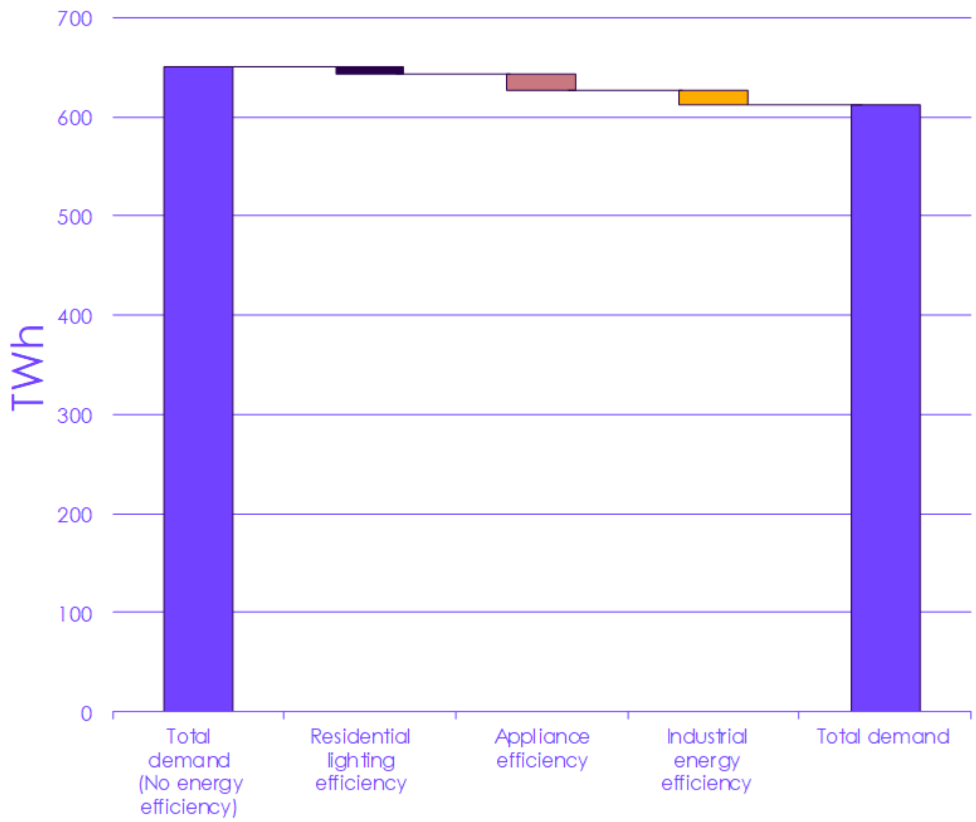
Electricity demand doubles in our scenarios out to 2050, compared to current levels of around 300 TWh.

Figure 5.7 Electricity demand from sectors (2035 and 2050)



Source: CCC analysis.

Figure 5.8 Energy saved in the Balanced Pathway from efficiency measures (2050)



Source: CCC analysis.

Scenario selection

Our analysis favoured scenarios that were optimal across electricity and hydrogen supply.

The outputs provided us with over 4,000 possible generation mixes across years. We therefore proceeded to select an illustrative generation mix for each of our scenarios based on three criteria:

- **Hydrogen and power optimum.** The outputs of the DDM informed us of the level of curtailment in each run. In addition, the DDM was able to model how much of that curtailment could be captured by different levels of electrolyser capacity. For each run, we estimated the value of producing hydrogen with surplus electricity, which we factored in as a negative cost to the electricity system.* This placed a value on the curtailed electricity that could be used for hydrogen production, thus reflecting the value of inflexible generation to the system once a system perspective is taken into account.
- **Path-dependency.** Selected generation mixes had to be consistent with capacity developed to meet demand in 2050. In other words, the capacity in scenarios for 2030 and 2035 could not be higher than those in 2050, to ensure no plant was built and decommissioned before the end of their lifetime.
- **Cost-effectiveness.** Thereafter, we selected the least-cost scenario.

* The value of electrolytic hydrogen production was estimated by calculating cost avoided by running an electrolyser on free electricity and hydrogen production from fossil gas reforming with CCS.

Additional analysis

We supplemented the DDM modelling with additional analysis to take into account a wider range of technologies and more detailed estimates of distribution costs.

- Some generation technologies, such as BECCS and hydrogen plants, are not included within the scope of the DDM. However, other technologies in the model could play a similar role, albeit at different costs and emission factors. We used gas CCS as a proxy for BECCS and unabated CCGT as a proxy for hydrogen plants, adjusting for changes in costs and emissions accordingly.
- We assume hydrogen plants start displacing unabated gas in the 2020s, assuming that the policy framework incentives its dispatch ahead of unabated gas, contributing to the phase-out of unabated gas (Box 5.3).
- Distribution costs are not estimated within the DDM. We used the BEIS electricity Distribution Network Model to estimate distribution costs, using the same assumptions from the DDM modelling. However, these models are not able to futureproof investment in networks, which could help limit costs. As a result, investment in networks tends to increase in proportion to generation. However, in practice front-loading one-off investment in 'future-proofing' network upgrades is likely to be the lowest-cost solution, given that the majority of the costs are in the civil works rather than the equipment. The cost estimates for electricity networks are therefore likely to be overestimated.

Anticipatory investment in network upgrades is likely to be a low-regrets solution.

Box 5.3
Phasing out unabated gas generation

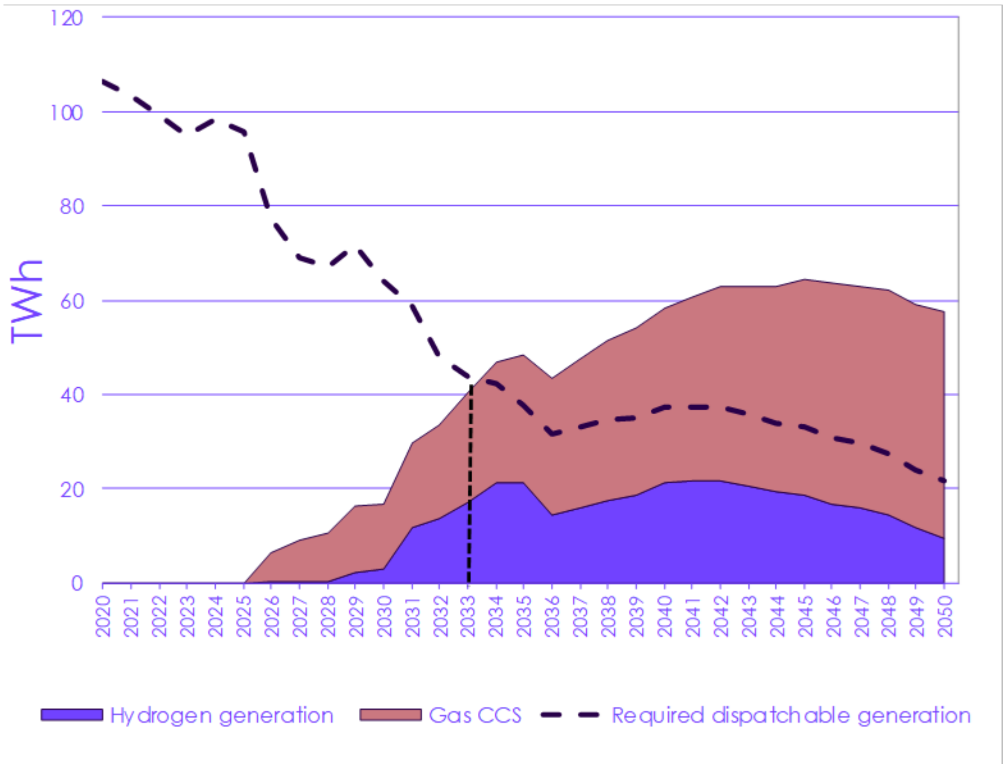
Our analysis shows that unabated gas could be phased out by 2035, provided alternative technologies are deployed at pace to deliver security of supply.

- **Retirement of unabated gas capacity.** There are currently 33 GW of Combined Cycle Gas Turbines (CCGT) and Open Cycle Gas Turbines (OCGT) in the UK.
  - Most of these plants were built in the 1990s during the 'dash-for-gas' period. The last plant was built in 2016. This means that existing plants are likely to retire by 2041, assuming an average operating life of 25 years.
  - These retirements represent an opportunity to phase out unabated gas generation, as new plants should prepare to retrofit with CCS or hydrogen. For that, new gas plants will need to demonstrate their ability to store hydrogen on-site and show their preparedness for using hydrogen-blending or their ability to retrofit CCS. Proximity to planned hydrogen or CCS infrastructure should also be a key criterion applied to all new gas plants.
- **Carbon price**. Our analysis suggests that a strong carbon price could move unabated gas down the merit order, thus reducing its role in the generation mix.
  - CCGTs currently cost £50/MWh, excluding the cost of carbon. In comparison, a gas CCS plant is expected to cost around £85/MWh in 2025.[19] Based on our hydrogen analysis, we assume costs for a hydrogen plant would range from £85/MWh to £130/MWh in the same year. Based on these costs, unabated gas would continue to play a significant role in the system without a carbon price.
  - However, a carbon price of £125/tCO_2 in 2030 - or equivalent policy - would be sufficient to bring the cost of a CCGT to £130/MWh, making it more expensive than the alternatives. As a result, a carbon price could push gas generation down the merit order such that it would play a more marginal role, particularly in meeting security of supply.

- **Security of supply**. Although a carbon price could displace gas generation, the phase-out of unabated gas is contingent on the deployment of low-carbon alternatives that can provide relatively flexible dispatchable generation. Our analysis suggests that hydrogen and gas CCS generation could be deployed at scale by 2035 to ensure security of supply.
  - In the Balanced Pathway, demand for electricity increases to 460 TWh in 2035 of which 335 TWh are met by renewables. The deployment of cheap renewables contributes to reducing the need for unabated gas. By 2035, 50 TWh of dispatchable generation would be needed to ensure security of supply (Figure B5.3). This could be provided by low-carbon generation.
  - Deploying less than 1 GW/year of hydrogen capacity in the second half of the 2020s could contribute to understanding the performance of hydrogen burning in gas turbines. Further deployment could take place in the 2030s, when the technology has been proven. Thereafter, deploying 3.5 GW/year between 2030 and 2035 could help deliver 15 TWh/year of hydrogen on average. These build rates are consistent with historical build rates achieved by CCGT deployment in the 'dash-for-gas' period.
  - In addition, deploying around 1 GW a year of gas CCS between 2025 and 2035 would enable it to provide 5 TWh of generation in 2026 increasing to 27 TWh by 2035.
  - Together, hydrogen and gas CCS generation could therefore displace unabated gas before 2035.
- **Phasing out unabated gas by 2035**. With sufficient deployment of low-carbon alternatives and the support of a carbon price and/or other policy mechanisms, unabated gas could be phased out by 2035, subject to ensuring security of supply.
  - This date is contingent on the development of CCS and hydrogen infrastructures, and appropriate incentives across the energy system.
  - It may also be necessary to maintain some unabated gas capacity for periods where renewable output could be particularly low (e.g. wind droughts). This would require the development of business plans or policy that could support these marginal plants which would run at very low load factors.

Further detail on the policy implications for phasing out unabated gas is set out in Chapter 5 of the accompanying Policy Report.

Figure B5.3 Deployment of dispatchable low-carbon generation in the Balanced Pathway (2020-50)



Source: CCC analysis.

Source: CCC analysis

ii) Scenarios

Offshore wind is the backbone of all our scenarios, providing 65-70% of total generation by 2050.

We have developed four exploratory scenarios for emissions to 2050, and a Balanced Pathway which keeps open the option to 2035 of achieving any of these by 2050. These scenarios are based around significant deployment of low-cost renewables, which meet 75% to 90% of electricity demand in 2050.

- **Offshore wind is the backbone of electricity generation across all scenarios.**
  - Offshore wind is able to meet a substantial share of demand with wind patterns correlated to seasonal demand, which supports the uptake of heat electrification. As a result, our scenarios include at least 65 GW of offshore wind in Headwinds and up to 140 GW in Widespread Innovation by 2050. The Balanced Pathway has 95 GW.
  - The high share of offshore wind is made possible by its low costs. Despite higher system costs, technology costs of £25/MWh-£40/MWh in 2050 contribute to running a system at lower costs than one based on fossil fuels.
  - An increase in interconnection could limit the need for new offshore wind capacity. Our analysis suggests that an additional 9 GW of interconnectors in our scenarios would reduce the need for 4-7 GW of offshore wind capacity.

- **All scenarios see new onshore wind generation being deployed by 2050**.
  - Onshore wind has similar benefits to offshore wind, albeit with lower capacity factors.
  - Our modelling reflects this by almost doubling onshore wind capacity to 25-30 GW in all scenarios by 2050.

Solar generation could produce hydrogen during summer that could be used in periods of higher demand in winter.

- **Solar contributes to decarbonising power at low costs, providing 10% to 15% of generation in 2050.**
  - Solar generates mostly during the summer when solar radiance is strongest. As a result, solar generation is less suitable to meet the seasonal pattern of demand, which is higher in winter periods due to heating demands. However, our modelling suggests high levels of solar generation in the summer could be stored (e.g. as hydrogen) to be used when demand is higher.
  - If solar deployment were to be lower than considered in the Balanced Pathway, an extra GW of offshore wind could replace the generation of 3 GW of solar capacity.

Pumped hydro could play a role in providing medium-term storage.

- **Other renewables could provide predictable generation, which would complement variable generation.**
  - Technologies such as tidal and wave that have not been commercialised at large scale could provide predictable power to a variable renewables-driven system. However, costs would need to decrease substantially to be competitive against other technologies.
  - Pumped hydro could be further developed in the UK (Box 5.2), which would be beneficial as a source of storage.

In a generation mix driven by renewables, other technologies will need to play a role in balancing the system. In addition, they provide optionality if renewable deployment were to encounter significant bottlenecks.

- **The role of nuclear is dependent on its cost and the share of renewable output in the system.**
  - In scenarios with a high share of renewables (i.e. more than 75% of generation), continuous power from nuclear might be curtailed in periods of low demand. This surplus could be used to produce hydrogen, albeit at higher costs than renewables, depending on electrolyser capacity factors.
  - However, nuclear offers a zero-carbon alternative to renewables, which could help meet new demands if renewable deployment were to slow down. This would increase overall generation costs, given nuclear is more expensive than offshore wind.

Gas CCS and BECCS can offer valuable dispatchable generation.

- **All our scenarios benefit from having gas CCS and BECCS on the system, which provide 7% to 15% of generation in 2050.**
  - These technologies offer a flexible dispatchable source of low-carbon generation, which can supplement variable weather-dependent renewables.
  - The role of these technologies varies across scenarios, as they are dispatched 40% to 45% of hours in the year.

– If gas CCS and BECCS were to be run more flexibility to help meet security of supply, costs and emissions would increase. Alternatively, gas turbines burning hydrogen could displace these technologies.

Table 5.1 summarises the role of different technologies across our scenarios.

Table 5.1
Role of technologies in the scenarios

	Capacity 2050	Average build rates 2030-50	Levelised cost 2050
Balanced Pathway	**GW**	**GW/year**	**£/MWh**
Offshore wind	95	3	40
Solar	85	3	40
Gas CCS	15	1	80
Nuclear	10	<1	85
BECCS	5	<1	125-185
Headwinds	**GW**	**GW/year**	**£/MWh**
Offshore wind	65	1	40
Solar	85	3	40
Gas CCS	15	1	80
Nuclear	10	<1	85
BECCS	10	<1	125-185
Widespread Engagement	**GW**	**GW/year**	**£/MWh**
Offshore wind	100	3	40
Solar	80	2	40
Gas CCS	5	<1	80
Nuclear	5	<1	105
BECCS	10	<1	125-185
Widespread Innovation	**GW**	**GW/year**	**£/MWh**
Offshore wind	140	5	25
Solar	90	3	25
Gas CCS	15	1	80
Nuclear	5	<1	105
BECCS	5	<1	125-185
Tailwinds	**GW**	**GW/year**	**£/MWh**
Offshore wind	125	4	25
Solar	75	2	25
Gas CCS	5	<1	80
Nuclear	5	<1	105
BECCS	10	<1	125-185

Source: CCC analysis based on BEIS (2020) Electricity Generation Costs and Wood Group (2018) Assessing the Cost Reduction Potential and Competitiveness of Novel (Next Generation) UK Carbon Capture Technology.
Notes: Costs in 2019 prices. Capacities and costs rounded to the nearest 5.

b) Deriving the paths for emissions in the devolved administrations

Our approach to developing emission pathways for Scotland, Wales, and Northern Ireland is based on the UK-wide approach and takes into account the specific circumstances of each devolved administration.

In common with the UK-wide approach, pathways for the devolved administrations reflect an increasing demand for electricity to 2050. That is decarbonised through a significant expansion of low-carbon generation, in particular low-cost renewables and decarbonised back-up generation, in conjunction with more flexible demand and use of storage.

Electricity demand across the devolved administrations doubles by 2050.

- **Demand.** The pattern for electricity demand across the scenarios reflects the same drivers as for the UK-wide analysis, with demand broadly doubling out to 2050. That includes an increasing switch towards electrification in transport, heating, and manufacturing and construction. Further detail on the drivers of this increase is set out in the relevant sector chapters of this Methodology Report.
  - **Scotland.** Demand broadly doubles by 2050, reaching 55-65 TWh. The fastest growth comes in the Widespread Innovation scenario, and the slowest growth is in the Headwinds scenario. The Balanced Pathway reaches 60 TWh in 2050.
  - **Wales.** Demand increases to 30-35 TWh in 2050, with the Balanced Pathway in the middle of this range.
  - **Northern Ireland.** Demand in Northern Ireland is relatively low, at around half of Welsh and a fifth of Scottish levels. It increases from less than 10 TWh in 2019 to 15-20 TWh in 2050, with the Balanced Pathway towards the lower end of the range.

Scenarios phase out unabated gas in electricity generation by 2035 in Scotland and Wales, in line with the UK-wide scenarios.

- **Carbon intensity.** Our approach to decarbonisation pathways for Scotland and Wales follows the methodology developed for our previous advice on devolved administration targets.[20] For Northern Ireland we use the pathways for carbon intensity published by the System Operator for Northern Ireland.[21]
  - **Scotland and Wales.** After the phase out of coal by 2024, remaining emissions will come from use of unabated gas and any residual emissions from the small proportion of CO_2 emissions not captured at fossil CCS plants.
    - For unabated gas plant we make a bottom-up assessment of the profile for retirements of existing capacity over time, based on an assumed 25-year lifetime. Onto this we overlay the change in load factors by scenario from the UK-wide analysis. The scenarios phase out use of unabated gas in electricity generation by 2035, except Headwinds in which it happens by 2040.
    - For gas CCS, we distribute UK-wide generation proportionately to the DAs based on their share of industrial CCS in our scenarios. In the Balanced Pathway that is 15% and 25% for Scotland and Wales respectively in 2050.
  - **Northern Ireland.** We use the pathways for carbon intensity published by the System Operator for Northern Ireland. These imply an intensity of less than 10 gCO_2/kWh in 2050.

    We have aligned the Balanced Pathway and the Headwinds scenario to the 'Addressing Climate Change' scenario, and the remaining scenarios to the 'Accelerated Ambition' scenario.

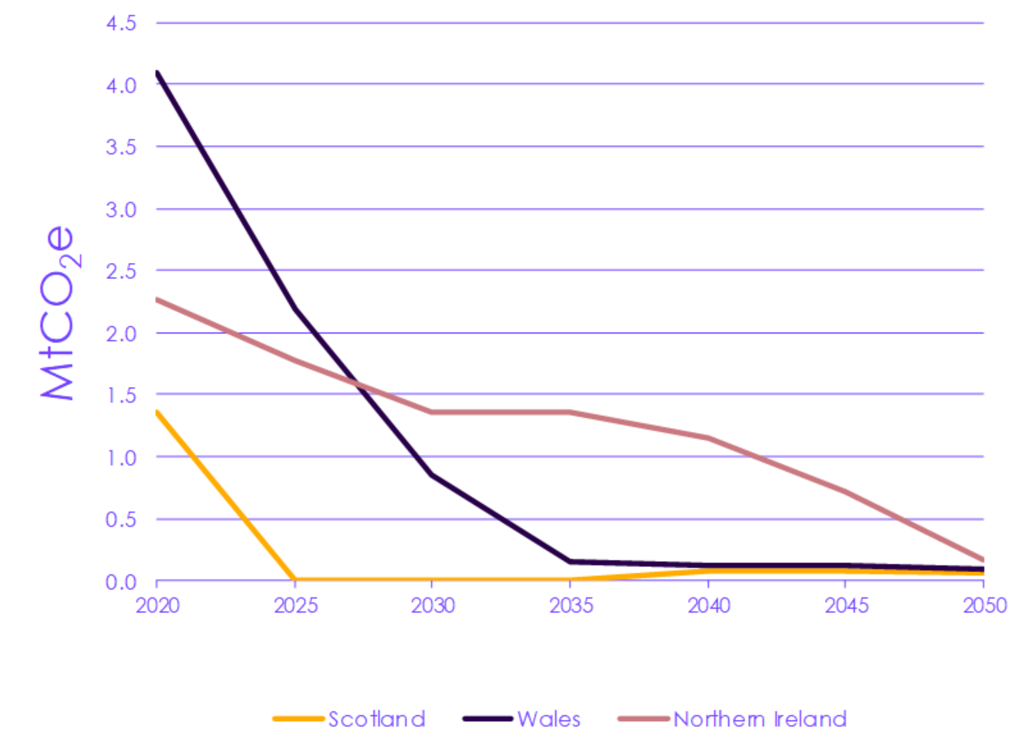
Our scenarios show near-zero emissions from electricity generation from the devolved administrations by 2050.

- **Emissions.** Figure 5.9 shows emissions under the Balanced Pathway for the devolved administrations. Emissions fall to near-zero by 2050.
  - **Scotland** has no remaining coal plants, and one remaining large gas plant. Once this closes, emissions are only from gas CCS, which is deployed through the 2030s and 2040s, but remain at very low levels to 2050.

- **Wales** has a higher share of existing gas capacity than it does of demand. Unabated gas capacity is phased out by 2035 in line with the UK-wide scenarios. Emissions stabilise at very low levels thereafter, reflecting the small proportion of CO_2 emissions not captured at gas CCS plants.
- **Northern Ireland.** The reduction in emissions plateaus somewhat in the 2030s, reflecting that the scale up in demand increases at a faster rate than carbon intensity declines. Emissions fall faster in the 2040s, reaching near-zero by 2050.

Overall, our scenarios show it is possible to reduce emissions from electricity generation to near-zero in the devolved administrations by 2050, while still meeting a doubling of demand and ensuring security of supply.

Figure 5.9 Devolved administration emissions under the Balanced Pathway (2020-50)



Source: CCC analysis.

c) Approach to uncertainty

Our scenarios are designed to reflect a wide range of uncertainty about future development of electricity demand, availability of generating technologies, and costs. Nonetheless, significant uncertainties remain, particularly on a 2050 timescale. These include:

- **Technologies.**
  - **Capture rates, especially with flexibility.** We assume that capture rates for CCS plants improve from 90% in 2030 to 95% in 2050. If capture rates were lower, the value of gas CCS as an abatement option would decrease and other technologies would need to play a more significant role.
  - **Storage.** Our scenarios maximise the role of hydrogen as a form of storage in power by producing hydrogen with surplus generation and burning hydrogen in gas plants to meet security of supply. However, other medium to long-term storage solutions could play a similar role, although it is unclear which mix of storage technologies could bring the most value to a renewable-driven generation mix.

There are significant uncertainties on future costs, particularly for renewables that could continue experiencing cost reductions.

  - **Costs.** There is significant uncertainty around generation technology costs in the future, as well as the impact of renewables on total system costs. While offshore wind has experienced significant cost reductions, it is unclear whether they will be sustained in the 2020s and beyond. This uncertainty applies to all generation technology costs that could experience capital cost reductions or support from policy that could decrease levelised costs.
  - **Carbon intensity of interconnector imports.** There is uncertainty around the carbon intensity of electricity imported from other countries. Our scenarios suggest the UK could become a net exporter of electricity, thus limiting residual emissions from interconnection.
- **Demand flexibility.** Consumers could be incentivised to provide flexibility services to the grid. However, the extent to which consumers would be willing to participate in these services is unclear. If cost incentives are not enough to prompt behavioural change, power would decarbonise at higher costs.

Unabated gas should be phased out by 2035, however this is contingent on meeting security of supply.

- **Phase-out of unabated gas.** Our analysis suggests that unabated gas-fired generation could be phased out earlier than other sectors, during the period of the Sixth Carbon Budget. However, in our scenarios, security of supply is contingent on its replacement with hydrogen and on the ability to build a CO_2 and hydrogen infrastructure for electricity generation and industry. Without these technologies, the electricity system would require further reductions in demand, higher flexibility, and/or extensive storage. In addition, nuclear would likely play a role in providing baseload generation to ensure security of supply.

Our scenarios could lead to water savings, provided sea water is used for cooling of nuclear plants.

- **Water use for electricity generation.** Freshwater could become scarcer in the future, depending on the level of climate change that takes place. Our scenarios suggest that water could be saved as we transition from a generation mix reliant on nuclear and fossil generation that require water for cooling. Nonetheless, the uptake of electrolysers could increase overall demand for water.
  - Our scenarios indicate a 10% decrease in water use by 2050, including water use for electrolysis. This is contingent on new nuclear capacity using sea water over freshwater. If this were not the case, water use could increase by 20%.
  - In a recent report commissioned for the Third Climate Change Risk Assessment,[22] future projections of water availability were modelled for a range of socio-economic and climate adaptation scenarios. While this analysis did not directly evaluate the impact of changing water availability on energy generation, the projected changes in naturally available resource under different climate scenarios show the potential exposure of energy generation to risks from reduced water availability.
  - This risk can be mitigated by using seawater or desalinating seawater.

Our scenarios show that it is possible to run a low-carbon electricity system from the mid-2030s, and a near-zero emission system by 2050. The success of delivering that will depend on the policy framework that is put in place. We discuss the implications of our scenarios for policy in Chapter 5 of the accompanying Policy Report.

Endnotes

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[2] BEIS (2020) *Energy Consumption in the UK.*

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[22] HR Wallingford (2020) *Updated projections of future water availability for the third UK Climate Change Risk Assessment.*

Chapter 6

Fuel supply

Introduction and key messages

This chapter sets out the method for the fuel supply sector's Sixth Carbon Budget pathways. The scenario results of our costed pathways are set out in the accompanying *Advice report*. Policy implications are set out in the accompanying *Policy report*.

For ease, these sections covering pathways, method and policy advice for the fuel supply sector are collated in *The Sixth Carbon Budget – Fuel Supply*. A full dataset including key charts is also available alongside this document.

The key messages from this chapter are:

- **Background.** Existing emissions in the Fuel Supply sector come largely from fossil fuel supply. These are expected to reduce over time, as North Sea oil and gas production declines and as demand for fossil fuels declines across the energy system, with knock-on impacts for output of refineries.
- **Options for reducing emissions.**
  - There are opportunities to reduce existing fossil fuel supply emissions, through measures to improve efficiency, electrify offshore platforms, apply carbon capture and storage (CCS) and reduce venting, flaring and leakage of methane.
  - Production of low-carbon hydrogen and bioenergy play roles in displacing emissions from fossil fuel combustion elsewhere in the economy. Hydrogen can be produced in the UK in a range of low-carbon ways, either from electrolysis or with CCS applied to fossil gas or biomass. A variety of routes from biomass to fuels exist (including biojet, biodiesel, bio-heating fuels and biomethane), many achieving negative emissions with the use of CCS (see Chapter 12).
- **Analytical approach.**
  - Opportunities to reduce emissions from fossil fuel supply are largely covered by the modelling by Element Energy set out in Chapter 4, with some further inclusion of information from the Oil and Gas Authority on opportunities to electrify offshore oil and gas platforms.
  - The low-carbon hydrogen supply mix varies across scenarios, according to the level of electrolytic production (determined in the power sector modelling – see Chapter 6) and allocation of biomass to hydrogen supply, as well as the level of demand. Hydrogen production from fossil gas with CCS is assumed to fill most of the remaining supply gap, with a smaller role for imported hydrogen.
  - Bioenergy and waste supply estimates have been updated to align with latest Land use, Agriculture and Waste sector analysis. Resources are allocated to end-use sectors starting from known 2018 positions, transitioning to best use (maximal GHG savings) by 2050.

- Our analysis of the best uses of bioenergy has been updated and still supports the need for bioenergy to maximise sequestered CO_2 and displace high-carbon fossil fuels. As with wastes, the availability of CCS causes strong convergence between all routes in terms of GHG abatement.

- **Uncertainty.**
  - Uncertainty in the low-carbon hydrogen supply mix is reflected in considerable variation across our scenarios. The role for electrolysis depends on developments in the power system and use of biomass with CCS on developments in gasification technology. The contribution from fossil gas with CCS depends on achieving sufficiently low lifecycle emissions.
  - Cost competitiveness of domestic biomass production vs biomass imports and developments in the global bioenergy market remain key uncertainties. Our biomass import dependency in the Balanced Pathway is not assumed to change from today, although our scenarios explore a doubling in import dependency to phasing out imports.

We set out our analysis in the following sections.

1. Sector emissions
2. Options for reducing emissions
3. Approach to analysis for the Sixth Carbon Budget

a) Current emissions

Greenhouse gas emissions from fuel supply were 39 $MtCO_2e$ in 2018, 7% of the UK total (Figure 6.1).

These were all produced from fossil fuel supply, from a combination of refining, oil and gas platforms, oil and gas processing terminals, gas distribution, coal mines (open and closed), and other fossil fuel production.

- Refining represents one third (13 $MtCO_2e$) of these emissions.
- Oil and gas platforms comprise 40% (16 $MtCO_2e$) of these emissions. This includes gas any production of onshore petroleum.
- Gas transmission and distribution contributes 13% (5 $MtCO_2e$) of these emissions. These emissions almost all come from methane leakage in the gas transmission and distribution networks.
- Oil and gas processing terminals, including for LNG, are 11% (4 $MtCO_2e$).
- Most (80%, 31 $MtCO_2e$) emissions were of CO_2, 19% (7 $MtCO_2e$) were of methane (CH_4) and 1% (0.4 $MtCO_2e$) of nitrous oxide (N_2O).

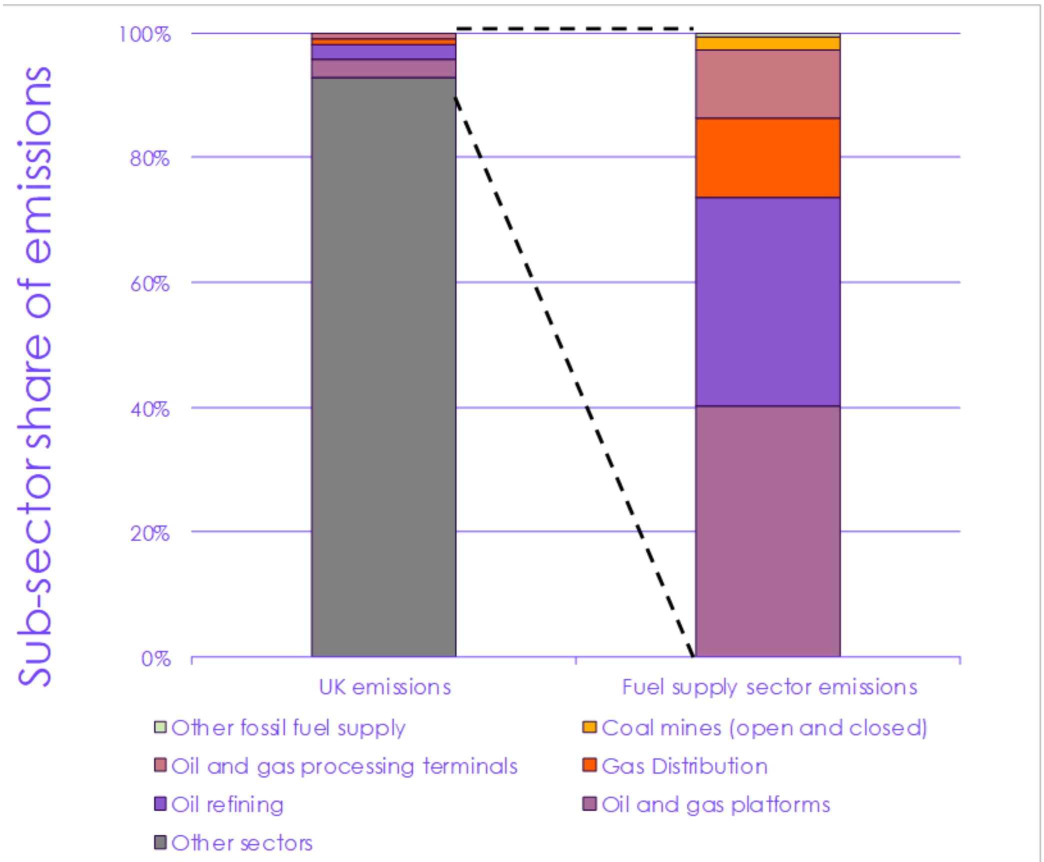
We also include within the sector direct emissions from production of low-carbon hydrogen, low-carbon ammonia and synthetic fuel production for energy use. However, our best estimate of emissions from these is currently zero, with most hydrogen and ammonia being produced for feedstock purposes, and no synthetic fuel produced commercially in the UK.

As such, all emissions from existing production of hydrogen and ammonia, used mainly in refineries and fertiliser production, are included within manufacturing and construction (see Chapter 4).

Emissions from existing UK production of bioenergy are either included within manufacturing and construction (see Chapter 4) for pre-processing and conversion, within surface transport for trucking of feedstocks and fuel, and within LULUCF and Agriculture sectors for any land-use change, cultivation and harvesting of UK forestry and perennial energy crops. This categorisation remains for all parts of the supply chain (i.e. these other sectors account for their parts of the supply chain emissions in our scenarios), except for new conversion facilities.

We include within the fuel supply sector direct emissions from the conversion facilities of new bioenergy vectors (e.g. biojet, bioLPG, biohydrogen), although as all these new facilities have been modelled as being energy self-sufficient (using their feedstock to provide power and heat onsite), only conversion facilities that convert waste to jet fuel will have some associated fossil emissions. We also include GHG savings from additional biomethane injection into the gas grid to offset fossil gas, as part of the sector emissions.

Figure 6.1 Breakdown of fuel supply emissions (39 $MtCO_2e$ in 2018)

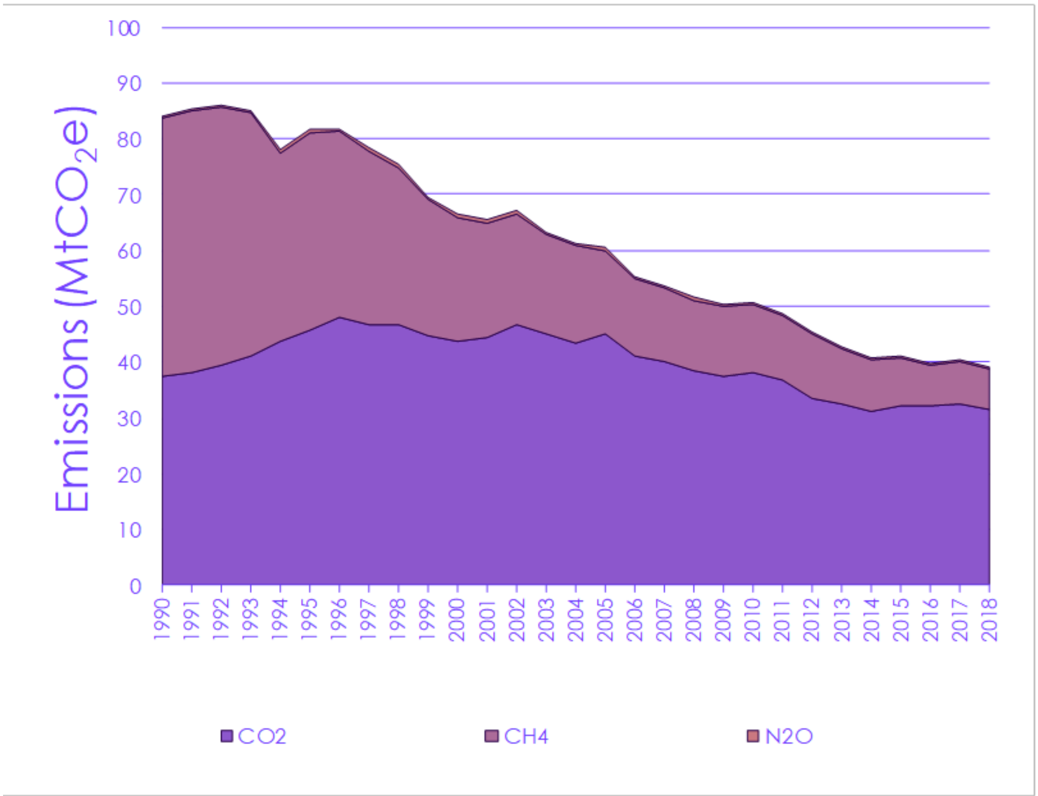


Source: CCC analysis.
Notes: All emissions are from fossil fuel supply. Groupings are based on Element Energy (2020) *Deep-decarbonisation pathways for UK Industry, report for the Climate Change Committee.*

b) Trends and drivers

Direct emissions from fossil fuel supply rose by 1% in 2019. Emissions were 53% below 1990 levels (Figure 6.2). More detailed sectoral data are produced with a one-year lag. The 1% rise in emissions in 2017 was largely due to rises in the production and transport of fossil fuels; emissions from refineries over this period were static. There are currently no significant emissions from production of low-carbon hydrogen or ammonia for energy use.

Figure 6.2 Trends in fuel supply emissions



Source: National Atmospheric Emissions Inventory (2020) Breakdown of UK GHG emissions by source and greenhouse gas; CCC analysis.
Notes: All emissions are from fossil fuel supply.

This section sets out the different options for reducing emissions from existing fuel supply in the UK (i.e. those from fossil fuel supply).

a) Resource Efficiency and Energy Efficiency

We detail our approach to resource and energy efficiency savings in section 2 of Chapter 4. In the fossil fuel supply sector, there are small direct savings to be made from resource and energy efficiency, although efficiency measures from across the economy can flow through to reduced demand for oil from refineries. Fossil fuel supply facilities can also become more energy efficient through measures such as heat recovery in refineries.

b) Fuel-switching

Electricity, hydrogen and bioenergy can all be used to meet heat, motion (and electrical) demands, thus replacing the use of fossil fuels and reducing GHG emissions in the fuel supply sector.

- There are a range of hydrogen and electrical heating technologies, which are designed to provide different types of heat demand.
- Some fuels or heating technologies have wider potential than others. The applicability of fuels in the fuel supply sector is informed by Element Energy's 2019 report on fossil fuel production.[1]
- Fuel switching of processes on offshore platforms can be limited by the lack of connection to onshore electricity (or potentially in future, hydrogen) networks. This currently results in onsite generation of electricity using fossil fuels. Connecting platforms to the mainland grid or offshore wind turbines can allow them to reduce direct emissions.
- Biomass should only be used in energy applications with CCS (i.e. BECCS) in the long-term, based on the assessment of best use in our Biomass Review.[2] BECCS has the net effect of removing CO_2 emissions from the atmosphere. These removals are counted in our Greenhouse Gas Removals sector (see Chapter 12).

Fuel-switching away from petroleum elsewhere in the economy results also results in lower demand for petroleum from oil refineries, which can reduce emissions.

c) Carbon Capture and Storage (CCS)

CCS can be used to capture CO_2 produced by industrial point-sources, and transport it to a storage site, thus reducing emissions to the atmosphere. The captured CO_2 may alternatively be used in Carbon Capture and Use (CCU), although the potential amount of CO_2 that could be used is expected to be substantially smaller than that which could be stored.

CCS can capture non-combustion process CO_2 emissions (from refineries, reforming and offshore fossil fuel production) and combustion emissions, including those arising from the combustion of internal fuels (gases that are produced as part of the industrial process).

d) Reduced methane venting, flaring and leakage

The amount of methane that is vented or flared from oil and gas production, and from exploration and leaked from the gas pipe network, can be reduced through a series of measures. Venting and flaring from oil and gas production can be reduced by recovering the gas and selling it.

When safety requires that methane cannot be recovered, an alternative way to reduce venting emissions is to flare the methane instead of venting. Venting from exploration wells can be reduced through reduced emissions completions. Leakage of methane from the gas network can be reduced through periodic leakage detection and repair or continuous monitoring, to find the leaks as early as possible and limit the volume of methane released.

e) Low-carbon hydrogen supply

Four main routes for hydrogen supply were included in this analysis:

- **Fossil gas reforming with carbon capture and storage (CCS).** Hydrogen can be produced by autothermal reforming of methane, plus a shift reaction, to produce hydrogen and CO_2. The CO_2 is assumed to be captured and stored geologically. Although the efficiency (85%) and CO_2 capture rate (95%) of this process are both assumed to be relatively high, even then this process would only provide hydrogen with a lifecycle emissions saving of up to 85% compared to unabated use of fossil gas due to the emissions from upstream fossil gas production.[3] Costs of hydrogen supply via this route are assumed to be £38/MWh.
- **UK-based electrolysis.** This supply route entails using electricity generation that would otherwise be 'curtailed' from renewable and/or nuclear capacity at times when generation from these sources exceeds other 'direct' demands for electricity. The electricity is used with 80% efficiency to produce hydrogen. Costs of electrolytic hydrogen depend on the capital cost of the electrolyser, its utilisation (or 'load factor') and the non-electricity operating costs, as curtailed power is assumed to be available at no added cost (see Chapter 5). The cost of hydrogen from fossil gas reforming with CCS is used as a threshold for electrolytic hydrogen costs produced with curtailed electricity. The cost assumed in the fuel supply sector is therefore on average below that for fossil gas reforming with CCS, varying depending on electrolyser capacity factors.
- **Imported hydrogen.** Hydrogen could be produced outside the UK (e.g. from low-cost solar in sunnier latitudes) and supplied, potentially via ammonia, at similar costs to domestic hydrogen production from fossil gas reformation.[4] We have assumed that a modest proportion of hydrogen/ammonia supply is from these routes. Assuming that these imports will only occur if competitive with UK-based production, we have costed them at the same cost as fossil gas reformation.

- **Bioenergy with CCS.** Hydrogen can be produced from biomass with CCS, via gasification and catalytic shift reactions. Sequestration of this biological CO_2 means that this supply route has negative lifecycle emissions. Costs of hydrogen supply via this route are assumed to be £86/MWh today falling to £71/MWh by 2050 as efficiency improves and deployment scales up. In the fuel supply sector this is counted as having zero emissions, with both the CO_2 removal and the added costs of this route compared to a low- (rather than negative-) carbon hydrogen supply alternative accounted for in the Greenhouse Gas Removals sector (see Chapter 12).

Two further processes using low-carbon hydrogen are also modelled within the fuel supply sector:

- **Ammonia for shipping**. Ammonia is produced from combining nitrogen (from air separation) with low-carbon hydrogen (supplied as outlined above), in the Haber-Bosch process. With some of the hydrogen used for on-site power and process heating, plant efficiencies are 75% from hydrogen to ammonia (HHV basis). Given the commercial maturity, we have not assumed improvement in ammonia capital or operating costs over time, only changes in the hydrogen costs. Ammonia costs are around £75/MWh in the Balanced Pathway.

- **Synthetic jet fuel for aviation**. Direct Air Capture is used to extract CO_2 from the atmosphere, catalytically combined with low-carbon hydrogen to form syngas, and then Fischer-Tropsch (FT) catalysis to jet fuel. Process efficiency from hydrogen to jet, including the low-carbon used for Direct Air Capture, is 43% today rising to 52% by 2050. Synfuel costs fall to £114/MWh by 2050 in the Balanced Pathway.

f) Bioenergy and waste supply

A number of different bioenergy production routes were included in our analysis, along with the use of wastes. Feedstock costs have been held fixed over time, whereas conversion processes have been assumed to become cheaper and more efficient over time. All our bioenergy conversion processes are assumed to be energy self-sufficient (i.e. no external inputs of fuel or electricity required), which is reflected in the conversion efficiencies used. The addition of CCS increases conversion costs and lowers efficiencies. Costs are set out in section 3.

- **Solid biomass.** Domestic feedstocks (forestry residues, perennial energy crops, straw & waste wood) and imported biomass feedstocks are supplied directly (without conversion) to the Power, Manufacturing & Construction, Residential & Non-residential Buildings and Agriculture sectors. These end-uses increasingly transition to CCS, or phase out over time. Current informal supplies of biomass for building heating (~8 TWh/year) are assumed to phase out in line with biomass combustion boilers in buildings.

- **Residual waste**. After re-use & recycling, any residual waste not exported or landfilled is predominantly used in energy-from-waste plants (in the Waste sector, with CCS being fitted to all plants by 2050), plus some small use in Manufacturing. Use in waste to jet plants is also possible.

- **Biohydrogen**. Solid biomass feedstocks are gasified then catalytically converted into hydrogen, with CCS.

- **Biojet**. Waste fats/oils can be hydrotreated into biojet. Solid biomass or residual waste feedstocks can also be gasified then undergo FT catalysis for conversion into biojet, with CCS.

- **Heating biofuels.** A range of liquid biofuels made from biomass (with CCS) or from waste fats/oils can be used for home heating, including bio-LPG and biokerosene (heating oil). We assume some use with hybrid heat pump systems situated in homes off the gas-grid.
- **Biodiesel**. Biodiesel is used in surface transport, off-road machinery and agricultural equipment Conventional routes to biodiesel involve trans-esterification or hydrotreatment of waste fats/oils. Solid biomass feedstocks can also be gasified then undergo FT catalysis for conversion into biodiesel, with CCS.
- **Bioethanol**. Arable crops are fermented into bioethanol in existing facilities.
- **Biomethane & biogas.** Biogas is produced from anaerobic digestion of food waste, sewage sludge & animal manures, plus captured landfill gas. Maize biogas is assumed to phase out by the mid-2030s from ~10 TWh/year today. Biogas is used in power and manufacturing, but can also be upgraded to biomethane for gas grid injection, along with the capture of biogenic CO_2 for sequestration.

We have drawn together a range of new evidence to underpin the analysis of long-term decarbonisation that is presented in the *Advice report*. This predominantly updates and adds to the evidence base collated for our 2019 advice on Net Zero, which considered decarbonisation to 2050.

a) Fossil fuel supply

The Balanced Net Zero Pathway and the four exploratory scenarios in this sector differ in several ways, including their energy mix and rates of decarbonisation. More information on this is in Chapter 3 of the *Advice report*, and the dataset that accompanies the report. These scenarios are underpinned by updated evidence and analysis.

- We commissioned Element Energy to undertake new research on the deep decarbonisation of industry and produce a model for location-specific decarbonisation options (for more information, see Box 4.2 and Chapter 4, section 3). This included deep decarbonisation of fossil fuel supply, building on the Element Energy (2019) study produced for our 2019 Net Zero advice, 'Assessment of options to reduce emissions from fossil fuel production and fugitive emissions'.
- New evidence on the possible abatement from the electrification of offshore platforms and its costs was applied to the model outputs.
- We have also updated our synthesis of evidence on resource and energy efficiency options, and our baselines.

The structure of our analysis follows the following steps:

- It starts by considering a baseline world where there is no new climate change mitigation policy beyond 2019.
- From the emissions baseline in this world we deduct, in sequence, demand reductions from across the economy, abatement from resource efficiency and energy efficiency.
- This is followed by deducting abatement from 'deep decarbonisation' options - fuel switching, CCS and measures to reduce methane flaring, venting and leaking.
- We set out the approaches we have taken for each of these steps, below.

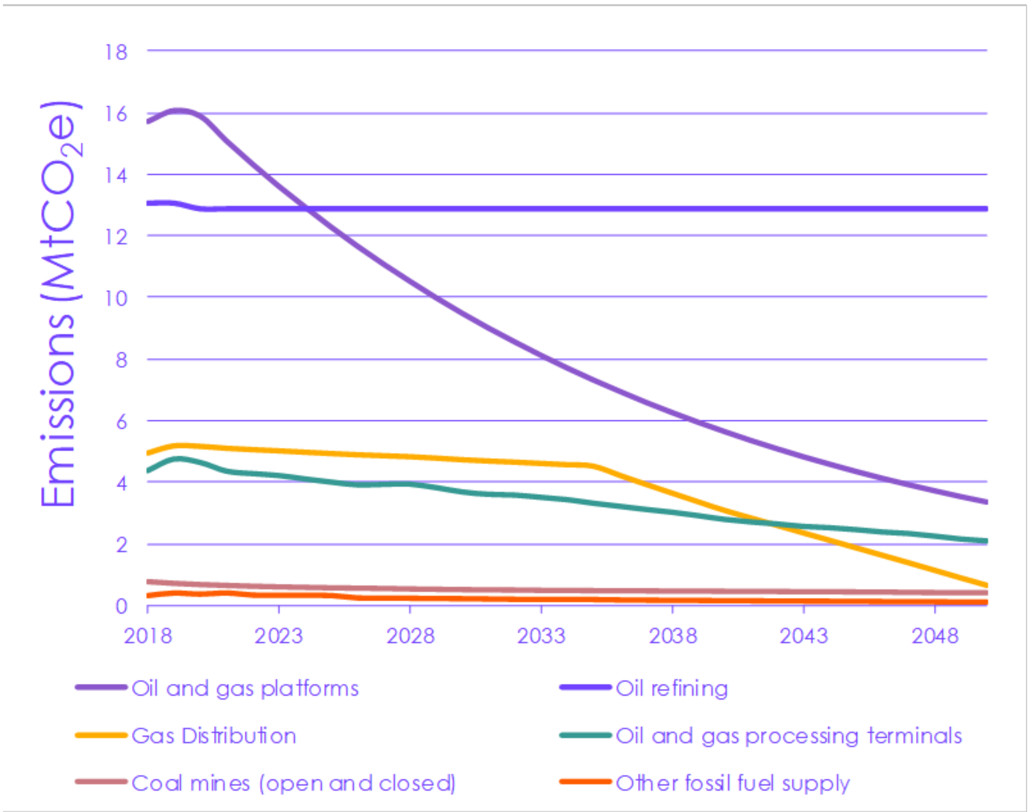
Baseline projections

Our emissions baseline starts aligned to historical emissions for 2018, the latest year with fully reported data, based on the National Atmospheric Emissions Inventory (NAEI).[5] For combustion emissions, corresponding energy data is drawn from a mix of the NAEI and the Digest of UK Energy Statistics (DUKES),[6] allowing for the inclusion of existing electricity use (which is not reported in the Inventory).

Future refinery energy and emissions are projected from the historical 2018 data using the scaling (% change from 2018) of the BEIS Energy and Emissions Projections 2019 reference case.[7] Future emissions from other fuel supply sectors (excluding refining) are projected using a 2019 study from Element Energy.[8]

Figure 6.3 shows our baseline projections. Baseline emissions from these sources are projected to reduce to 19.5 $MtCO_2e$ in 2050.

Figure 6.3 Baseline projections for subsectors in fuel supply



Source: CCC analysis.
Notes: All emissions are from fossil fuel supply. Groupings based on Element Energy (2020) *Deep-decarbonisation pathways for UK Industry, report for the Climate Change Committee*.

Resource efficiency, energy efficiency and fuel-switching from across the economy

To establish pathways for abatement from resource efficiency, energy efficiency and fuel-switching across the economy we refreshed our synthesis of evidence on the abatement potential of these measures.

From the baseline, first we accounted for significant changes across the economy that would affect demand.

Decreased use of petroleum for transport and other applications leads to large reductions in demand for oil refineries. In all scenarios, this demand reduction equates to 0.4 $MtCO_2e$ of abatement in 2019, rising to 9.5 $MtCO_2e$ of abatement in 2050.

Next, we applied resource efficiency savings; in fossil fuel supply, these are very small and spread across the subsectors. Energy efficiency for refineries is based on the 'Max Tech' scenarios from the '2015 BIS Industrial Decarbonisation and Energy Efficiency Roadmaps to 2050'.[9] We also assume some small additional energy efficiency in sub-sectors that are not covered by the Roadmaps.

Deep decarbonisation measures

To establish our pathways for abatement from deep decarbonisation measures, we commissioned Element Energy to substantially extend previous analysis produced for the CCC and BEIS and develop pathways for the CCC. This involved gathering new evidence and using this within a new Net Zero Industrial Pathways (N-ZIP) model. Further details of the Element Energy evidence-gathering and N-ZIP modelling are presented in Chapter 4 and Box 4.2.

Some amendments were applied to the deep decarbonisation abatement measures coming from the fuel supply pathways and scenarios from the Element Energy analysis, resulting in a difference between the results reported in the Element Energy report and our final results.

In particular, new evidence from the Oil and Gas Authority (OGA) on the electrification of platforms was also included at this stage.[10]

- The OGA study sets out cost-effective electrification of platforms and sets out a potential pathway that could abate 3 $MtCO_2e$ per year.
- In all scenarios, we have applied their pathway and used grid electricity to provide power to generators and compressors on oil and gas platforms.
- Use of grid electricity keeps open the future option of using dedicated renewables (e.g. wind) to power these platforms.

We also adjusted CCS capture rates in the period pre-2040 to 90%, from higher rates used in the Element modelling (that now apply from 2040 only).

b) Low-carbon hydrogen supply

End-use sectors were given hydrogen costs to use in their analysis for the decarbonisation pathway in their sectors. Due to different assumed hydrogen costs between scenarios, but also different assumed end-use sector choices in the different scenarios, there is considerable variation in hydrogen demands by sector, and in aggregate, across scenarios.

Once the hydrogen demands at the sectoral level had been determined, an assessment was made of the mix of hydrogen supply routes to meet these:

- **Electrolysis.** Supply of hydrogen from electrolysis was co-optimised with electricity supply, as outlined in Chapter 5, by placing a value on the hydrogen produced via electrolysis from electricity generation that would otherwise be curtailed. This value is based on the avoided cost of producing hydrogen from reforming of fossil gas with CCS.
    - The largest volume of electrolytic hydrogen supply by 2050 is in Widespread Innovation, as the lower costs of renewable electricity mean it is more economic to build more renewable capacity to meet a combination of electricity and hydrogen demands.
    - Headwinds, which has the lowest share of variable renewable generation, also sees the lowest volume of electrolytic hydrogen production.

- **BECCS.** Hydrogen production from BECCS relies on biomass gasification technology, which is not fully mature. As such, less biomass was used for hydrogen production in each scenario than for BECCS power generation, where technology readiness is higher.
  - The largest volume of BECCS hydrogen production is in Tailwinds, where low renewable electricity costs made BECCS less valuable to the power sector, but where demands for hydrogen significantly exceeded electrolytic hydrogen supply alone.
  - Widespread Engagement does not feature any hydrogen production from BECCS, which is instead prioritised for power generation.
- **Fossil gas reforming and imports.** Once contributions to UK hydrogen supply that are limited by economics and build rates (electrolysis) and available resource (BECCS) were established, the remaining requirement for hydrogen supply was allocated between domestic production from fossil gas reforming with CCS, and imports of low-carbon hydrogen. In each scenario, imports represented less than 20% of overall hydrogen supply, while fossil gas reforming with CCS comprised the remainder.
  - Fossil gas with CCS made by far the biggest contribution to hydrogen supply in the Headwinds scenario, partly due to the much higher hydrogen demand in that scenario and partly due to the lesser contribution of electrolysis.
  - The contribution from fossil gas with CCS in other scenarios such as Tailwinds and Widespread Innovation was much smaller by 2050, due to the high share of electrolysis. However, fossil gas with CCS has an important transitional role in both scenarios in providing low-carbon hydrogen during the period when hydrogen demands grow faster than electrolytic hydrogen supply.

Supply of low-carbon hydrogen in the baseline is assumed to be zero.

Low-carbon ammonia and synfuel production

Low-carbon hydrogen is used in a variety of end-use sectors, but some is also converted into ammonia for shipping and synthetic jet fuel for aviation in our scenarios.

- **Zero-carbon ammonia**. Ammonia production is commercially mature, as is the distribution and storage infrastructure. All of our shipping scenarios require 70 TWh/year of zero-carbon ammonia by 2050, although profiles to 2050 vary. Most of this ammonia is assumed to be produced in the UK from the available low-carbon hydrogen, however, we also assume there will be imports of renewable ammonia. In the Balanced Pathway, these imports are 25% of UK demand, with 0% in Headwinds (self-sufficiency with fossil gas with CCS) or 50% in other scenarios (to reflect higher global innovation in renewable energy costs).
- **Synthetic jet fuel**. Synthetic fuel production is at early demonstration scale at present, as is Direct Air Capture. By 2050, our aviation scenarios require 30 TWh/year of synthetic jet in Widespread Innovation and Tailwinds, and 10 TWh/year in the Balanced Pathway. We assume the same proportion of imports across the scenarios as for ammonia above.

Supply of zero-carbon ammonia and synthetic jet fuel in the baseline is assumed to be zero.

c) Bioenergy and waste supply

Emissions in the sector fall into two categories: additional GHG savings from increased biomethane injection into the gas grid, or fugitive fossil emissions from waste to jet fuel plants. All other emissions are either nil or are accounted for outside of the fuel supply sector (hence our baseline has nil emissions). The focus of the bioenergy analysis is therefore on supply and use, and new conversion technology costs.

Bioenergy supply estimates from CCC's 2018 *Biomass in a low-carbon economy* were used as the starting point for our analysis. These biomass, biogas, biofuel and waste supply estimates for 2018-2050 were then updated for each scenario, based on the latest assumptions and results from the LULUCF, Agriculture, Waste and fossil fuel supply sectors.

- New forestry and perennial energy crop harvest data from the Land Use sector analysis, based on new work on yield classes and planting rates with the Centre for Ecology & Hydrology.
- Straw, poultry litter and livestock manures are scaled over time with respective arable crop production, poultry numbers and livestock numbers from the Agriculture sector scenarios.
- Total waste wood arisings held flat, as previously.
- Landfill gas estimates now use the devolved administration landfill gas modelling in the Waste sector, with new assumptions on waste prevention and recycling rates, and ban dates on landfilling different wastes. This resource shows significant declines.
- Food waste arisings scale with population, before waste prevention efforts from the Waste sector scenarios are applied. Collection rates for anaerobic digestion rise to 90% by 2030.
- Sewage sludge scales with population, and biogas production increases with shift to advanced anaerobic digestion in the Waste sector.
- Municipal solid waste (MSW) and commercial & industrial (C&I) waste arisings were updated using latest Defra statistics, rescaling previous Defra projections, before waste prevention and recycling efforts from the Waste sector scenarios are applied to calculate residual wastes not landfilled or exported (exports phase out by 2030). Biogenic and fossil fractions vary over time from the Waste sector analysis with the different landfilling bans.
- Informal biomass supplies from DUKES are phased out in line with Residential buildings use of solid biomass.
- The difference in 2018 between our waste sector biogas supply and DUKES UK biogas production is assumed to be maize silage anaerobic digestion (this also matches Defra statistics on maize silage areas for AD). Maize AD is assumed to phase out by 2035.
- Bioethanol production and imports match the demand for bioethanol in light duty vehicles, which increases in 2021 with higher bioethanol blending in petrol. As petrol demand falls over time, bioethanol imports are assumed to phase out first before domestic bioethanol production.

- Waste fats/oils biodiesel production and imports match the near-term demand for biodiesel. UK supplies are assumed to vary with used cooking oil supply (held fixed) and tallow (declines with Agriculture sector livestock numbers). These waste fats/oils biofuel imports increasingly become biojet as biodiesel demands fall.
  - The Balanced Pathway follows a 'fair share' of a global biofuel resource scenario from 2035, which is not dissimilar to Widespread Innovation which holds these imports fixed.
  - Widespread Engagement phases these imports out by 2040.
  - These imports in Tailwinds and Headwinds increase 70-80% from today by the early 2030s (as a 'fair share' of a more ambitious global scenario), before Tailwinds holds these fixed and Headwinds returns to close to 2018 levels.
- Biomass imports have a maximum availability which varies by scenario.
  - Headwinds follows a 'fair share' of an ambitious global bioenergy governance world, resulting in biomass imports increasing to 155 TWh/year by 2050 (as in Scenario 4 of our 2018 *Biomass* report). Tailwinds also assumes this same high level of imports is available.
  - Widespread Innovation focuses strongly on UK biomass production, so phases out biomass imports by 2050 (similar to Scenario 3 of our 2018 *Biomass* report).
  - Widespread Engagement and the Balanced Pathway hold the current biomass import availability of 52 TWh/year steady to 2050, ensuring sufficient supply to reach Net Zero.[*]
  - Actual biomass imports in any year are determined by the balance of total UK biomass supply and total UK biomass demand, and so biomass imports in all years before 2050 are lower than the maximum scenario availability.

Once these biomass and waste availabilities were established, the next step was to allocate these resources to each of the sectors to use in their pathway analysis.

- Our starting position was the 2018 split of bioenergy and waste use by sector from DUKES and NAEI.
- This allocation was accompanied by bioenergy costs and emission intensities for each product consumed by the end-use sectors, from 2020-2050 (a summary is given in Table 6.1).
  - Bioenergy costs, efficiencies and emissions intensities can change over time, but are not assumed to vary across the scenarios.
  - Feedstock costs come from industry benchmarks, with bioenergy conversion plant costs and efficiencies taken from the Energy System Catapult's ESME model, using the same feedstock costs. The added costs of CCS include £15/tCO_2 for downstream transport and storage of CO_2. All conversion plants of one type are assumed to run at their given utilisation rate, which is fixed over time. An investment interest rate of 8% is applied.

[*] 52 TWh/year is based on 2018 biomass import levels plus new biomass power plants built since 2018 or under construction, in effect an estimate of 2021 potential biomass import levels.

Plant lifetimes are assumed to be 30 years for all plants converting biomass, and 20 years for those converting wastes.

– Constant properties over time from Defra[11] are assumed for biomass, waste, biogas, biofuels and biomethane densities, calorific values and combustion values (only residual waste varies with biogenic vs. fossil fractions over time).

– Emission intensities of the delivered fuels (only used for sector £/tCO_2e calculations, not for direct emissions) are derived using these feedstock factors, supply chain emissions (see section 3(f)), and our CO_2 capture rates (Chapter 12).

Table 6.1
Bioenergy conversion technology and feedstock assumptions

	£/MWh 2020	£/MWh 2050	Efficiency 2020	Efficiency 2050	gCO_2e/kWh 2020	gCO2e/kWh 2050
Domestic biomass	22	22	NA	NA	7	1
Imported biomass	31	31	NA	NA	33	3
Residual waste	0	0	NA	NA	8	1
Biogas	29	29	NA	NA	22	2
Bioethanol	64	64	NA	NA	93	28
Waste fats/oils biodiesel	91	91	NA	NA	28	3
Waste fats/oils to biojet	105	102	88%	90%	28	3
Biomass to FT biodiesel with CCS	127	86	34%	42%	-457	-485
Biomass to FT biojet with CCS	132	89	34%	42%	-457	-485
Residual waste to FT jet with CCS	89	48	29%	37%	-250	-285
Biomass to heating fuel (2020 without, 2050 with CCS)	72	70	52%	54%	28	-400
Biogas to biomethane	38	35	92%	94%	43	4
Biogas to biomethane with CCS	49	46	88%	90%	-49	-118
Biomass to bioSNG with CCS	61	52	60%	66%	-229	-286
UK biomass to H2 with CCS	86	71	51%	55%	-508	-571
Imported biomass to H2 with CCS	103	871	51%	55%	-460	-567

Sources: Defra (2020) Greenhouse gas reporting: conversion factors 2020; Argus (2020) Biomass Markets; ESC (2019) ESME Data References Book; Ofgem (2019) Biomass Sustainability Dataset 2017-18; CCC analysis.
Notes: All values are in HHV. Emissions intensities are full lifecycle emissions, not what the fuel supply sector or end-use sector accounts for. Residual waste costed at £0/MWh, as we do not include landfill tax/transfers.

Some sector analysis then phases out the use of bioenergy as end-use efficiencies improve and as other low-carbon alternatives (e.g. heat pumps, electric vehicles, low-carbon hydrogen, offshore wind) become available.

- These phase-outs include solid biomass in buildings heating, agriculture and unabated power, along with bioethanol and biodiesel in surface transport, off-road machinery and agricultural equipment.
- Manufacturing also has a gradual decline in unabated bioenergy use over time, but not a full phase-out.

This led to sectors returning unused bioenergy resources for reallocation. Along with the growth in available supplies which are also available to be allocated, these new allocations to sectors were based on the findings from our analysis of best uses of bioenergy, discussed in section 3(f) below.

- 2050 was the focus, as this is the Net Zero date and when all available feedstocks are used. We reallocate to BECCS applications in power, biohydrogen, biojet and industrial heating, to maximise GHG savings.

Differences between these allocations also reflect the different scenario framings, as discussed in the *Advice Report*, Chapter 3, section 5.

- We then worked backwards in time to scale-up different supply chains and conversion technologies from their starting points in the late 2020s or early 2030s, to meet the 2050 allocations. Some routes, such as BECCS power, can reach sector limits around 2040 in some scenarios, and are assumed to not increase further beyond 2040.
- This ramping up to 2050 means that there is typically a modest surplus of biomass in earlier years (as several existing uses of biomass tend to ramp down faster/earlier). We therefore reduce biomass imports accordingly so that demand matches actual supply in each year.
- Several conversion technology ramp-ups in the late 2020s and early 2030s are constrained by technology readiness and the number of developers globally, in order to ensure early growth is realistic.
- Some bioenergy conversion facilities are built in the 2020s without CCS but retrofit CCS during the 2030s. All new conversion facilities from the early 2030s are built with CCS.
- It is technically feasible that some plants built during the 2020s and early 2030s could transition to a different product spread at relatively low marginal capital cost. During the 2030s, we model a biodiesel to biojet transition (both for plants based on waste fats/oils and biomass FT gasification) and from bioSNG to biohydrogen (if bioSNG is deployed). However, any early pre-transitional capacity increases are typically very modest given that biodiesel use is declining during the 2030s, as is fossil gas use, and technology scale-up constraints still apply. Biojet and biohydrogen facilities are still constructed on the original timelines, but there is also a minor boost during the 2030s with these transitions. There is no significant surge into one sector, and then wide-spread retrofitting of capacity 10 years later.
- We do not allow overbuilding of conversion technologies (i.e. there is no early scrappage or early retirement of plants).

The waste allocation analysis is carried out separately. After accounting for niche uses in manufacturing, fuel supply and clinical/chemical waste incineration, the remaining residual waste tonnages are sent to energy-from-waste plants in all scenarios, except in Widespread Engagement when 70% is sent to jet fuel production by 2050. Unlike for biomass where supply can exceed demand (and biomass imports fall), we assume all waste must be used each year.

The final allocation of bioenergy and waste to end-uses therefore differs across scenarios, as set out in the *Advice Report*, Chapter 3, section 5. The resulting volumes of biogenic CO_2 captured from BECCS applications are given in Chapter 12 of this report.

The capital and operating costs of the different bioenergy conversion routes are then calculated bottom-up from the added capacity in a year, and the total deployment of a route (and hence feedstock consumption).

- Our analysis assumes increasing efficiencies and capture rates, and declining capital and operating costs over time. Given the complexities of handling 24 different routes, it was only possible to implement a fleet/sales approach for capital costs (i.e. plants built earlier cost more) and the added capital costs of transitioning a plant to another output (e.g. biodiesel to biojet in a particular year).

- It was not possible to implement this approach for other metrics – this means that in each year, the efficiency, operating costs and capture rate of a route is the same across all the plants in that route, regardless of when each plant was built.
  - Our assumptions regarding efficiency improvements are therefore relatively modest to account for this fleet impact.
  - Operating costs are expected to fall over time with experience and greater automation, sharing overheads across a fleet of plants, and as plants scale up in size with commercialisation.
  - Capture rates could be improved after installation, with process optimisation, new equipment or improved materials/solvents.

d) Devolved administrations

The use of site-level data in the N-ZIP model provided emissions, abatement and costs data that could be attributed to the devolved administrations (DA). We have used this data to produce a pathway for each DA for each scenario.

For hydrogen supply, the only relevant allocation to devolved administrations are the fugitive emissions from fossil gas reforming with CCS, due to CO_2 capture rates being below 100%. We distribute UK-wide gas reforming proportionately to the DAs, based on their share of industrial CCS in our scenarios. In the Balanced Pathway that is 15% and 25% for Scotland and Wales respectively in 2050.

For bioenergy conversion, our approach to allocating biogenic CO_2 captured is detailed in Chapter 12. We do not specifically allocate BECCS plants to the devolved administrations, but present DA trajectories without engineered GHG removals and then discuss the amount of BECCS or DACCS (Direct Air Capture of CO_2 with storage) that would have to be assumed to be built within each devolved administration. This approach also extends to the capital and operating costs of BECCS plants not being specified within the DAs. The exception is the use of biomass with CCS in Manufacturing & Construction, which will be location-specific, and follows the Element Energy N-ZIP model results.

There is some abatement in Fuel Supply from the injection of additional biomethane into the gas grid at above baseline levels, displacing fossil gas. This abatement and cost is allocated to the DAs according to the location of the biogas resources.

For bioenergy supply, each DA is assumed to produce:

- Forestry and perennial crop feedstocks according to DA data from the Land use sector.
- Straw, poultry litter and livestock manures are split by respective arable crop production, poultry numbers and livestock numbers from the Agriculture sector scenarios.
- Landfill gas is from DA specific landfill gas modelling in the Waste sector.
- Food waste, sewage sludge, waste wood, MSW and C&I waste arisings are assumed to be split by population, and waste prevention and recycling efforts from the Waste sector scenarios.

- Informal biomass supplies are assumed to be apportioned to existing forestry areas, and maize biogas is apportioned to maize areas.
- Bioethanol and waste fats/oils biofuels are assumed to be apportioned to DAs based on existing facilities and their assumed production over time.

e) Uncertainties

Fossil fuel supply

We have used the results of our analysis to inform our recommendations around future deployment of deep-decarbonisation measures and CO_2 and hydrogen infrastructure. However, there is much uncertainty about many of the assumptions that we have used in our analysis. Therefore, we have considered a range of sensitivities to the assumptions, to form different pathways, with the purpose of identifying a range of different futures and the most – and least – robust conclusions of the analysis. More detail on the model parameters is given in the accompanying report by Element Energy[12]. Some model sensitivities are described in Chapter 4, section 5.Uncertainties for fossil fuel supply also include those that have been seen in the past, relating to the volatility of global prices.

Low-carbon hydrogen supply

Uncertainties in our assessment of low-carbon hydrogen supply options could imply a different supply mix and/or supply costs in the future:

- **The role for electrolysis.** The role for electrolysis depends on both its interaction within the electricity system and its cost-competitiveness with other ways to supply hydrogen.
  - While our modelling of the electricity system using the BEIS Dynamic Dispatch Model (DDM) considers in sufficient detail the potential for electrolysis to utilised otherwise 'curtailed' generation, it does not include a sufficiently wide range of alternative electricity storage options that might have lower costs and/or higher efficiencies. However, while a larger role for other electricity storage technologies may imply a lesser role for electrolysis, these alternative forms of storage would also reduce the need for back-up generation, implying lower hydrogen demand from the power sector.
  - As the economics of electrolytic hydrogen in our analysis rely on the electricity being otherwise curtailed and therefore available at no additional cost, the cost of electrolytic hydrogen is driven by the capital cost and utilisation of these electrolysers. Both of these factors are uncertain.
  - Electrolytic hydrogen production from a given set of electricity system capacities will tend to have some year-to-year variation, depending on the weather and therefore levels of wind and solar generation. Our analysis represents a typical year. In years with significantly higher renewable generation, the surplus from the electricity system may be substantially greater, and vice-versa in a year with low renewable generation. The availability of capacity to produce hydrogen and electricity from fossil gas with CCS, which has relatively low-utilisation by 2050 in a typical year, ensures that sufficient capacity is available to meet electricity and hydrogen demands in a low-carbon way.

- **Hydrogen production from biomass gasification with CCS.** While our analysis assumes some use of biomass gasification to produce hydrogen, with up to 90% of the biogenic CO_2 captured and sequestered, biomass gasification technology is not yet mature.

  While it is desirable to have a diverse mix of hydrogen supply routes and minimise reliance on imported fossil gas, the same demands for hydrogen can be met with a supply mix that excludes biomass gasification with very similar emissions. This is assuming that biomass used in hydrogen production can otherwise be used for other BECCS applications (see Chapter 12).

- **Hydrogen production from fossil gas with CCS.** Reforming of fossil gas can provide large-scale low-carbon production of hydrogen. Its role depends on it being sufficiently low-carbon on a lifecycle basis and on economics:

  – We have previously estimated that this would provide an emissions saving of up to 85% compared to unabated direct use of fossil gas (e.g. in gas boilers) on a lifecycle basis. This saving depends on both achieving a 95% CO_2 capture rate at the gas reformation stage, but also on upstream emissions from fossil gas production being at the bottom end of our estimated range of 15-70 gCO_2e/kWh.[13] While Equinor has suggested that upstream emissions from Norwegian fossil gas production could be considerably lower than 15 g/kWh,[14] it is possible that a substantial fraction of fossil gas imported to produce hydrogen could be in the form of liquefied natural gas (LNG), which could have a considerably larger footprint.[15] Higher residual lifecycle emissions from fossil gas reforming would imply a more limited role.

  – The large majority of the costs of hydrogen supply via this route are from use of fossil gas. These means that its economics are highly dependent on future gas prices.

- **Cost competitiveness and domestic production vs imports**. A key uncertainty is the future relative cost-competitiveness of UK low-carbon hydrogen production vs. other world regions, and transport logistics. This will determine whether UK is entirely self-sufficient for its hydrogen, ammonia and synfuel production, or imports the majority of its hydrogen, ammonia and synfuels from world regions with even cheaper renewable power than in the UK. On the basis that we need to show the costs of UK decarbonisation to Net Zero, including the associated network impacts on UK power generation, and without over-relying on low-carbon energy sourced from other countries that will also be looking to decarbonise, we have limited imports in the Balanced Pathway to only 14% of hydrogen supply, 25% of ammonia supply and 25% of synthetic jet fuel supply.

Bioenergy and waste supply

- **COVID-19**. We have not attempted to calculate a long-term reduction in energy demand due to structural changes in GDP due to COVID-19; nor have we considered any potential reductions in supply via failures of feedstock suppliers, supply chain actors or potential plant operators. There remain some uncertainties as to the size of the energy industry that will emerge after COVID-19, and the level of investor appetite for less mature technologies.

- **Best use of bioenergy.** The best use of bioenergy analysis relies on CCS being widely available from the late 2020s onwards. A significant delay in CCS becoming available that significantly constrains BECCS deployment by 2050 may, depending on CCS readiness of these uses, shift the balance of best uses away from power and hydrogen (where 90-95% of feedstock carbon is captured, but the counterfactual product is increasingly low-carbon) and towards industry heating (displacing fossil fuels) and transport biofuels (where less feedstock carbon is captured in processing, but fossil fuels are displaced).

- **Cost competitiveness and domestic production vs imports**. A key uncertainty is the future relative cost-competitiveness of UK sustainable bioenergy production vs. other world regions, and transport logistics. This will determine whether UK is entirely self-sufficient for its biomass production, or imports a significant share of its biomass from world regions with larger biomass basins and more established supply chains. On the basis that we need to show the costs of UK decarbonisation to Net Zero, without over-relying on energy sourced from other countries, we have limited biomass imports in the Balanced Pathway to only 21% of total biomass supply (the same import dependency level as in 2018).

- **Sustainability criteria**. Tighter sustainability standards including GHG thresholds could potentially favour UK biomass over imports, given shorter distances and faster decarbonisation of energy inputs to UK supply chains than in many other world regions.

- **Perennial energy crop and short-rotation forestry biomass characteristics**. While being high-yielding than long-rotation forestry, fast growing biomass resources also typically grow containing higher contents of ash, halides and alkali metals. These chemical components can present operational issues in biomass combustion boilers and gasification plants. Solutions typically fall into modifying existing assets, designing new-build plant specifically for these feedstocks, or pre-treatment to remove/reduce some of these components. These solutions may add costs to the use of these feedstocks.

- **Application of costs**. Our costs for bioenergy conversion plants are indicative. There is likely to be a broad range of costs around our estimates, given differences in site size, location, existing equipment, cost of capital and lifetimes. Smaller projects or projects further from feedstock sources or CCS hubs might cost significantly more than modelled.

f) Best use of bioenergy and waste

Best use of bioenergy

As detailed in Chapter 5 of the CCC's (2018) *Biomass in a low-carbon economy* report, the highest GHG savings when using biomass are achieved with high CO_2 sequestration rates and displacement of high-carbon alternatives. This analysis was focused on woody biomass in 2050, for use in timber frame buildings, industry, hydrogen, power, aviation and cars, and was also conducted prior to the UK's Net Zero target being set.

In the Sixth Carbon Budget analysis, we have extended and updated this 'best use of bioenergy' analysis:

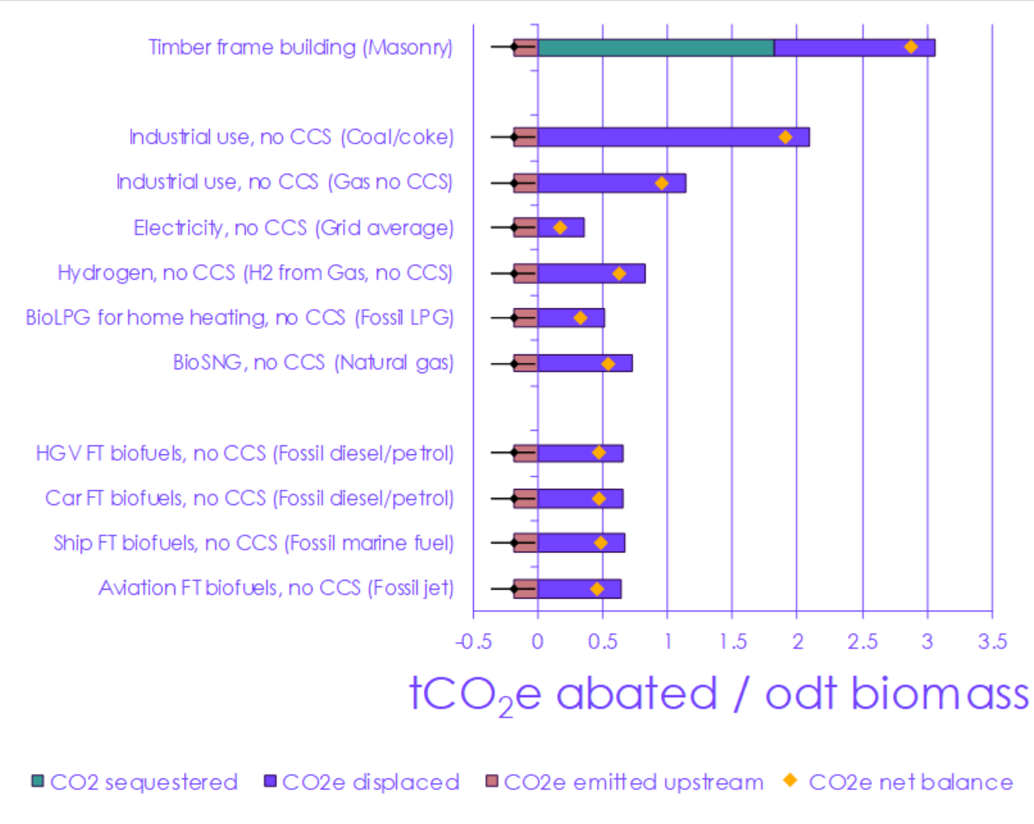
- Analysis has been conducted in 2020, 2035 (the mid-point of the Sixth Carbon Budget period) and 2050.
- The scope of the routes considered has been broadened, to cover woody biomass use in aviation, shipping, cars, HGVs, gas grid, home heating liquid fuels, hydrogen, power, industry and timber frame & wood panel construction. Best use of wastes across power, aviation, gas and hydrogen have also been considered for the first time.
- Assumptions regarding route efficiencies and c apture rates have been updated to be aligned with the latest evidence from the end-use sectors and GHG removals sector analysis, and these rates improve over time. For transport biofuels, we are assuming gasification and Fischer-Tropsch (FT) catalysis, although other similar routes would achieve a similar outcome.
- The number of potential counterfactuals (i.e. high-carbon or low-carbon alternatives to the use of bioenergy in a sector) have been increased, and the counterfactual GHG intensities have been updated to align to the Balanced Net Zero Pathway.
- Estimates of upstream biomass supply chain GHG emissions have been added to the analysis, from Ofgem sustainability data,[16] as these were previously missing. Assumptions are made that these upstream emissions will decline over time as supply chain energy and chemical input components decarbonise, in line with the Balanced Pathway. Upstream biomass supply chain emissions are assumed to reduce by 66% from today's values by 2035 and 90% by 2050.
- No land-use change emissions or sequestration have been accounted for in this analysis, despite UK forestry and perennial energy crops both being expected to lead to significant carbon sinks (Chapter 7).
- Abatement for timber construction is calculated based on a whole-house unit designed to meet the same SAP ratings, implying lifetime operational emissions for each house equal to masonry counterfactuals. Counterfactual emissions for concrete, cement & brick are assumed to reduce by 69% from today's values by 2035, and by 95% by 2050, in line with our Balanced Pathway for the manufacturing & construction sector.

The following set of charts show the estimated GHG abatement provided by one oven dried tonne of biomass used in various sectors, considering the most appropriate counterfactual in each sector for that year.

We show abatement broken down by sequestered carbon (the amount of CO_2 stored and/or not released into the atmosphere due to CCS technology); displaced carbon (the amount of fossil CO_2 that would have been emitted to the atmosphere in the counterfactual case had biomass not been used); and upstream carbon (from the feedstock supply chain).

With no CCS available in 2020, the best use of biomass is currently either locking up biogenic CO_2 as wood in construction, or displacing coal in industrial applications (Figure 6.4). The UK electricity grid has already decarbonised significantly, hence additional use of biomass in unabated power is not a best use of biomass.

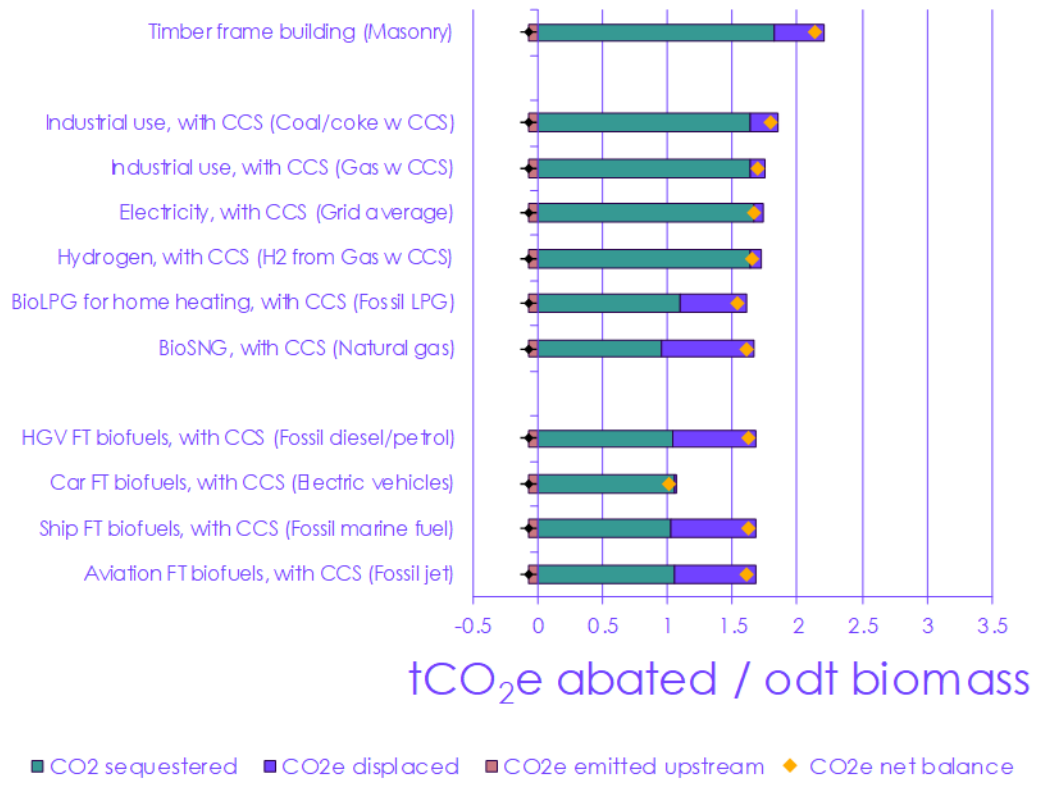
Figure 6.4 Best use of biomass in 2020



Source: Ofgem (2018) *Biomass Sustainability Dataset 2016-17*; CCC analysis.
Notes: Counterfactuals given in brackets. Upstream emissions include cultivation, processing, transportation and direct land-use change, but indirect land-use change and changes in land carbon stocks when no land-use change occurs are excluded. Upstream min-max range from Ofgem feedstock data (sawmill co-products, Miscanthus, SRC, wood pellets, forest residues and brash bales).

By 2035 (Figure 6.5), CCS is assumed to be widely available and deployed at bioenergy conversion facilities. Use of biomass in industry, power and hydrogen result in similarly high total levels of abatement, due to high CO_2 capture rates, although there is little abatement from displacement of fossil fuels as the grid has decarbonised and CCS has been added to much of industry (Figure 6.5).

Figure 6.5 Best use of biomass in 2035



Source: Ofgem (2018) *Biomass Sustainability Dataset 2016-17*; CCC analysis.
Notes: Counterfactuals given in brackets. Upstream emissions include cultivation, processing, transportation and direct land-use change, but indirect land-use change and changes in land carbon stocks when no land-use change occurs are excluded. Upstream min-max range from Ofgem feedstock data (sawmill co-products, Miscanthus, SRC, wood pellets, forest residues and brash bales).

Use of biomass in bioliquids/bioLPG for home heating, gas grid injection, and transport biofuels* can achieve high overall abatement, but only if high-carbon fuels are being displaced, since sequestration is lower (due to carbon remaining in the final fuel). If the counterfactual is a low-carbon option, such as electric cars, then this displacement abatement disappears – so the use of biomass in the car fleet is not a best use by the 2030s.

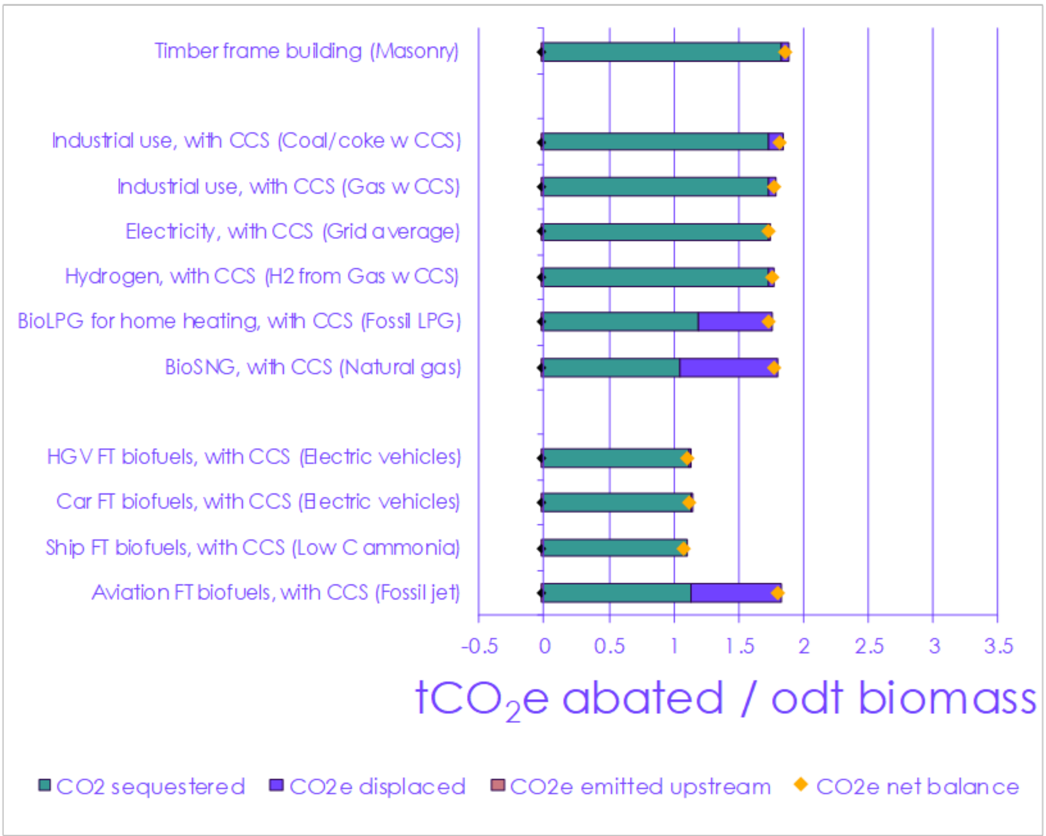
The use of wood in construction is still a best use, although the displaced emissions associated with production of the counterfactual (e.g. bricks, cement) are expected to fall in line with UK manufacturing & construction sector emissions. Upstream GHG emissions have also fallen, in line with the improved carbon intensity of biomass transport and any pre-processing.

* For example in aviation. Shipping & HGVs are starting to decarbonise with use of low-carbon ammonia in shipping and electricity/hydrogen use in HGVs by 2035, so the counterfactual may be lower than shown.

By 2050 (Figure 6.6), the main change is that the counterfactual in some sectors will have changed – for example, HGVs and shipping will be fully decarbonised using electricity and low-carbon hydrogen/ammonia fuels. The use of biomass in industry, power and hydrogen remains a best use (Figure 6.6), and the use of biomass in producing fuels is only a best use if high-carbon fuels are still being displaced, as in aviation.

There might still be a small niche for bioliquids/bioLPG for home heating if still displacing fossil fuels off-gas-grid, although these opportunities will be very limited due to efficiency and electrification. Fossil gas will still be used in the UK in 2050, however, as much of this fossil gas is going to hydrogen production (with CCS), it would be a more efficient use of biomass to make biohydrogen directly, instead of via bioSNG.

Figure 6.6 Best use of biomass in 2050



Source: Ofgem (2018) *Biomass Sustainability Dataset 2016-17*; CCC analysis.
Notes: Counterfactuals given in brackets. Upstream emissions include cultivation, processing, transportation and direct land-use change, but indirect land-use change and changes in land carbon stocks when no land-use change occurs are excluded. Upstream min-max range from Ofgem feedstock data (sawmill co-products, Miscanthus, SRC, wood pellets, forest residues and brash bales).

In summary, the findings from this new analysis support and strengthen the conclusions reached in the 2018 CCC Bioenergy report. Upstream emissions will diminish, best uses in 2035 already align well with those in 2050, and new bioenergy conversion facilities have to either be built with CCS or CCS ready, and their output products already aligned, or able to align, to long-term best uses.

- Upstream biomass supply chain GHG emissions (excluding land-use change*) will not significantly change the benefits of BECCS if policy & governance frameworks are well designed, and will improve significantly over time as harvesting, transport, storage and pre-processing steps decarbonise.
- With the widespread use of CCS on bioenergy facilities by the mid-2030s, the 2035 outlook is similar to 2050, as improvements in bioenergy process efficiencies and CO_2 capture rates are only modest. Changes in counterfactuals or their emissions intensities are a much bigger factor over this period.* However, BECCS applications that have high sequestration rates are not significantly impacted by the choice of counterfactual.
- Bioenergy use in the UK, which will be driven by policy incentives, already needs to focus on long-term best uses. There is unlikely to be sufficient time to undergo an intermediate transition before another final transition occurs, given assets built in the 2020s will still likely be operational by 2050.
    - There is therefore limited scope to develop biofuels for HGVs or shipping, given these are not best uses from the mid-2030s. Biofuel plants will need to focus on maximising biojet instead – although recognising that biojet plants may also output some heavier fuel co-products for HGVs or shipping, and lighter co-products such as bioLPG.
    - There is also likely to be a limited role for bioSNG, given the use of fossil gas will be declining to 2050, although bioSNG plants can be retrofitted to biohydrogen production to ensure best use.

* Land-use change emissions are covered under the LULUCF sector.

* This analysis is simplistic in terms of choosing a set of snapshot counterfactuals, whereas a more sophisticated analysis might consider blended counterfactuals to match sector decarbonisation profiles (without the use of bioenergy).

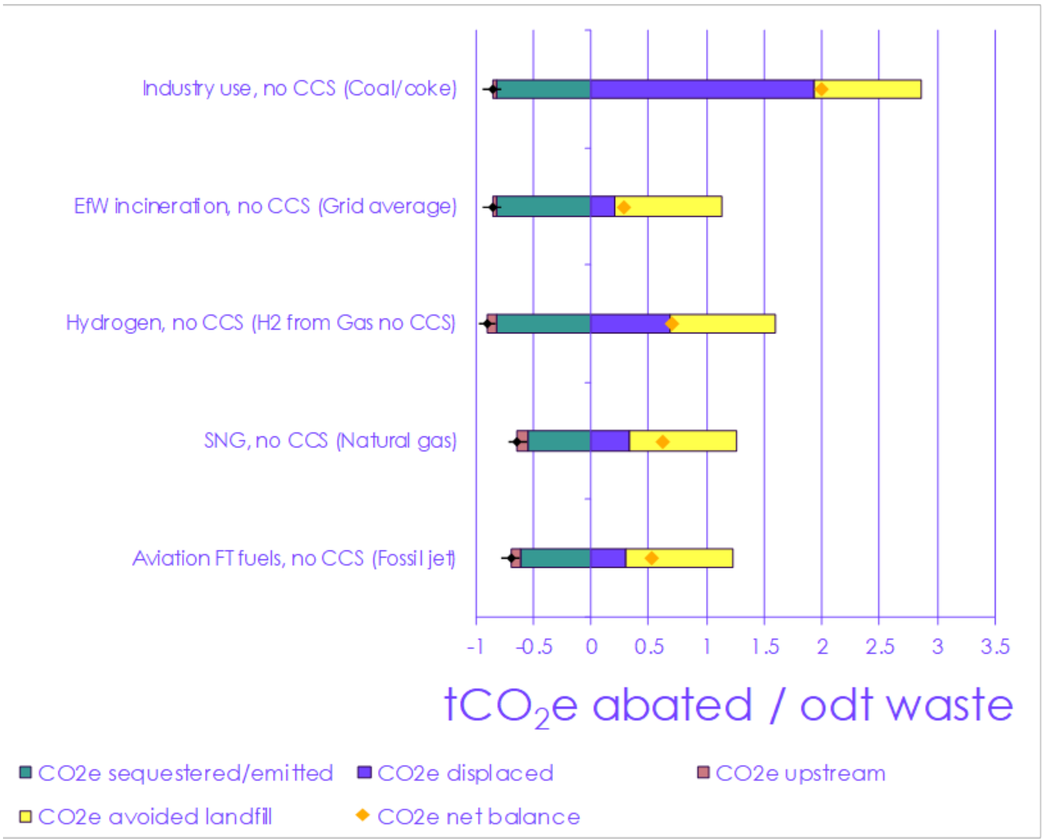
Best use of waste

The following set of charts show the estimated GHG abatement provided by one oven dried tonne of residual waste (with mixed biogenic/fossil fractions) used in various sectors, considering the most appropriate counterfactual in each sector for that year.

Today (Figure 6.7), without CCS, conversion of waste into different energy vectors results in fossil CO_2 emissions (negative sequestration bars). These emissions are, however, offset by the methane emissions avoided from diversion away from landfill.

Upstream supply chain emissions in waste transport and pre-processing are small. The largest displacement savings are achieved in industry, via displacing high-carbon feedstocks. Savings in other applications are more modest – particularly energy-from-waste power plants, as UK electricity is now lower carbon than other vectors. Use of waste in energy-from-waste plants is still just about better than landfilling today, but other routes are able to achieve higher abatement in the near-term.

Figure 6.7 Best use of waste in 2020

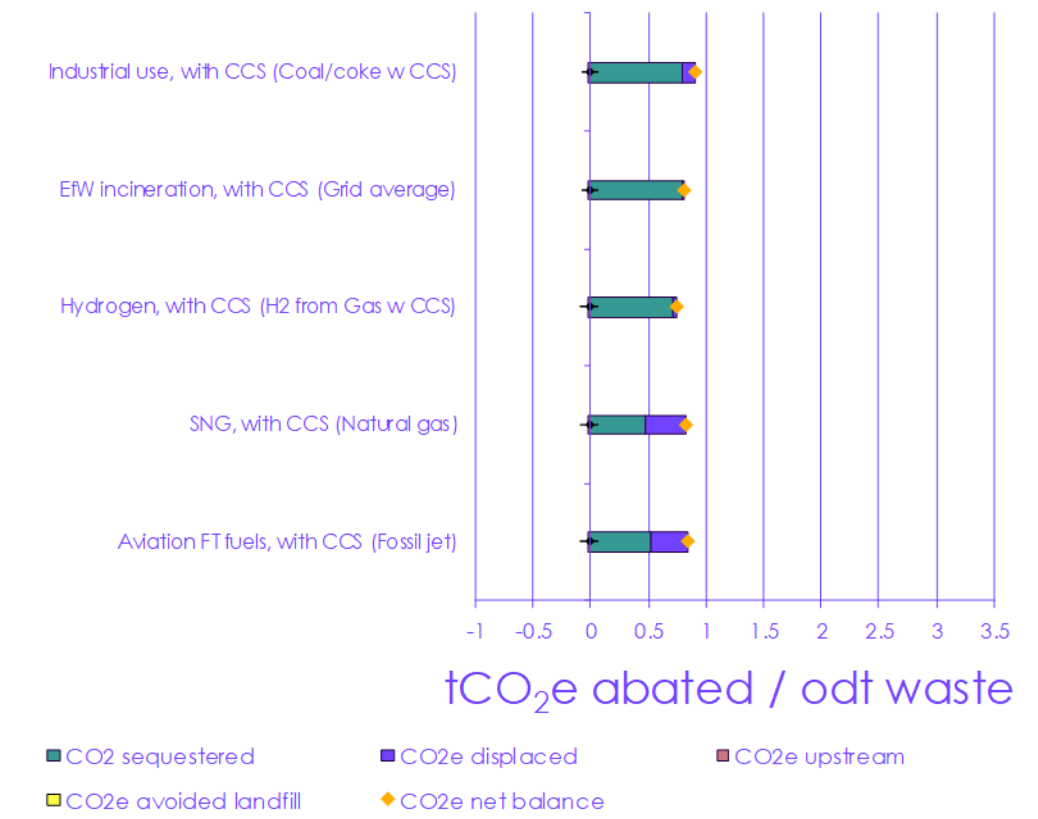


Source: CCC analysis.
Notes: Counterfactuals given in brackets. Upstream emissions include processing and transportation. Indicative min-max range given.

However, by 2050 (Figure 6.8), there is strong convergence between all the routes. High capture rates mean that 5-10% fugitive fossil CO_2 emissions in conversion are small compared to the 90-95% of biogenic CO_2 sequestered from conversion. Given no waste is sent to landfill from 2040 (under the Balanced Pathway), the landfill counterfactual savings no longer apply to this 2050 snapshot. The abatement from displacing fossil fuels has shrunk in several sectors due to the addition of CCS to the counterfactuals, and further decarbonisation or fuel-switching. This leads to the different routes achieving similar levels of overall abatement by 2050 (well within the uncertainty range of this analysis).

Our analysis of the best use of waste is more limited in scope than for biomass but has identified that adding CCS to energy-from-waste power plants leads to similar GHG savings outcomes as waste to jet fuel plants with CCS or other routes to hydrogen or gas. The addition of CCS is critical in turning fossil emissions from waste into net biogenic CO_2 sequestration, and given asset lifetimes, all waste conversion facilities have to either be built with CCS or CCS ready, and their output products already aligned, or able to align, to long-term best uses.

Figure 6.7 Best use of waste in 2050



Source: CCC analysis.
Note: Counterfactuals given in brackets. Upstream emissions include processing and transportation. Indicative min-max range given.

Endnotes

[1] Element Energy (2019) *Assessment of options to reduce emissions from fossil fuel production and fugitive emissions*. https://www.theccc.org.uk/publication/assessment-of-options-to-reduce-emissions-from-fossil-fuel-production-and-fugitive-emissions/

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[7] BEIS (2020) *Updated energy and emissions projections: 2019*. https://www.gov.uk/government/publications/updated-energy-and-emissions-projections-2019

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[15] Oil and Gas Authority (2020 https://www.ogauthority.co.uk/news-publications/news/2020/north-sea-gas-has-lower-carbon-footprint-than-imported-lng/

[16] Ofgem (2018) *Biomass Sustainability Dataset 2016-17*

Agriculture and land use, land-use change and forestry (LULUCF)

Introduction and key messages

This chapter sets out the methodology for the agriculture and land use, land use change and forestry (LULUCF) sectors for the Sixth Carbon Budget pathways.

The scenario results of our costed pathways are set out in our accompanying Advice report (*The Sixth Carbon Budget - The UK's path to Net Zero*), and policy implications in our accompanying Policy report (*Policies for the Sixth Carbon Budget & Net Zero*). For ease, these sections covering pathways, method and policy advice for the agriculture and land use sector are collated in *The Sixth Carbon Budget - Agriculture and Land Use*. A full dataset including key charts is also available alongside this document on the CCC website.

The key messages from this methodology chapter are:

- **Background.** GHG emissions in agriculture and land use were 54.6 $MtCO_2e$ and 12.8 $MtCO_2e$ respectively in 2018. The two sectors account for 12% of all UK emissions.
- **Options for reducing emissions and increasing removals**. These include behavioural change within wider society; productivity improvement; significant land use change for planting more biomass and restoring degraded peat; sustainable management of existing broadleaf woodlands and cropland peat; the take-up of technological options to reduce non-CO_2 emissions from soils, livestock and waste and switching away from fossil fuel use in agricultural machinery to low-carbon alternatives.
- **Analytical approach.** The analysis is based on a detailed review of available evidence, including academic research and literature, monitoring of latest developments and trends in the sectors, modelling conducted by the CCC and two research projects commissioned by the CCC, which are published alongside this report.[1]
- **Uncertainty.** The scenario framework is used to test the impacts of uncertainties, to inform our Balanced Net Zero Pathway. The key areas of uncertainty include behaviour change; productivity improvements, scale of land use change and costs.

We set out our analysis in the following sections:

1. Current and historical emissions from agriculture and land use
2. Options to reduce emissions in these sectors
3. Approach to analysis for the Sixth Carbon Budget

a) Agriculture

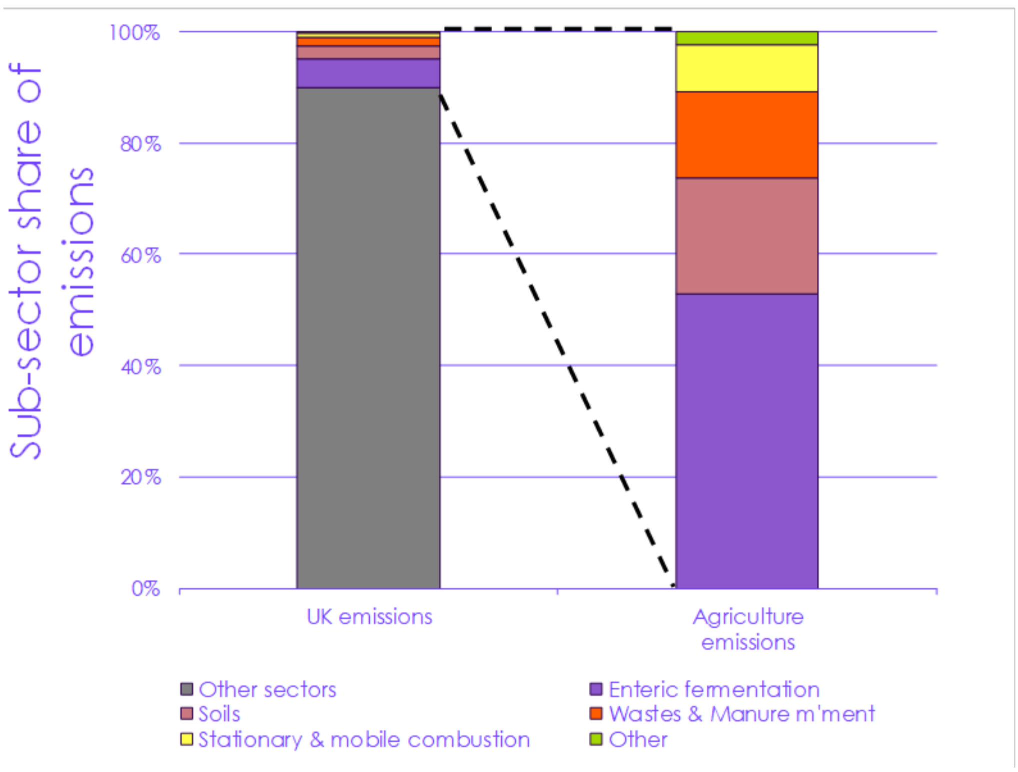
Agriculture GHGs as a share of all UK GHGs has increased from 7% in 1990 to 10% in 208.

Agricultural emissions were 54.6 $MtCO_2e$ in 2018 using the Global Warming Potential of AR5 for methane. This represents 10% of UK GHG emissions in 2018 compared to 7% in 1990. This increase reflects both the slow rate of progress in reducing the sector's emissions, and the faster pace of decarbonisation elsewhere in the economy. Agricultural emissions are mainly from livestock and soils. Key sources of emissions in 2018 were:

- 63% of emissions were methane from livestock, 26% are nitrous oxide (N_2O) mainly from soils and 11% are carbon dioxide (CO_2) from the use of fossil fuels.
- Enteric fermentation from the digestion process of ruminant livestock is the largest source (53%), agricultural soils (21%), wastes and manure management (16%), and mobile and stationary machinery 8% (Figure 7.1).

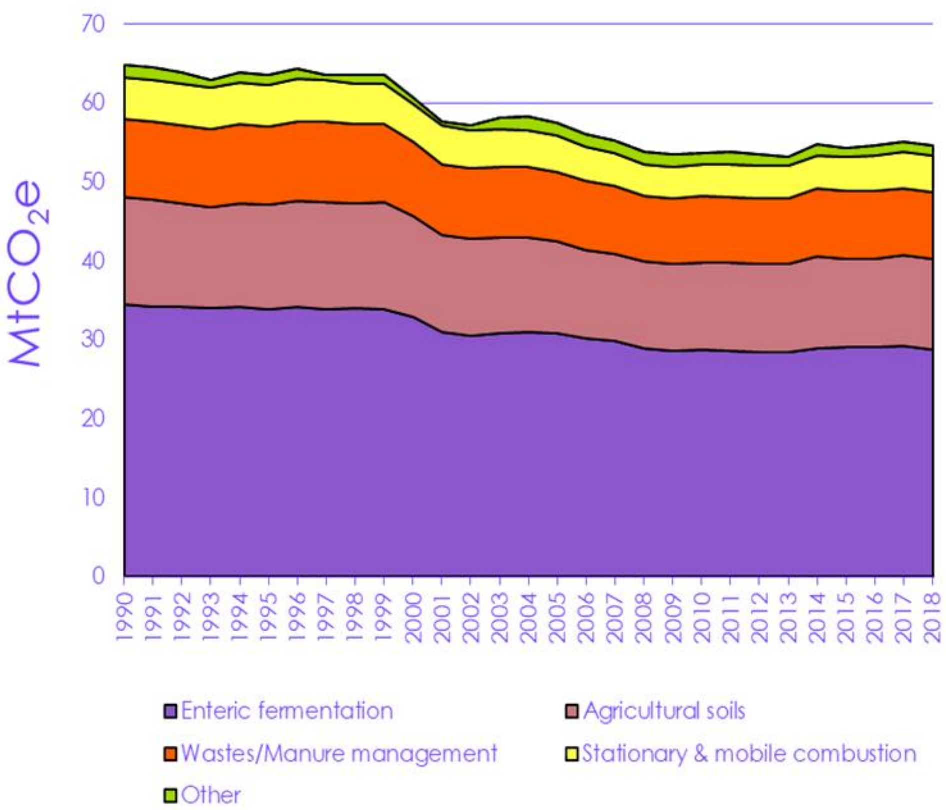
Emissions have declined by 16% since 1990. This is mainly due to successive reform of the Common Agricultural Policy (CAP) in the 1990s and early 2000s, which reduced livestock numbers, coupled with changes in farming practices due to EU environmental legislation to address non-GHG pollutants (e.g. Nitrates Directives). There has been little change in emissions since 2008 (Figure 7.2).

Figure 7.1 Breakdown of agriculture emissions (2018)



Source: BEIS (2020) Provisional UK greenhouse gas emissions national statistics 2019; CCC analysis.

Figure 7.2 UK agricultural emissions (1990-2018)



Source: BEIS (2020) Provisional UK Greenhouse Gas National Statistics for the UK; CCC analysis.

b) Land use, land use change and forestry

Land can remove CO_2 from the atmosphere, which makes it unique among sectors in the GHG Inventory.

The land use, land use change and forestry sector (LULUCF) captures carbon removals and GHG emissions from the use and change in use of different land types in the UK. The main land categories are forestry, cropland, grassland, wetlands and settlements. There is also an additional category that captures changes in carbon stocks of harvested wood products (HWP).

Under the current methodology of the Greenhouse Gas Inventory, the LULUCF sector is a net carbon sink.[2] The sector sequestered 10.3 $MtCO_2e$ in 2018, which is equivalent to abating 2% of UK emissions.

Future improvements to the GHG LULUCF inventory will move the sector from a net sink to a net source of emissions:

- Only about 6% (1.5 $MtCO_2e$) of peatland emissions are currently reported in the inventory. Capturing all sources of peatland emissions would bring total peat emissions to between 18.5 and 23 $MtCO_2e$ in 2018 depending on the method to estimate forestry peat.
- The adoption of the new Global Warming Potential (GWP) values in 2024, in line with IPCC guidance, will increase methane emissions by 36% and N_2O emissions will be unchanged if the GWP values include for feedbacks on the carbon cycle.[3]

Including all peatland emissions in the GHG inventory will turn the sector from a net sink to a net source of emissions.

Including the higher estimate of peatland emissions of 23 MtCO2e would leave the LULUCF sector a net source of emissions of around 11 MtCO2e in 2018. This rises to 12.8 MtCO2e (2% of UK emissions) using the new GWP AR5 values, which we use as the starting point in our analysis.

A breakdown of land emissions and removals in 2018 shows the dominance of peatland and forestry (Figure 7.3):

- Peatlands are the largest emissions source (24.5 $MtCO_2e$), followed by non-organic cropland (9.8 $MtCO_2e$) and settlements (7 $MtCO_2e$).
- Forestry is the largest net sink at around 18 $MtCO_2e$, which is equally split between broadleaf and conifer woodlands. Non-organic grassland sequesters a further 9 $MtCO_2e$, and HWP just over 2 $MtCO_2e$.

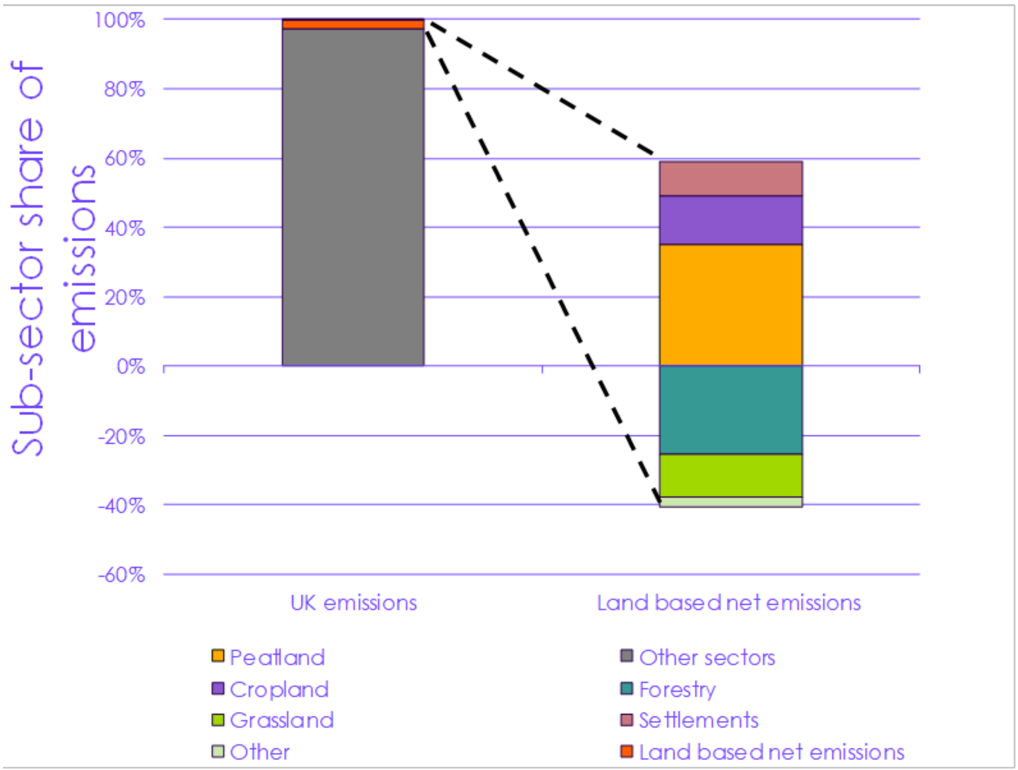
The ageing profile of existing woodlands in the UK is weakening the strength of forests to absorb CO_2.

The sector's net emissions decreased by 1% on the previous year. Since 1990 net emissions have fallen by 43% (equivalent to 9.6 $MtCO_2e$) since 1990 (Figure 7.4):

- A strengthening of the forestry sink by around 3 $MtCO_2e$, driven by a steady programme of afforestation from the 1960s saw annual planting rates reach 40,000 hectares in the early 1970s and close to 30,000 hectares in the 1980s. The non-organic grassland sink increased by 2 $MtCO_2e$ over the period.
- Emissions from non-organic croplands have fallen by 4 $MtCO_2e$.
- The pace of emissions reduction has slowed since 2011. This is due to the weakening of the forestry sink with the ageing profile of existing woodlands and the decline in planting rates, with an annual average of 9,000 hectares planted between 2008 and 2018.

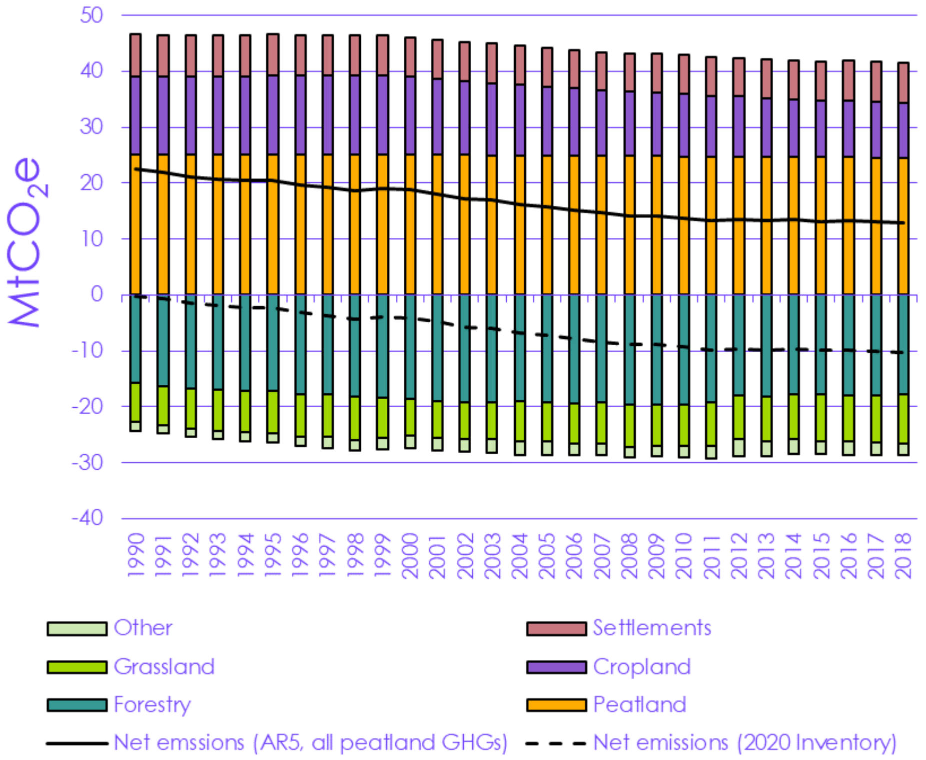
Peatlands are the largest source of land emissions and forests the largest sink.

Figure 7.3 Breakdown of land emissions (2018)



Source: BEIS (2020) Provisional UK Greenhouse Gas National Statistics for the UK; CEH (2020) CCC analysis.

Figure 7.4 Land based emissions and removals (1990-2018)



Source: BEIS (2020) Provisional UK greenhouse gas emissions; CCC analysis.

Meeting Net Zero and other key objectives of land means we need to change the way we use and manage our land.

Our previous work (*Land Use-Policies for a Net Zero UK* (2020) and *Net Zero Technical report* (2019)) has shown that deep emissions reductions in the agriculture and land sectors cannot be achieved without changes in how we use our land. The contribution to emissions reduction from these sectors requires actions to change farming practices and consumer behaviour to release agricultural land for uses that reduce emissions and sequester carbon. Our analysis assumes that land needed for food production, housing and other activity is met before climate mitigation objectives. Key actions are set out in the following sections:

a) Low carbon farming practices and technology
b) Options to release agricultural land for other uses
c) Afforestation and forestry management
d) Agroforestry and hedges
e) Peatlands
f) Bioenergy

a) Low carbon farming practices and technology

i) Low-carbon farming practices

It is not possible to reduce agricultural emissions to zero on current understanding of biological and chemical processes in food production.

Based on current understanding and knowledge, it is not possible to reduce agricultural non-CO_2 emissions to zero due to the biological and chemical processes inherent in crop and livestock production. Emissions can be reduced through the take-up of farming practices and the adoption of technological options that improve nitrogen use efficiency, livestock diets and breeding and the management of wastes and manures.

We commissioned the Scottish Rural College (SRUC) to assess the abatement potential of such measures.[4] SRUC was able to draw upon updated evidence from Defra's on-going project, Delivering Clean Growth through Sustainable Intensification, which aims to deliver sustainable growth in agriculture (Box 7.1).

Our scenarios include the deployment of 18 measures. A more detailed description of each measure is set out in the accompanying SRUC report:

Livestock measures

- **Breeding measures:** breeding aims to select animals with beneficial traits (e.g. to improve health and fertility), which can also lower emissions intensity of production as well as increase profitability. We include four measures:
  - Genomics. Genetic improvement can be enhanced by using genomic tools in current breeding goals (the specification of the traits to be improved). This requires farmers to collect performance information on the individual animals which is used to develop the breeding goal. This measure can be applied to 90% of dairy and 20% of beef cattle.

Low-carbon farming measures can reduce emissions from soils and livestock but would still leave agriculture as one of the largest emitting sectors.

– Current breeding. Using current breeding goals to improve genetic material. Current uptake is around 25% for the dairy herd and lower for beef cattle, but this measure is applicable to 90% of dairy.

– Low methane. This includes selecting lower-emitting animals for breeding which can reduce the methane emissions in subsequent generations.

– Genetic modification of cattle involves altering the genetic material to reduce enteric methane emissions. This measure is currently not legal within the UK and the EU, and yet to be proven. Deployment should only occur once current uncertainties relating to efficacy, animal welfare, and the unknown wider impacts on ecosystems are fully addressed. We therefore assume this measure is deployed from 2040 at the earliest.

- **Increasing the milking frequency** from the common practice of twice to three times a day can reduce N_2O emissions. More milking increases the nitrogen utilisation of the cow, which leads to a fall in nitrogen excretion. Milk yields are assumed to increase by 10%, which can partly offset the infrastructure costs (robotic milk parlour).

Measures such as breeding, diets and health can help reduce emissions from livestock and improve productivity.

- **Livestock diets.** We include measures comprising animal feed and additives that can reduce enteric emissions in cattle and sheep, and one that improves the feed conversion efficiency (FCR):

– Feeding high sugar content grasses (HSG), grown on grassland for grazing livestock, and a high starch diet for dairy cattle reduce methane emissions. A high starch diet will also reduce methane emissions from waste. Current uptake of HSG is 9% and 30% for high starch diet.

– 3NOP (3-nitrooxypropanol) is a chemical that can inhibit the production of methane in livestock rumen. It is a novel option which we assume is available from 2025. Nitrate additives can partially replace non-protein nitrogen sources or high protein sources (e.g. soya).

– Precision feeding involves monitoring and adjusting feed intake to better match each animal's nutritional requirements with the aim of improving the feed conversion ratio (FCR). It is suitable for housed livestock (dairy cattle, pigs and poultry). As well as lowering feed costs, increasing the FCR can reduce N_2O and methane by reducing the rate of nitrogen and volatile solid excretion in manure.

- **Livestock health:** Grazing livestock are particularly vulnerable to endemic disease. Improving health can reduce emissions intensity by improving the FCR and fertility and reduce mortality, all of which can increase growth rates and milk yields. Better health includes preventative measures e.g. changing housing and management to reduce stress and exposure to pathogens, vaccination, and improved screening, and curative treatments such as anti-parasitics and antibiotics.

Soil measures

- **Grass and legumes** (e.g. clover) mix fix nitrogen into the soil thereby reducing the need for synthetic nitrogen fertiliser (e.g. by 200 kg per hectare), which reduces N_2O emissions. Current uptake is assumed to be 26%.
- **Cover crops** are non-cash crops that are incorporated into the main crop rotation to minimise soil erosion and maintain soil carbon. Depending on the type of cover crop used, they can also reduce N_2O emissions by reducing nitrogen leaching and when ploughed in as green manure can reduce nitrogen use. Current uptake is assumed to be zero.
- **Grass leys** are perennial non-woody biomass that are planted as part of an arable and temporary grassland rotation. It can improve the soil structure and increase soil organic matter. Current uptake is assumed to be zero.

Waste and manure management

- **Anaerobic digestion (AD).** We include two types of AD plants, one fed with cattle manure (536 kW capacity) and the second using pig and poultry manure (984 kW capacity), both of which are co-digested with maize silage. Current uptake is 2.5% for both systems.
- **Covering slurry tanks** with a retrofitted impermeable cover. There is no current uptake of these on beef and dairy farms, while around a quarter of pig slurry tanks are fitted with a cover. The measure is applicable to all slurry tanks and lagoons.

Box 7.1:
Modelling abatement from low-carbon farming practices

SRUC developed a long-list of 31 measures covering crop and soils management, livestock and management of wastes and manures, that could be deployed to reduce non-CO_2 emissions across farms in the UK. These were assessed according to their technical abatement potential and cost-effectiveness against our assumed carbon values (£181/tCO_2e in 2035).

This resulted in 18 measures which we deployed in our scenarios. Each of these was assigned a feasibility rating and categorised into type of measure, reflecting whether they mainly relied on behaviour change, or mainly on innovation which determined the level of ambition of our scenarios:

- A feasibility rating (hard, medium or easy) corresponding to the ease of implementing the measure on-farm. The ratings were derived based on farmer feedback undertaken as part of Defra's Sustainable Intensification project (Work Package 2: *Improving the understanding of social factors*).
- We used this rating to determine an uptake rate for each measure, with the 'easy' measure assigned a high uptake ranging 75-80% dependent on scenario, and the 'hard' measures a lower take-up rate of 50-60%.
- Measures were categorised as either 'behavioural' (e.g. planting cover crops) or 'innovative' (e.g. genomics breeding), and we assume that the Wider Engagement scenario has the highest uptake of behavioural measures, while the Wider Innovation has the highest uptake of innovative measures.
- A lead-in time to deployment to reflect technical and/or policy readiness. We assume that measures we categorised as being low-cost and low-regret could be deployed immediately (from 2022) achieving a higher-level of uptake earlier, while a lead-in time of between five, 10 and 20 years was assumed for the more innovative measures (e.g. GM cattle is deployed from 2040).

Source: SRUC (2020) and CCC analysis.

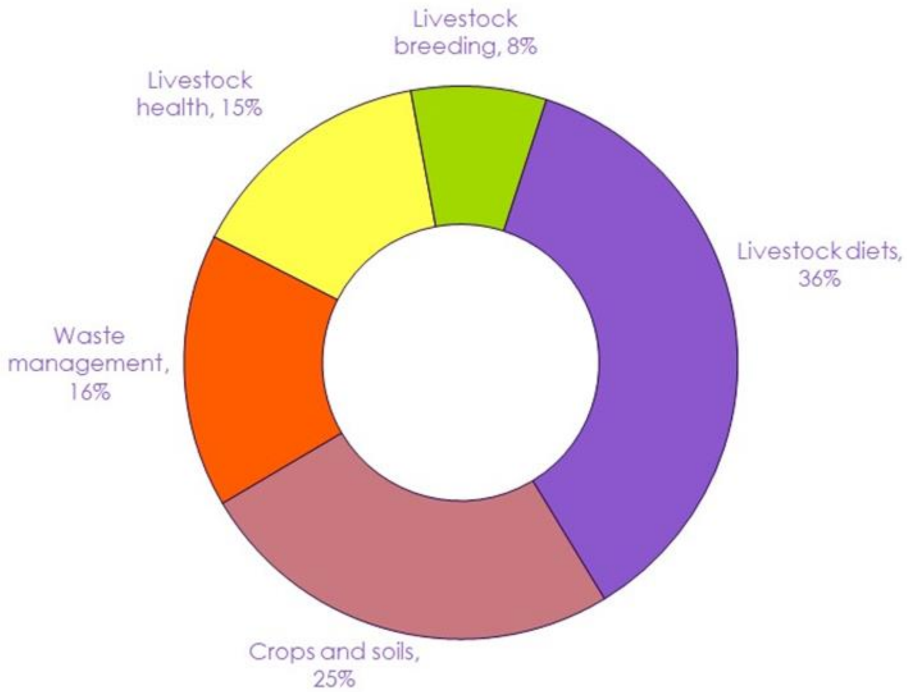
The abatement potential from these measures depends on the area of land used for agriculture and the structure of production. The measures set out in section (b) below already imply large changes in livestock numbers and land use in the UK:

- The number of cattle, sheep, pigs and poultry falls by between 6% and 24% by 2035.
- Grassland area decreases by 12–32% and land for crops by10–23% by 2035. The land release from these measures is used productively for other uses.

This reduces the abatement potential from the take-up low-carbon farming practices relative to a baseline with no change in land use and livestock numbers:

- Where there is no change in land use and agricultural production remains as in 2018, the implementation of a high level of low-carbon farming practices could deliver around 6 $MtCO_2e$ emissions savings by 2035 (Figure 7.5).
- Abatement from the take-up of low-carbon farming practices falls to between 3–5 $MtCO_2e$ after taking account of changes in the composition of agricultural production resulting from the measures in our scenarios.
- Our scenarios exclude the take-up of four crop and soil related measures assessed by SRUC; pH crops, crop health, bio-stimulants and precision crop farming. Our assumptions on crop yield improvements (section b), already imply a more efficient use of nitrogen and adding these to our scenarios would be double-counting. Although we have not included the abatement savings from these measures, it is important that farmers are encouraged to take these up to reduce emissions from crops and soils.

Figure 7.5 Abatement potential of low carbon farming practices (2035)



Source: SRUC (2020), CCC analysis.
Notes: Cost-effective abatement up to our assumed carbon value of £181/tCO2e in 2035.

i) Low carbon technology

Fossil fuels used in agricultural machinery and buildings are currently responsible for 4.6 $MtCO_2e$. There were around 40,000 sales of new agricultural equipment in 2019, covering a wide range of uses including tractors, loaders, ploughs, utility vehicles and combines. These can be decarbonised through take-up of zero carbon technologies with our assumptions on decarbonisation technologies aligned to those in the industry and the off-road machinery sectors. We assume that electrification of smaller machinery and equipment starts around 2023, with larger electric machinery entering the market after 2025. Hydrogen options start to be taken-up in the 2030s.

- **Stationary machinery**. Emissions are reduced to zero by 2050. Opportunities to switch to zero carbon options (e.g. renewables and low-carbon electricity) will reflect action undertaken in the wider-commercial sector.
- **Mobile machinery**. The bulk of agricultural vehicles switch away from diesel and biofuels by 2050. Options include hydrogen and electrification and the uptake of robotics. This sector can draw on advances made to commercialise low-carbon heavy goods vehicles (HGVs) e.g. reduction in battery costs and deployment of hydrogen in buses. Data on fleet size, composition and turnover was drawn from various sources.[5] [6]

b) Options to release land for other uses

Societal behavioural change and farm productivity improvements play a crucial role in shifting land use.

The use of the UK's land has evolved over time. Deep emissions reduction in agriculture and land cannot be met without further changes in the way UK land is used. The options we consider shift land use from traditional agricultural production towards alternative uses to reduce carbon and increase sequestration. These changes will present new challenges to farmers and landowners. Policy will need to be designed to ensure new opportunities and revenues are created to reflect the benefits these measures bring to society (see Policy Report).

In this section we consider the following measures to change the way land is used while maintaining a strong food production sector:

i) Improving agricultural productivity

ii) Moving horticulture indoors

iii) Diet shift towards healthier eating guidelines

iv) Food waste reduction

v) Summary of impact of measures

i) Improving agricultural productivity

Crop yields

Cereal crop yields in the UK have risen modestly (e.g. 0.5% annual average increase for wheat, barley and oats) or fallen (e.g. for rye) over the past three decades. While these yields are higher than the EU average, they remain lower than key competitors such as France, Germany and the Netherlands.[7] Within the UK there are also wide yield variation between the best and worst performing farms, irrespective of soils and climate.

Crop yield improvements can deliver productivity improvements on farm, enabling the same level of production with less land and other inputs. Our scenarios for future crop yields are based on the latest literature, discussion with experts and internal analysis.[8] They take account of climate impacts, management practices and the role of technology and innovation:

We sought feedback on our crop yield assumptions from experts in Defra, AHDB, Rothamsted Research, ADAS and academia.

- **Climate impacts**. The scenarios are designed to be compatible with limiting global average temperatures to 1.5°C. Climate impacts represent both risks and opportunities to crop yields:
    - Higher CO_2 concentrations leading to higher fertilisation rates and longer growing seasons.
    - Risks from reduced water availability, particularly in East Anglia and the south of England.
    - Increased risk of soil erosion (e.g. through increased incidents of high intensity rainfall).
    - Increased incidence of floods in winter may limit planting of winter crops.
    - Risk of increased incidence and severity of native and non-native pests and diseases.

- **Management practices.** There is evidence of a large gap between the best and worst performing farms and wide distribution of yield rates, irrespective of soils and climate. Better management practices through measures such as good soil structure and fertility (e.g. through crop rotation); selecting the optimum planting period and tillage; ensuring good crop nutrition (both optimum fertiliser and trace elements) and protection from weeds, pests and diseases could support higher average yields and close the performance gap between the best and worst farms narrows.

  There is also the opportunity to maximise the land resource through spatial planning and the protection of better-quality land, which could also address the inefficiencies in the use of land for crops.[9]

- **Technology and innovation.** Crop breeding and selection could lead to higher yields through development of new cultivars/traits that allow the next generation of wheat and other crops to be more sustainably productive and resilient to disease in a warmer climate. It is assumed that policy will enable technological developments to be transferred to farmers (e.g. through information, skills and other incentives) to ensure the take-up of climate-resilient varieties that are most suitable to local conditions.

It should be possible to sustainably increase crop yields in the future. If climate risks dominate then yields could fall – we demonstrate the impact of this.

Our scenarios assume average crop yields rise from 8.2 tonnes/hectare for wheat (the average over the past four years) to between 11 and 13 tonnes/hectare by 2050 (and equivalent increases for other crops). We also include a sensitivity to reflect a reduction in crop yields, where the adverse impacts of climate change dominate (Table 7.1).

Table 7.1
Crop yield assumptions

Average crop yields (wheat), with equivalent increases for other crops	Description
Baseline 8.2 tonnes/hectare	Current farming practices and agronomy largely continue, with no focus on improvements in the sector. R&D leads to some new varieties but these do not deliver across the board increases in yields. Some areas are negatively impacted by climate impacts, which affect yields in some years. No improvement in soil fertility, and continued degradation in some areas. These impacts offset the CO_2 fertilisation effect and longer growing season.
Medium 11 tonnes/hectares	Some positive impacts of climate change on yields through increased CO_2 fertilisation rates and longer growing season. Risks of higher temperatures and flooding do not significantly impact on yields. No significant water scarcity constraints, but on-farm adaptive measures including increased water storage capacity help to overcome periods of water shortage. More widespread take-up of good agronomy practices leading to better soil fertility and structure which reduces the yield gap between the best and worst farms. R&D and innovation leads to improvements in crop varieties and policy supports a moderate level of take-up in the sector.
High 13 tonnes/hectare	Increased fertilisation rates from climate change lead to positive gains on yields. Risks of higher temperatures and flooding do not significantly impact on yields. On-farm reservoirs help to overcome periods of water shortage. High take-up of good agronomy practices across the sector leads to substantially improved soils. R&D and innovation in crop breeding results in new cultivars and traits. There is a concerted effort across the sector to improve yields, and a co-ordinated effort between industry and farmers to share learning and experience. Lower productivity farms are driven out of the sector/taken-over by higher productive farms, with some more innovative techniques such as vertical farming becoming more widespread for certain crop types.

Climate risk sensitivity 6 tonnes/hectare	Climate risks dominate future yields. Risks of higher temperatures significantly impact on yields e.g. heat stress affects yields during flowering time. Crops are affected by water related constraints, including reduced water availability from trends to drier summers and increased incidents of water-logged fields from increased flood events in winter. There is insufficient planning and take-up of measures to mitigate these impacts on crop production. Increased susceptibility of plants to diseases and genetic improvements and breeding lead to failure connected to unanticipated crop susceptibility to new pests and diseases. Farming practices continue as present, with no focus on improving soils and adapting to climate impacts.

Livestock stocking density

Grass, as grazed grass and cut for silage for the winter months, is an important feed for ruminant livestock. It can provide 85% -95% of the energy requirements of beef and sheep in England.[10] But it is estimated that most of the grassland area is under-utilised by as much as half, such that grazing cattle and sheep eat just 50% of the grass that is produced.

Utilisation can be improved by grazing at the right time, to the right height and with the right amount of livestock. This presents an opportunity to increase stocking rates without impacting feed requirements (quantity and quality) to enable some grassland to be used for other uses.

There is considerable scope to improve grassland utilisation, improve productivity and enable land to be used for other uses.

Key to achieving this is good grassland management, which includes grazing management systems. The Agriculture and Horticulture Development Board (AHDB) estimate that switching away from set-stocking to alternative grazing management systems can increase grass yields and reduce costs:

- Increasing utilisation rates (i.e. the grass that is eaten) from the current 50% to 80% with paddock grazing can lead to a near-doubling in yields as measured by dry matter per hectare.
- These can deliver multiple benefits and offset additional costs to improve farm profitability:
  - Extending the grazing period reduces the costs of housing.
  - An increase in improved grass quality can lead to higher livestock yields, higher dry matter yields and more silage. This reduces the need to buy in more expensive feed for the winter.
  - There will be additional costs associated with infrastructure (e.g. fencing) and additional labour hours needed to move animals and fencing.

Our scenarios model the impact of increasing livestock stocking rates by:

- Moving livestock in upland grazing areas and redistributing to other grassland, resulting in an overall increase in the stocking rate on the remaining grassland by 5–10%.
- A higher level of ambition with stocking density on both uplands and other grasslands increasing by 10%.

ii) Moving horticulture indoors

Indoor horticulture can raise productivity while reducing nutrient, land and water footprints.

Horticultural products such as fruit, vegetables and salad crops are grown on 163,000 hectares, or 3% of cropland in the UK. Indoor systems such as vertical farming, where crops are grown in stacks in a controlled environment, can raise productivity while reducing the nutrient, land and water footprint.

Indoor horticulture in the UK is mainly for high value salad crops and is currently small scale. Some systems are based on hydroponic and vertical production systems using LEDs. Our analysis assumes that this system could be applied to 10–50% of current horticultural production.

Given the small area of land currently used for horticulture, moving production indoors has a limited impact on land area and carbon impacts. More significant emissions savings would come from moving horticultural production from lowland peat, although we have not included this in our analysis.

Greater benefits could accrue from shifting arable crop production indoors. The controlled environment could allow for quicker and multiple harvests each year. Estimates suggest that combined with a ten-tier stacking system, yields could be 220 to 600 times higher than the current global average annual wheat yield of 3.2 tonnes/hectare.[11] However, this production method is still at the experimental stage, with trials on-going at Rothamsted Research, while the costs of energy (e.g. LED lighting) would also have to reduce to make this a cost-effective option. Indoor wheat production is not included in our scenarios.

iii) Diet shift towards healthier eating guidelines

A shift in diets away from meat and dairy products is good for health and the climate.

There is good evidence that a shift in diets away from meat and dairy products to more plant-based options is good for both climate change mitigation and for human health. The National Food Strategy is committed to looking at sustainable diets (including GHG emissions) as part of its second report, due out in 2021.

Climate change mitigation

Protein can be sourced from a wide range of plant and animal products, some of which have high GHG and other environmental footprints. The most comprehensive and up-to-date life-cycle assessments (LCAs) identifies several robust conclusions regarding the GHG-intensities of different food types produced around the world (Figure 7.6):

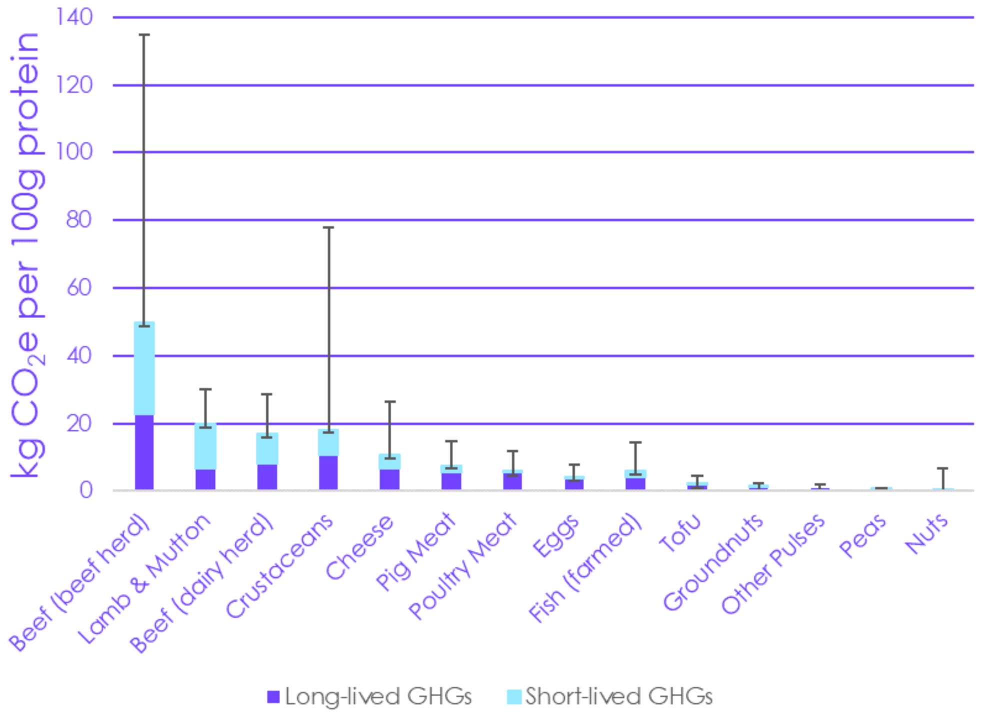
- Ruminant meat is the most GHG-intensive source of protein. In general, beef from dedicated beef herds has the highest level of total GHGs, beef from the dairy herd is generally less GHG-intensive, with a similar emissions intensity to lamb.
- Plant-based protein sources have significantly fewer GHG emissions than animal-sourced proteins when compared on a like-for-like basis. The most GHG-intensive production methods for plant-based proteins generally have lower emissions than even the most GHG-efficient sources of animal-based protein.
- Although pigs and poultry produce less emissions directly compared to ruminant livestock, there are concerns that imported animal feed, in particular soy, may have high embedded emissions and wider environmental costs (e.g. loss of natural habitats and biodiversity) associated with land use change. A 2019 study assessing the livestock supply chains of 11 European retailers including UK supermarkets found that only 25% of the 1.8 million tonnes of soy sourced was certified to a deforestation free standard.[12]

As well as being the most carbon-intensive protein sources, meat products have a high land footprint.

In addition to the emissions impact, livestock require land for grazing and cropland to grow feed. A study published in 2017 illustrates the relative land inefficiency of producing livestock products:[13]

- In 2010 only 15% of UK agricultural land area was used to grow crops that are directly grown for human consumption with a further 22% to grow livestock feed crops. Grassland for livestock accounted for the remaining 63% of agricultural land.
- 85% of the land footprint used to produce animal products contributed about 32% of total calorie supply and 48% of total protein supply.
- However, cropland and grassland should not be treated equally. In some regions, crops and livestock farming do not compete for the same land as many grassland areas (e.g. the uplands) are not suitable for crop production.

Figure 7.6 Lifecycle GHG emissions associated with different protein sources



Source: Poore, J. & Nemecek, T. (2018) Reducing food's environmental impacts through producers and consumers. Science, 360 (6392), 987-992.
Notes: Solid bars indicate the production weighted global mean GHG-intensity of different food categories from studies looking at production across the world. Lifecycle emissions are expressed on the basis of equal protein content. Error bars indicate the 5th and 95th percentile of studies within the database. GHG emissions are aggregated using the GWP100 metric. Long-lived GHGs refer to CO2 and N2O and short-lived GHGs to methane.

There has been a growing interest in 'alternative' meats that are not animal-based. Initial LCA studies suggest that these products can have significantly lower lifecycle emissions than animal-based protein (Box 7.2).

Box 7.2
Novel protein sources

There are a number of 'alternative' protein sources that have a less developed LCA literature than conventional animal and plant-based sources:

- **Lab-grown meat** is produced from animal cells cultured in a lab and is a possible replacement for animal-based meat in the longer-term, but it is currently far from large commercial scales. If it can be made economically competitive at scale and achieve customer acceptability, it could offer significant environmental benefits with no non-CO_2 emissions and very small land footprints. Electricity requirements (and its carbon intensity) are the biggest uncertainty in assessments of GHG-intensity. Estimates in the literature range from 1.1 - 3.7 kgCO_2e per 100 grams of protein.
- **Insects** are efficient converters of their feed into edible calories and protein and are consumed by humans in some parts of the world. If they could achieve widespread acceptability with consumers and lower production costs more insects may be eaten in western diets. Insects could also be used for animal feed. When fed on waste biomass, insects can be a low GHG protein source (around 0.2 kgCO_2e per 100 grams of protein) and have minimal land-use impacts, but scale may be limited by the available waste resource. If fed with dedicated crop feedstocks, emissions and land-use impacts are higher.

Source: SRUC and ADAS (2019) *Non-CO_2 abatement in the UK agricultural sector by 2050.*

Human health

Current UK average protein consumption is significantly higher than the recommended daily amount based on the Dietary Reference Values.

A healthy diet requires eating a sufficient amount of protein. The recommend daily protein consumption is 55.5 grams per person for adult men and 45 grams per person for adult women based on the Dietary Reference Values:[14] Particular individuals or groups may need to consume more or less than this to remain healthy, depending on age, lifestyle and medical conditions. Current consumption of protein in the UK is on average significantly above these levels:

- Average daily protein intake was 76 grams per person per day in 2018/19.[15] 60% of this protein is derived from animal sources, with 40% from plant-based sources.
- Modelling by Oxford University of Public Health's *Eatwell Guide*, the Government's official guide to achieving a healthy and balanced diet, estimate that meeting the Guide would require an average reduction in the consumption of meat by around 89% for beef, 66% for pork and 63% for lamb, and a 20% reduction in dairy products.
- The assumed levels of meat reduction in our scenarios (20–50%) are below the Oxford University estimates. Dairy reduction in our Balanced Pathway is in line with the Oxford modelling with further reductions post-2030 in some scenarios. In both cases we assume that the same amount of protein intake is delivered through plant-based options, but we also include lab-grown meat in the Widespread Innovation Scenario.

Consuming more of a plant-based diet can reduce non-communicable diseases like diabetes, heart disease and a range of dietary-related cancers, which in turn can lower the risk of developing severe complications from COVID-19. People with Type 2 diabetes (both controlled and uncontrolled) are 81% more likely to die from the virus.[16] NHS England estimate that over 100,000 lives could be saved each year from healthier diets.[17]

Official data indicate that consumption of some meat and dairy products has fallen in the UK. Recent survey data suggests an increased willingness to adopt more of a plant-based diet, while the increased focus on healthier diets due to the impact of COVID-19 may be leading an acceleration in this trend amongst certain groups (Box 7.3).

Box 7.3
Trends in UK food consumption

Official government data shows that the consumption of some meat and dairy products have fallen between 2008 and 2018.* Recent survey data points to an increased willingness to adopt more of a plant-based diet than official estimates suggest with the impact of COVID-19 providing an added impetus:

- The average per person meat consumption decreased by 6%, with fresh meat (i.e. beef, lamb and pork carcass) down by 23%. However, processed meat, which accounts for around 80% of the meat consumed has remained broadly constant.
- The consumption of dairy products has decreased by 16%, largely due to cuts in milk and milk products, while cheese consumption increased by 14% over the period. The overall consumption of fruits and vegetables also decreased by 13%.
- Official data suggest that the proportion of the UK population that is vegetarian or vegan has increased from 1.6% in 2009/10 to 2.5% in 2015/6. However, more recent survey data suggests higher figures and a willingness to eat less meat in the future:
  - Around 9% of the 2,095 people that participated in a public attitude survey don't eat meat. The 2020 survey commissioned by the Eating Better Alliance also found that around 65% of those surveyed were willing to eat less meat in the future, citing that more knowledge on how to plan and cook less meat dishes would help them to cut back.
  - Research from Mintel reveal that due to COVID-19 a quarter or people between 21-30 years of age (and 12% of all people surveyed) would find a vegan diet more attractive. The same research found that consumption of fruit and vegetables had increased since the start of the pandemic.

Source: Public Health England (2019) *National Diet and Nutrition Survey;* Mintel (2020).

Our ambition on diet change are within range of the Climate Assembly's recommendations for a 20-40% change in diets by 2050

In our previous 'Further Ambition' scenario set out in our Net Zero advice, we assumed a 20% shift away from beef, dairy and lamb by 2050 towards plant-based alternatives. All but one of one of our Sixth Carbon Budget scenarios go further than this, with the Balanced Pathway towards the middle of the Climate Assembly's recommendations for a 20-40% change in diets by 2050.[18]

In this stylised analysis, our model assumes that farmers do not respond to the change in diets by increasing meat and dairy exports. This has three main impacts:

- It reduces emissions from livestock (e.g. methane from enteric fermentation) and from managing grassland and cropland used to grow animal feed (e.g. N_2O from fertiliser use).
- It increases the area of cropland used to grow crops for human consumption and reduces land required for livestock production – both grassland for grazed livestock and cropland for livestock feed.
- There is a corresponding fall in imports of meat, dairy and animal feed which reduces the carbon footprint of the UK's food imports.

There are uncertainties as to whether these could all be achieved in practice. This will require a strong policy framework in place to encourage a shift in diets and, incentives for farmers to improve productivity and to use their land for measures to sequester carbon (see our accompanying Policy Report: *Policies for the Sixth Carbon Budget & Net Zero*).

iv) Food waste reduction

UK households waste between one fifth and a quarter of food they buy.

The Waste Reduction Action Programme (WRAP) estimate that around 13.6 million tonnes of food and drink is wasted each year. Of this, around 3.6 million tonnes occurs on-farm, with the remainder post-farm gate.[19] Householders account for the largest share of post-farm gate waste (70%), while the supply chain comprising manufacturing (17%), hospitality and food service (9%) and retail (2%) make up almost all of the remainder.

Reducing the level of food waste could reduce agricultural emissions by avoiding unnecessary food production and enabling land to be used differently. It would also reduce emissions downstream (e.g. from avoided emissions from landfill), which is covered in the Waste chapter of this report.

The private sector has signed up to various international commitments to reduce food waste and some devolved administrations have their own targets:

- The UN's Sustainable Development Goal 12.3 has the objective of cutting per capita global food waste at the retail and consumer level by half compared with 2007 levels and reducing food losses along production and supply chains (including post-harvest losses) by 2030.
- This UN target has been adopted by WRAP and the Institute of Grocery Distribution, in its UK Food Waste Reduction Roadmap (2018) but goes further by also including on-farm food waste. Around 260 organisations, including 16 retailers and 162 producers/manufacturers had signed up to the Road Map as of September 2020.[20]
- The Welsh Government is aiming to meet the UN target five years earlier and are proposing to go further beyond 2025.[21]
- The Scottish Government are targeting a 33% reduction (against 2013 levels) by 2025.[22]

WRAP announced this year that the UK is halfway to achieving UN SDG12.3.[23] All our Sixth Carbon Budget scenarios deliver a 50% reduction (pre-and post-farm) by 2030 as a minimum, with a higher level of 60-70% reduction by 2050 in all but one scenario.

v) Summary of impact of measures

Diet change has the biggest potential to change how land is used.

Our analysis shows that 1.1 million hectares (7%) more land will be needed to maintain current levels of per capita food production and for settlement growth by 2035 if there is no change in productivity. The measures we identify above could free up between 3 and 6 million hectares (or (17–35%) of current agriculture land for other uses. Diet change has the largest impact followed by improvements in crop yields and increased stocking rates (Figure 7.7).

- 1.1 million hectares of agricultural land is needed to maintain existing per capita levels of food production and settlement growth to 2035.
- In the Balanced Pathway, diet change alone accounts for almost two-thirds (3 million hectares) of land released in 2035.

- Improvements in crop yields, higher livestock stocking rates and food waste reduction release about the same area of land (0.5 to 0.6 million hectares each) in 2035.
- The impact of moving horticulture indoors is limited (7,000 hectares by 2035) due to the current low land footprint of these products.

Figure 7.7 Agricultural land area released by different factors in the Balanced Pathway

Source: CCC Analysis.
Notes: A negative number indicates land is released; a positive number land is required.

c) Afforestation and forestry management

i) Afforestation

Planting new woodland on previously unforested land delivers carbon sequestration as well as a range of other benefits for health and well-being and the environment e.g. air quality and flood alleviation. The future profile of carbon and other impacts depend on assumptions on the planting and rates, planting density, tree type and productivity.

Planting rates

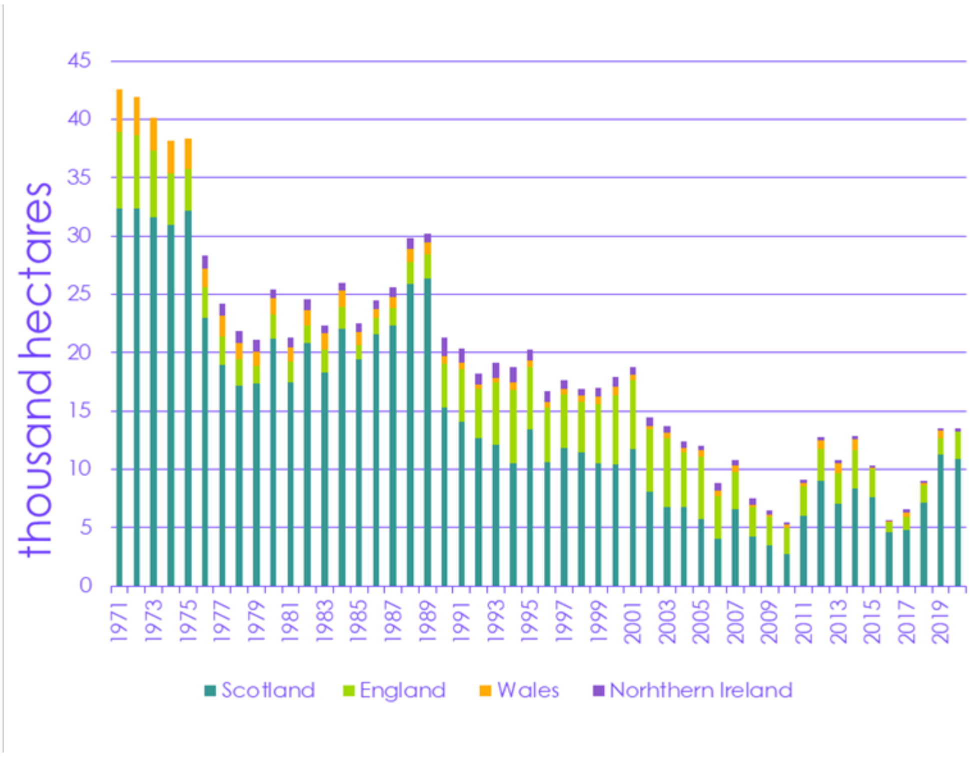
UK Woodland area could increase from 13% of land to 17-20% by 2050 in our scenarios.

Around 13% of UK land area is woodland currently, compared with 43% for the EU-28 area.[24] We assume annual planting rates range reach 30,000–70,000 hectares from 2035, recognising it will take time for the sector to scale up to reach these levels. This would increase woodland cover to between 17% and 20% by 2050.* The lower bound corresponds to the Government's commitment to plant 30,000 hectares in 2025 while the upper bound is within range of our assessment of what is feasible:

- A programme of afforestation after the Second World War increased UK woodland area from 6% in 1947 to around 8.7% over a 30-year period.[25] This corresponds to planting around 22,000 hectares each year.
- Annual afforestation rates averaged 40,000 hectares in the early 1970s and close to 30,000 hectares in the late 1980s in Great Britain. If we include the restocking of existing forested areas, planting rates reached over 50,000 hectares in the early 1970s and over 40,000 hectares in the late 1980s. This serves as a useful indicator of the supply chain's capability to meet higher levels of tree planting (Figure 7.8).
- In France, woodland area expanded by almost 7% between 1990 and 2015 to 17 million hectares.[26] This is equivalent to an average annual afforestation rate of 46,000 hectares during the period. The UK has a similar ratio of population to land area as Germany, but Germany has over 30% of land that is forested compared to the UK's 13%.
- Studies by industry and the voluntary sector suggest higher levels of UK planting:
  - The Confederation of Forest Industries' (Confor) call for UK planting rates to reach 40,000 hectares a year by 2030 takes account of their assessment of the industry's capacity to scale-up (e.g. nurseries and foresters).[27]
  - The Woodland Trust set out an ambition to deliver 19% of UK woodland cover by 2050, with preference given to the planting of native woods and trees.[28]
  - Friends of the Earth cite an ambition to double woodland to 26% by 2045, both to support efforts to increase carbon removals and protect and restore nature.[29]

* This excludes the area of small woodlands of less than 0.5 hectares in size, and less than 20 metres in width, which currently totals 355,000 hectares.

Figure 7.8 Afforestation rates (1971-2019)



Source: Forestry Commission, Natural Resources Wales, Forest Service and Forestry Commission statistics.
Notes: Planting year ends end March. Data not available for Northern Ireland from 1971-1975.

Type of woodland created

The right trees need to be planted in the right place and take account of soil, climate and other land uses.

The UK Forestry Standard prohibits the planting of mono-cultures and limits the planting of any one species on one site. The ratio of broadleaf and conifer planting vary across our scenarios to reflect different objectives for woodland creation, and regional differences in climate and soils (e.g. conifers can withstand cold weather in the north of Scotland). Existing woodlands in England are predominantly broadleaved and conifers dominate in Scotland:

- We develop different scenarios in favour of broadleaved forestry and in favour of conifers:
    - A 67:33 planting ratio in favour of broadleaves is assumed for the UK where the focus is on biodiversity. Taking account of regional differences, the ratio increases to 80/20 in England, and is lower in Scotland at 50:50.
    - A 33:67 planting ratio in favour of conifers is assumed where the focus is on productive forestry. This increases to 75% for conifers in Scotland.
- In our modelling, Sitka spruce is used to represent conifer forestry and sycamore/ash/birch to represent broadleaf forestry.

We model different planting densities to better reflect differences between broadleaf and conifer woodland creation.

Planting density

Tree planting density is important for determining tree growth, carbon sequestration and wood density as well as wider impacts such as soil health and biodiversity.

Our scenarios reflect different planting densities (number of stems planted per hectare) to better reflect differences between broadleaf and conifer woodland creation, and to understand the trade-off between maximising carbon sequestration and other impacts such as biodiversity. We assume:

- A planting density of 3,000 stems/hectare for conifers to maximise carbon sequestration and timber output, and 2,000 stems/hectare for broadleaves, which is commonly seen as the upper end.
- Where society places a higher value on biodiversity, the planting density for broadleaves is reduced to between 1,200–1,800 stems/hectares. Lower density planting also allows for the retention of landscape features and open views, and glades. Our range is consistent with the planting regime supported by the Woodland Trust.

While the planting density we use are averages for the UK, we recognise that in practice there will be variation across the UK than we can capture in our analysis.

Forest productivity

There is scope to increase productivity of new forests.

Different trees have different growth rates and levels of productivity as measured by their Yield class (YC). This has a bearing on the time profile and rate of carbon sequestration, and the quantity of timber output. We have updated our yield class assumptions since our Net Zero advice based on data from the National Forest Inventory (NFI) and stakeholder engagement (Box 7.4):

- The average yield class of existing conifer and broadleaf woodland is YC14 and YC6 respectively under the NFI.* We take this as the baseline yield class for new planting.
- Best practice in silviculture and innovation through breeding can increase productivity to an average of between YC16–18 for conifers and up to YC8 for broadleaves. We assume it takes 10 years before YC18 and YC8 are introduced in our scenarios.

Box 7.4
Tree productivity

Improving yields enables trees to be more productive both in terms of the amount of CO_2 they can sequester and the volume of harvested products. In addition, breeding can improve the quality of the wood to be used as timber and increase resilience to the impact of climate change. Our assumptions on improvements in average yield class follow discussions with a wide range of stakeholders that include the Forestry Commission, Scottish Forestry, Future Trees Trust, the Woodland Trust, Confor and Pryor and Rickett Silviculture. We considered two factors that could deliver higher productivity rates:

- **Silvicultural practices.** The adoption of best silvicultural practice covers the nursery stage, choice of planting stock and area, establishment and on-going management as the tree grows. Measures would include site preparation to ensure the successful establishment of saplings.

* Weighted mean yield class based on stands aged 15-50 years.

Selecting the right trees for the right area means taking account of the level of moisture and nutrients in the soil. For example, Sitka spruce does not tolerate drought and requires moisture, while beech is no longer considered a good option due to susceptibility to drought. On-going management could entail protection of young trees from deer and squirrels, managing the surrounding vegetation to reduce competition and ensure successful establishment, and decisions on when to respace, thin and fell.

- **Breeding.** Research is being led by the commercial sector with organisations such as the Conifer Breeding Co-operative, and the broadleaved focused Future Trees Trust. Work of the latter is focused on six major broadleaf species of British origin (ash, oak, sycamore, chestnut, birch and cherry) that are genetically diverse and resilient. Due to its susceptibility to drought beech is no longer considered an appropriate specie. Breeding requires selecting the best parents, whereby seeds are collected from the mother tree, and bringing them together to cross-fertilise. Their progeny breeding work to date is still based on theoretical gains (3-5% by 2030 and 10% by 2050 for the six broadleaf species) rather than real gains. More time is needed to test the real gains, with trees of at least 10 years old, when yield and height measurements can be assessed across a variety of UK situations and sites.

Open ground

We allow for an area of open ground in new woodland to improve biodiversity.

The UK Forestry Standard (UKFS) sets out a requirement that new woodland over 10 hectares in size should include a minimum 10% of open ground or ground managed for the conservation and enhancement of biodiversity as the primary objective.

Our scenarios are consistent with these standards, with the lower bound of open ground in line with the minimum 10% set out by the UKFS, and an upper bound of 20% is used where we place an increased value on biodiversity. This area of open ground increases the land area needed to meet our afforestation ambition by an additional 10-20%.

ii) Forestry management

Around 80% of broadleaf woodlands in England (74% of woodland area) are in an un-managed or under-managed state. Introducing sustainable management broadleaf woodlands that is compliant with the UK Forestry Standard has several benefits:

- It can improve woodland health and productivity and increase carbon sequestration by allowing young and better-quality trees to thrive.
- Improve habitat quality and biodiversity by allowing in more light.
- Increase the resilience of woodlands to wind, fire, pests and diseases, which could increase under a warming climate.
- Management can generate revenue from the sale of harvested material.

We assume that 67–80% of broadleaf woodlands are managed sustainably by 2030. The lower level is the ambition set by Defra, covering both broadleaf and conifer woodlands, to be achieved by 2018. The target was missed, with 59% of woodland currently managed. Management increases timber output and accounts for 75–90% of the material used for fuel across our scenarios by 2035. Our analysis assumes that all conifers are in some form of management, although not necessarily compliant with the UK Forestry Standard.

d) Bioenergy crops

Sustainable bioenergy crops make an important contribution to Net Zero.

Bioenergy crops are specifically grown for use in the energy sector, providing emissions savings from displacing fossil fuels (and/or engineered CO_2 removal if combined with carbon capture and storage – CCS) alongside any net carbon benefits that are derived while growing these crops. A sustainable UK supply of bioenergy is important in contributing to Net Zero. Issues around supply and best use of bioenergy are discussed in more detail in Chapter 6 of this report. Issues around sustainability are dealt with in our 2018 Report '*Biomass in a low-carbon economy.*'

The current area of miscanthus and short-rotation coppice (SRC) is only around 10,000 hectares (or 0.2% of UK arable area), and there is no short rotation forestry (SRF) planted for energy use. Our analysis includes these three types of energy crops and forestry:

- We assume an immediate scaling up of the industry would be required from the mid-2020s in order to deliver the rates in our scenarios: 10,000, 30,000 or 60,000 hectares being added annually by 2035. This results in a total planted area of 0.2 million, 0.7 million or 1.4 million hectares by 2050. The lower level corresponds to a scenario where there is low BECCs capacity, while the middle and upper levels correspond to work by the Energy Technology Institute (ETI):[30]

- To maximise carbon sequestration, planting of energy crops (miscanthus and SRC) in our scenarios is limited to cropland and excluded from permanent grassland. Due to the higher soil carbon stocks planting energy crops on permanent grassland can increase net emissions with on-going soil carbon losses exceeding the carbon sequestered by the energy crop. SRF is grown on both cropland and grassland.

- We assume planting rates are staggered, with miscanthus and SRC starting in 2022 and SRF starting in 2025. The faster growing miscanthus and SRC can be harvested two to three years after planting. SRF poplar is conventional forestry and the slower growth rate means its rotation length is around 26 years.

- Our modelling includes the carbon benefits (e.g. carbon stock changes in the soil and biomass) of bioenergy crops but not the additional emissions savings from reduced nitrogen use by moving from annual to perennial crops.

- Productivity improvements though better agronomy and breeding can boost yields from the current average of 12 oven dried tonnes (odt)/hectare to between 15 and 20 odt/hectare by 2050 for both miscanthus and SRC. Current SRF yields of YC12 are assumed to remain unchanged.

The roll-out of CCS elsewhere in the economy could determine how land is used. Bioenergy crops used with CCS deliver higher GHG savings than standing forest alone. However, if the requirement for bioenergy with CCS is low, it would be preferable to grow standing forest than bioenergy crops (Box 7.5).

Box 7.5
GHG impact from bioenergy crops and forestry

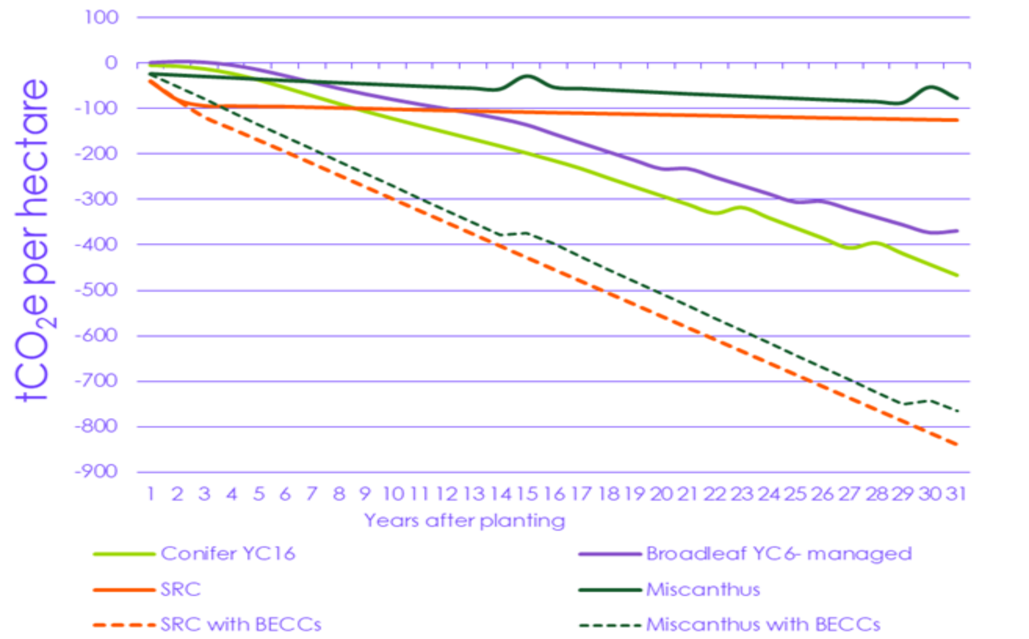
The optimum level of UK bioenergy crop production depends in part on the requirement for bioenergy with CCS (which is used for a range of activities in our scenarios, including electricity generation and production of low-carbon hydrogen, as set out in Chapters 2 and 3 of the accompanying *Advice report*).

To compare the emissions savings from planting trees versus energy crops for use with CCS we analysed how each can be expected to deliver emissions savings over time on a per hectare basis (Figure. B.7.5):

- The land-based emissions savings from planting a hectare of perennial energy crops are lower than from planting conifer and broadleaf forest with typical yield classes.
- Including savings from BECCs reverses this and bioenergy crops with BECCs deliver higher GHG savings than afforestation over 30 years.
- Standing forests will produce thinnings and harvested material as they grow and reach maturity which would add to the savings beyond the period shown below.

Different assumptions could change this picture, for example a lower CO_2 capture rate in BECCS facilities would reduce the emissions saving from energy crops. The value of BECCS will also depend, for example, on how cheaply low-carbon hydrogen and electricity can be made from alternative sources. Perennial energy crops are only grown on cropland in our scenarios as the soil carbon impacts when grown on grassland can be negative. The availability of cropland for energy crops relies on delivering diet change and crop yield improvements.

Figure B7.5 GHG savings from planting different types of biomass from year of planting



Source: CEH (2020) and CCC analysis.
Notes: Bumps in lines represent periods of harvesting of biomass, and the re-planting of miscanthus every 15 years.

e) Agroforestry and hedges

Trees on farm can sequester carbon, improve water quality, improve soil structure and fertility, enhance biodiversity and increase welfare of grazing livestock.

We use the term agroforestry to mean the integration of trees and/or shrubs on to cropland (silvoarable: trees and crops) and grassland (silvopastoral: trees and livestock). Agroforesty can sequester carbon in the biomass and soils, improve water quality from reduced nitrate leaching into water courses, improve soil structure and fertility from litter fall, increase livestock welfare and enhance biodiversity.

There is no official data on the amount of land currently used for agroforestry in the UK but a close proxy is the use of trees and hedges for buffer strips alongside water courses, fruit production in shrubs and shelter belts. It is estimated that these account for around 1% of UK agricultural land:[31]

Our modelling assumes that between 5-15% of agricultural land adopt silvoarable or silvopastoral systems by 2050. Our assumptions for planting densities are taken from Defra's Delivering Clean Growth through Sustainable Intensification project and CEH's CFlow model was used to estimate the carbon sequestration rates:

- The low planting densities of agroforestry systems results in 14% of the grassland area and 7% of cropland area dedicated to these systems.
- Silvoarable systems plant poplar YC12 in two-metre-wide rows, a spacing of 30 metres between each row and seven metres between each tree. The spacing takes account of the need to minimise shading which can adversely impact crop yields.[32]
- Silvopastoral systems are planted with broadleaf species (e.g. sycamore, ash and birch) with a YC6, and at a higher planting density of 400 trees per hectare.

For the purposes of our modelling we have adopted a particular set of assumptions, but we recognise that in practice agroforestry systems will vary considerably in terms of tree species and density, comprising both formal alley planting and alongside field margins.

Hedges

Historically, hedgerows were used to mark field boundaries. Hedgerows can provide a similar set of benefits to those derived from agroforestry in terms of carbon sequestration, improving farmland biodiversity and shelter for grazing livestock. The current length of hedgerows in the UK is around 120,000 hectares, of which around a half is under management.[33]

We assume that hedgerow length increases by between 30% to 40% by 2050:

- The lower bound corresponds to the level recorded in the 1984 Countryside Survey.
- We assume that 10% of the lower bound and 30% of the upper bound is managed for biomass fuel.
- Hedges are planted on permanent and temporary grassland only, and carbon stock changes in the soils do not change. This is because of the lack of robust evidence in this area but is likely to be a conservative assumption.
- Hedges are assumed to be 1.5 m wide and with biomass stock densities derived in the BEIS Biomass Extension project.[34]

f) Peatlands

Well-functioning peatlands can sequester carbon, regulate the quality and quantity of drinking water, and are important wildlife habitats.

Peatlands occupy around 12% of UK land area. Organic soils such as well functioning peatland (soils with more than 50% organic matter are defined as peats) can continuously accumulate carbon under water-logged conditions at a rate of around 1mm per year. Peatlands are therefore an important and potentially growing reservoir of carbon.

Well-functioning peatlands also provide a range of other vital services to society:

- They can regulate the quality of drinking water. It is estimated that up to 70% of UK drinking water is sourced from upland catchments that are peatland habitat.[35] Healthy peat in the uplands hold water, which can slow the flow of water, alleviating the risk of downstream flooding.

- Provide highly valued cultural services (e.g. recreation, archaeology) and are internationally important wildlife habitats supporting biodiversity.

Climate change strengthens the case for action to protect and restore peatlands. If functioning peatlands are to survive in a changing climate and continue to provide these key ecosystem services, they need to be in a good condition. Warmer and drier conditions in the future are likely to increase the rate of carbon losses from degraded peatlands and reduce the water-holding and filtering capacity of degraded peat. The longer the delay in reversing degradation, the more expensive it will become to deliver.

Under a quarter of the area is in a near-natural or re-wetted state and is a small net carbon sink. A wide range of uses over time have led to severe degradation of the remaining area. This includes grazing livestock with high stocking densities, drainage for forestry and agriculture, burning on moorlands for grouse shooting and peat extraction for horticultural use.

We assume that the area of UK peatland that is rewetted increases from the current 25% up to 60% by 2035.

Our scenarios assume the rewetting (raising the water table) of between 800,000 and 1 million hectares by 2035, which would increase the area of peat under restoration to between 53% and 60%. This would exceed current commitments by the UK government to restore 35,000 hectares in England by 2025, and 250,000 hectares over the next 10 years by the Scottish Government.[36] The water companies are also targeting to restore 20,000 hectares of their owned land by 2030.[37]

Our assumptions consider both restoration and sustainable management options where land remains in agricultural production. These are drawn from stakeholder engagement and on-going work from Defra's lowland peat project.[38]

i) Upland grassland

This represents the largest area of peatlands (40% or 1.2 million hectares) and has been mainly used for sheep grazing. We assume that all upland peat is restored by 2045 at the earliest and by 2050 at the latest. Where the level of degradation is so severe to prohibit the re-start of peat formation, we assume that action is taken to stabilise the peat to halt carbon losses. We also include an end to damaging practices (e.g. rotational burning of upland peat).

ii) Lowland restoration

Lowland fen peat comprises both extensive and intensive grassland and cropland. Although the lowland area accounts for 14% of UK peatland, it is responsible for around 56% of peatland emissions (Figure. 7.9) This is due to the high level of degradation with historic and on-going drainage resulting in significant peat loss and shrinkage. For example, it is estimated that over 100 years of drainage has resulted in peat shrinkage of around 4 metres at Holme Fen in Cambridgeshire.[39]

We consider the impacts of rewetting and sustainable management of lowland peat.

Our scenarios assume that between a quarter and 50% of grassland is rewetted by 2050. Although lowland cropland is highly productive agricultural land, it produces the most emissions per hectare of any peatland - of around 39.5 tCO_2e/hectare compared to 3 tCO_2e/hectare in the uplands.
Restoration and sustainable management can therefore deliver significant emissions savings and enable this area to be farmed productively for longer. At the current rate of degradation (observed to be between 10-30mm a year) most of the remaining peats will become wasted over the next 30 to 100 years, depending on current depths and usage.[40]

Our analysis includes two different approaches for full restoration of cropland, and we have updated the costs of full restoration based on stakeholder engagement (Box 7.6):

- **Full restoration to near-natural condition.** This takes land out of crop production and we estimate emissions would fall to around 2.5 tCO_2/hectare. Most rewetting has been done for nature conservation. Examples includes Wicken Fen, which has rewetted 350 hectares of land and the Great Fen Project, which is looking to create 3,700 hectares of fen landscape over a 50-year period. The project started in 2001 and to date has restored 1,200 hectares.
- **Paludiculture.** Switching crop production to 'wet-farming' covers both food and non-food crops that can be grown in water (e.g. blueberries, reeds, sphagnum). Emissions savings are slightly lower, falling to 3.6 tCO_2e/hectare. This represents a novel agricultural system and work has been on-going by Defra to evaluate its viability, while a pilot run by the Great Fen project is trialling different crops (Box 7.7)

'Given the limitations in the available scientific literature, the Tier 1 basic methodology assumes that there is no transient period and that rewetted organic soils immediately behave like undrained/natural organic soils in terms of CO2 flux dynamics.' *(IPCC 2014)*

CO_2 emissions from rewetting upland and lowland peat is assumed to fall to zero in the year of restoration. This is a simplifying assumption as there is a lack of robust scientific data on the time profile of emission reduction after restoration.[41] This is the currently accepted IPCC methodology, and is one of the many uncertainties associated with peatlands.

There are additional societal benefits from the avoided costs of maintaining road and rail infrastructure due to land subsidence from drainage (Box 7.6).

Box 7.6
Costs and benefits of restoring lowland peat

There has been less restoration of lowland fen peat compared to the uplands, with most centred on the creation of wildlife habitats and nature reserve. Consequently, there is less data available on the upfront costs of restoration.

The data we have used to estimate the average restoration cost is derived from costs provided by a wetland conservation centre in Norfolk and a water and land management company that carries out restoration work:

- The data shows a large range (£240/hectare to £4,900/hectare) based on the level of landscaping and revegetating:
  - The lower upper bound is indicative of light intervention such as the reseeding of arable land to allow for low levels of grazing at certain times of the year for conservation purposes.
  - A median level of costs (ranging £550-£950/hectare) could involve the use of machinery such as bulldozers to move soil and re-landscape, cleaning of ditches and planting of sphagnum.
  - The upper bound (£1,000-5,000/hectare) could include additional costs of woodland and scrub removal, and submersible electric pumps to keep the water table high.
- We use these costs to derive an indicative central cost estimate of £2,500 per hectare (ranging £800-5,500 per hectare).
- There are also on-going maintenance costs that can include water pumping, ecological surveys and the cutting of grass for silage if the land is not grazed

Lowland peat restoration can deliver wider societal benefits for nature and recreation, and scope to reduce road and rail infrastructure costs:

- WWT Welney Wetland Centre converted 38 hectares of arable peat to a wetland habitat in 2008. In addition to attracting wading birds, the reserve has recorded over 300 species of butterflies and moths, and rare wildflowers. It also offers recreational benefits for reserve visitors.
- Peat subsidence due to drainage has adversely impacted local road and rail infrastructure in East Anglia. Rewetting the land could potentially reduce deformation of roads and tracks, cracking and potholing of roads, resulting in reduced repair costs for the local authorities and Network Rail. Further work, including data collection and disaggregation of costs to directly attribute them to drained peatlands, is needed to be able to quantify the potential avoided costs of restoration.

Source: WWT Welney Wetland Centre; The Fen Group; Centre for Ecology and Hydrology and the Universities of Leeds, Leicester and York and (2020) *An assessment of the societal impacts of water level management on lowland peatlands in England and Wales*; CCC analysis.

Box 7.7
Paludiculture ('wet-farming')

There is growing interest in paludiculture (or 'wet-farming') as an option to reduce GHG emissions while continuing with agricultural production. It is estimated that under this rewetted farming system, emissions could fall by as much as 90% to 3.6 tCO_2e per hectare compared to conventional crop production on drained land. There is also scope to extend this system of farming to restored extraction sites:

- Rice is the most widely known crop grown in water-logged conditions, but crops for food, fibre and energy identified as suitable for the UK include:
  - Food crops include celery, water cress, cranberries and bilberries. It is estimated that 14% of the berry crop in Finland is grown on peatlands.
  - Suitable species for energy use include reed grass, bulrush, cattail, sedge, aquatic herb and trees such as alder, poplar and willow. The reed crops can also be used as fodder for livestock and is also already used as a construction material (e.g. thatched roofs).

– Sphagnum farming on rewetted extraction sites could be used as a substrate in the horticultural sector, potentially replacing peat obtained from the damaging practice of extraction.

- The Great Fen project has allocated five hectares of land to non-food crops such as bulrush, reeds and sphagnum. The 2019-2021 trial will be used to demonstrate to local farmers the viability of this type of agriculture, including the income potential, while measurements of CO_2 and methane will be recorded to quantify the emissions savings.

The Defra commissioned work on the viability of paludiculture concluded that while there was significant potential, practical and economic barriers would need to be addressed if large-scale adoption is to be achieved. Work to show-case to farmers as is being done by the Great Fen project is a clear example of the steps that will needed to widen its appeal.

Source: Defra Project SP1218 (2020); Great Fen – *Water Works project*.

iii) Lowland sustainable management

In some lowland areas current water levels are lower than may be needed for agricultural production and flood storage capacity.

The overriding control on the rate of emissions from peatlands is mean water-table depth. It is estimated that for every 10cm increase in the water table, there is a corresponding reduction in emissions of 3 tCO_2e/hectare. There is evidence that in some areas, current levels are lower than may be needed for agricultural production and flood storage capacity.[42] We consider two water-table management options for the area of lowland cropland peat that remains in conventional agriculture:

- **Dynamic water-table management** (seasonal re-wetting) involves raising the water-table up to 10cm below the peat surface during the winter months when there are no crops in the ground, which is then drained to between 40-100 cm below the surface during the growing season. Assuming an average water table depth of 50cm for the year, we estimate that emissions could fall by less than half to around 18 tCO_2e/hectare.

- **A permanent increase of the water-table** to an average of 40 cm below the peat surface all year round could deliver higher savings, with annual emissions falling further to 16 tCO_2e/hectare.

Both options represent new approaches that have not been trialled at scale, but on-going work to understand the practicalities and hydrology of the surrounding area is required to ensure that practices undertaken by one farmer do not impact a neighbouring farmer, and that flood storage capacity can still be maintained.

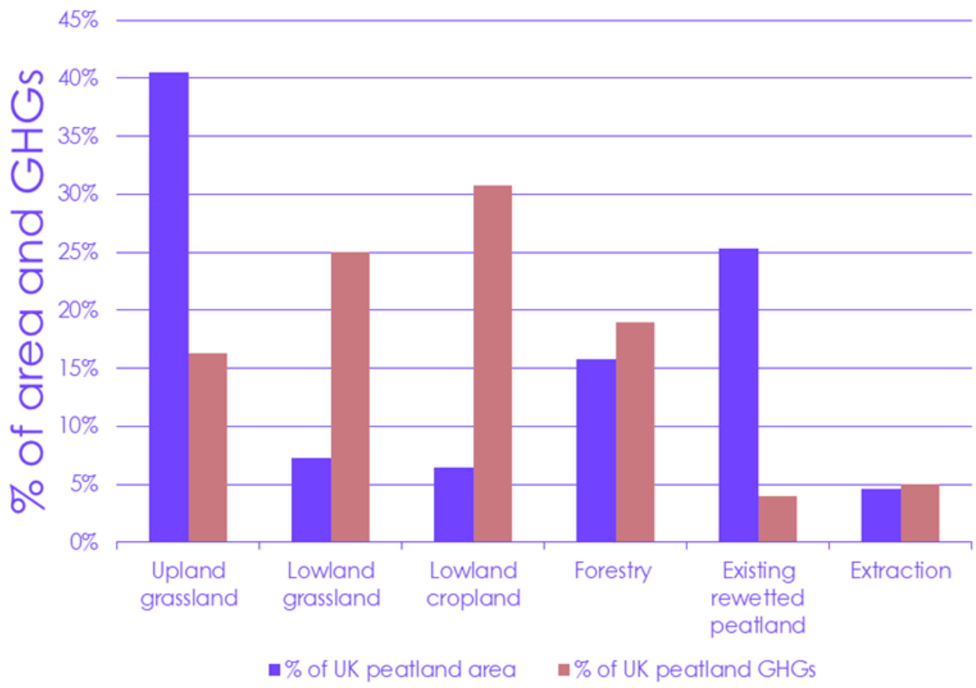
iv) Other peat

We include emissions savings from two further types of peatland that do not require the conversion of agricultural land. Ambition for these is the same across all our scenarios:

- **Removing low-productive trees off peat.** Around 13% of forestry is on peat mostly conifer woodland in Scotland. It is estimated that there are around 84,000 hectares of peat with low-productive trees of less than YC8. We assume removing these low-yielding trees improve the net carbon balance, with the peat emissions savings exceeding the carbon losses in the trees. Our ambition is to restore 84,000 hectares by 2035, of which over 80% would occur in Scotland.

- **Extraction sites**. Extraction of peat has largely occurred on lowland raised bog. Historically, it was mined for fuel and today its main use is in the horticultural sector, with smaller amounts for whiskey production. Our scenarios rewet around 144,000 hectares of peat extraction sites to semi-natural habitats by 2035. In our 2020 Land Use Policy report we recommended a ban on the sale of peat for use in horticulture and cessation of extraction by 2023, and this is assumed to be the case in our analysis.[43]

Figure 7.9 UK peatland area and GHGs by land use (2019)



Source: CEH(2020) and CCC analysis.

g) Other uses of land

Natural regeneration and wildflower meadows could have a role to play for carbon mitigation and wider environmental benefits, though the GHG impacts are uncertain.

Our analysis suggests that if all our land release measures are delivered on time, 1.8 million more hectares could be freed up than are required to deliver the land use change required in the Balanced Pathway by 2035. Choices on how to use this additional land include measures to increase emissions reduction further (e.g. more tree planting), conversion to other uses (e.g. wildflower meadows and rewilding/natural regeneration) to deliver wider environmental benefits and address biodiversity loss.[44] These options are not included in our scenarios due to the lack of robust evidence on the abatement potential. Land could also be used for less-intensive agricultural production (Box 7.8).

Box 7.8
Other uses of land to deliver environmental benefits

In addition to using land to actively plant trees and hedges and restore peatland, there are other uses of land that could deliver further environmental benefits to address biodiversity loss. This could also entail some form of low-intensive agriculture:

- **Rewilding** can be defined as the 'process of drawing back or de-intensifying agricultural or commercial forestry production in carefully selected areas using natural principles and processes' (Rewilding Britain). The most notable example is the Knepp Estate in West Sussex, which ceased intensive farming on its unproductive arable land for the benefit of nature 20 years ago. Fields soon gave way to scrub while free-roaming grazing animals including cattle and pigs are used to create a mosaic of habits on the 1,400 hectare estate, which over time has seen a large increase in the diversity and numbers of species, including rarities such as the nightingale and turtle dove.
- **Wildflower meadows.** With intensification of agriculture, the expanse of wildflower meadows and species-rich grasslands have almost disappeared with the loss of 99% of 'unimproved grasslands' since the 1930s. Replacing high input (e.g. fertilisers and pesticides) grassland mono-cultures with low input species rich-grass and wildflowers can support a wider variety of wildlife including pollinators, reptiles, small mammals and birds.
- **Low-intensive farming.** Examples include mixed farming, combining arable and livestock production to close the nutrient loop (e.g. use of animal waste to fertilise the fields), and organic farming, which avoids the use of synthetic fertilisers and pesticides in preference for livestock and green manures, and natural pest control methods.

Beyond land, 'blue-carbon' is the carbon sequestered and stored in marine and coastal habitats. Carbon stocks are found in saltmarsh, maerl seaweed, kelp forest, and seagrass beds. There is concern that degradation (e.g. from anchoring and mooring of boats), which could worsen with climate change could release this carbon. However, considerable uncertainty on the dynamics of blue carbon exists and work is needed to calculate a baseline assessment of stocks. Blue carbon is not currently included in the UK GHG Inventory.[45]

We assume that key priorities for land, producing food for a growing population and for settlement growth, are met before allocating land for climate mitigation.

Our starting point for our analysis is the 2019 Net Zero report, which showed that the Net Zero target requires transformative changes in how land is used in the UK. We recognise other strategic priorities for land, including food production, housing and economic and social uses, a range of environmental services and biodiversity. Most of our measures have positive synergies with these but we highlight areas of potential risks. We quantify costs and benefits where good data exist and qualitatively assess other impacts where data is lacking.

We have used a bottom up analysis to produce a set of pathways to deliver land's contribution to Net Zero by 2050. We use the scenarios to explore a range of different futures, including ones with higher levels of innovation and behaviour change. Our scenarios aim to demonstrate what can be achieved with an ambitious and effective policy package that deals with various barriers to action in these sectors.

The following sections set out our scenarios, the approach to deriving the pathways for the devolved administrations and our approach to uncertainty.

a) Analytical methodology

i) Baseline

Our scenarios compare trajectories consistent with meeting the Net Zero target, with a projection of baseline emissions where measures to reduce emissions are largely absent. Baseline emissions for agriculture are based on the BEIS Updated Energy and Emissions Projections[46] and the LULUCF sector is based on a projection derived for this report by the Centre for Ecology and Hydrology (CEH), which includes all sources of peatland emissions:

- For agriculture these emissions decrease to 52 $MtCO_2e$ by 2035. This includes an annual 0.6% efficiency improvement in the dairy herd, which leads to a decline in dairy cattle numbers.
- For land use we assume a continuation of past low rates of afforestation resulting in an increase in net emissions to 13 $MtCO_2e$ by 2035. The baseline also includes projected savings from firm Scottish Government policy to fund the restoration of 250,000 hectares of peatland before 2030.[47] If achieved this would deliver annual emission savings of around 1 $MtCO_2e$ by 2030.

We assume that key priorities for land, producing food for a growing population and for settlement growth to support housing and other economic activity, are met before allocating additional land for climate mitigation:

- The UK population is projected to increase from 66.4 million in 2018 to 70.9 million by 2035 and 73.6 million by 2050.[48]
- Maintaining the current level of per capita food production in 2035 and constant food exports would require 0.9 million hectares of additional land, assuming no change in yields, other productivity improvements or structural changes in agriculture.

- Land for settlements account for 7% of UK land today. The expected increase in land for settlement growth takes account of the projected increase in the number of households, household density and economic activity. Meeting this growth requires the use of brownfield sites and 'non-previously developed' land. For 'non-previously developed', we had classified this previously to mean agricultural land. For this report, we make a distinction between 'non-developed land' that is already classified as settlement but not built-on (e.g. outdoor recreation areas) and non-settlement land (e.g. agricultural land). This reclassification reduces the need to convert as much agricultural land to meet these demands. Land for settlements now accounts for 9% of UK land area by 2050 compared with 12% in our Net Zero report.

ii) The Balanced Net Zero Pathway

The Balanced Net Zero Pathway results in net emissions for agriculture and land use falling to 40 $MtCO_2e$ by 2035 and 16 $MtCO_2e$ by 2050

The Balanced Net Zero Pathway represents our central scenario for how the agriculture and land sectors will need to evolve to deliver Net Zero across the economy by 2050. It results in net emissions in agriculture and land use of 40 $MtCO_2e$ by 2035 and 16 $MtCO_2e$ by 2050. Key elements are:

- **Low-carbon farming practices and energy use**. Take-up ranges between 50-75% for both behavioural (e.g. cover crops, high sugar grasses and livestock health) and innovation (e.g. 3NOP, breeding and anaerobic digestion) low-carbon measures depending on ease of implementation on-farm. Biofuels and electrification options are taken-up from the mid-2020s and hydrogen fuel cells for larger applications from 2030 for mobile machinery. Building heating and cooling systems switch to low-carbon alternatives including heat pumps and hydrogen, with use of biomass phased-out by 2035.
- **Options to release land from agriculture** result in 3.8 million hectares freed up by 2035.
  - **Agricultural productivity**. Average crop yields increase to 11 tonnes/hectare by 2050, driven by improvements in agronomy and technological innovation such as breeding. Livestock stocking rates on lowland grassland increase by 10%. 10% of current horticultural production is moved indoors by 2050.
  - **Consumer behaviour change.** There is a 20% shift away from all meat and dairy products by 2030 which is substituted by plant-based proteins. The reduction in meat consumption rises to 35% by 2050. WRAP's UK Food Waste Reduction Roadmap target of a 50% reduction on 2007 levels is met by 2030 across the supply chain, with a 60% reduction by 2050.

Annual afforestation rates reach 30,000 hectares by 2025 and rise to 50,000 hectares between 2035 and 2050.

- **Afforestation and broadleaf management**. Woodland area increases to 18% of UK land area by 2050, most of which is under sustainable management. Forestry biomass output increases to 12 million oven dried tonnes (odt) by 2035 compared to under 5 million odt in 2019. The management of existing forests account for all the harvest, of which 60% is fuel-grade material.
  - Annual afforestation rates reach 30,000 hectares by 2025 and rise to 50,000 hectares between 2035 and 2050. An additional 15% of land is used as open ground for biodiversity.

- Tree planting density is 2,000 stems per hectare for broadleaves and 3,000 for conifers, and a planting density of 66:34 in favour of conifers for the UK. This corresponds to planting 143 million trees in 2035.
- Productivity yields of new conifers are YC16, which is higher than the average for existing conifer woodlands of YC14. Yields for broadleaf trees remain at YC6.
- Active management of 80% of the existing broadleaf woodland area by 2030 (up from the current 20%).

- **Agroforestry and hedges**. The Balanced Pathway improves on-farm diversification with the integration of trees on 10% of farmland and extending the length of hedgerows by 40% by 2050, with 30% of this actively managed.

The area of restored peat increases from 25% currently to 58% in 2035 and 79% by 2050, and 35% of lowland cropland is sustainably managed

- **Peatland restoration** increases the area restored from 25% currently to 58% in 2035 and 79% by 2050, with a further 35% of lowland cropland sustainably managed:
  - All upland peat is restored by 2045 (or stabilised if degradation is too severe to restore to halt carbon losses). 25% of the area of lowland grassland is rewetted by 2035, rising to half by 2050.
  - 75% of lowland cropland is either rewetted or sustainably managed by 2050:
  - A quarter of the area is rewetted to near natural condition (and crop production ceases), and a further 15% is rewetted but conventional crop production switches to paludiculture crops.
  - Water-table management options are deployed to 35% of the area.
  - All low-productive trees of less than YC8 are removed off peatland; and all peat extraction sites are restored by 2035.

- **Bioenergy crop** planting reaches 30,000 hectares by 2035, equally split between miscanthus, SRC and SRF. The total area with bioenergy crops rises to 0.7 million hectares by 2050. Energy crop yields increase to 15 odt/hectare by 2050 driven by better agronomic practices and innovation. Harvested biomass products reach 1.8 million odt by 2035 and 6.4 million odt by 2050.

Most of these measures have lower abatement costs than our assumed carbon values (£181 in 2035) and some deliver wider benefits (Table 7.2).

Table 7.2
Abatement costs in agriculture and land use in 2035 (£/tCO_2e)

	Measure	£/tCO_2e
Low carbon farming - crops	Cover crops	125
	Grass legumes mix	-1,040
Low carbon farming - livestock	Livestock breeding - current methods	-580
	Livestock breeding - low methane	-1,850
	Livestock breeding - genomics	-1,177
	Increased milking frequency	-850
	High sugar grasses	-415
	Precision livestock feeding	-15
	Adding nitrate to livestock diets	55
	3-NOP in livestock diets	85

	Improving sheep health	25
	Improving cattle health	-45
Waste and manure management	Cover slurry tanks	20
	Anaerobic digestion - pigs	-250
	Anaerobic digestion - cattle	-175
On-farm machinery	Stationary and mobile machinery	75
Land use measures	New conifer planting	65
	New broadleaved planting	105
	Miscanthus	180
	Short Rotation Forestry	240
	Silvoarable Agroforestry	155
	Silvopasotral Agroforestry	415
	Hedgerow Expansion	5
	Upland Peat Restoration	40
	Lowland Peat Restoration	5
	Woodland to Bog	30
	Short Rotation Coppice	-
	Broadleaf forestry management	150

Source: CCC analysis based on SRUC (2020) and Vivid Economics research.

iii) The exploratory pathways

These scenarios set out alternative pathways as to how agriculture and land could contribute to the UK's Net Zero commitment. They involve varying the deployment rate, timing and ambition of the measures outlined above. These result in different land use and residual emissions by 2050 than the Balanced Pathway (Figures 7.10 and 7.11)

Headwinds is the least ambitious pathway, with remaining emissions in agriculture and land use of 48 $MtCO_2e$ in 2035 and 26 $MtCO_2e$ by 2050.

Headwinds is the least ambitious pathway, with remaining emissions in agriculture and land use of 48 $MtCO_2e$ in 2035 and 26 $MtCO_2e$ by 2050. The key differences are the lower level of diet change which releases 1.7 million hectares less land by 2035 compared to the Balanced Scenario and the rates of afforestation:

- Consumer behaviour change is limited to a 20% switch away from meat and dairy products to plant based alternatives by 2050. Food waste is halved by 2030 with no further reductions beyond that date.
- Other behaviour change assumptions and take-up of low-carbon farming practices are the same as in the Balanced Pathway.
- Emissions savings from take-up of low-carbon farming practices are higher in this scenario, as more land is in agricultural production, resulting in higher emissions and higher abatement potential. This measure delivers 0.5 $MtCO_2e$ more emissions savings in 2035 than in the Balanced Pathway.
- Annual afforestation rates reach 30,000 hectares by 2025 and are maintained to 2050. Trees are integrated onto 5% of agricultural land, hedges increase by 30% and 67% of existing broadleaf woodlands are brought into active management by 2030.
- Peatland restoration extends to 52% of the peatland area by 2035, and 77% by 2050. There is lower ambition for lowland peat restoration, with only 25% of grassland and 20% of cropland area rewetted by 2050. A further 30% of the cropland area is under sustainable management. All upland peat is restored but five years later in 2050.
- Energy crop planting is aligned to the Balanced Pathway, and total biomass output from energy crops and forestry total 12.4 million odt in 2035.

Widespread Engagement reflects higher levels of engagement on climate and health issues by farmers and consumers, and emissions fall to 39 $MtCO_2e$ in 2035 and to 8 $MtCO_2e$ by 2050.

Widespread Engagement reflects higher levels of engagement by consumers and farmers, resulting in higher levels of diet change and land use change. This enables higher afforestation, peatland restoration and bioenergy crops. Residual emissions fall to 39 $MtCO_2e$ in 2035 and to 8 $MtCO_2e$ by 2050:

- Farmers adopt a high uptake of low-carbon behavioural practices of between 60-80%; and a lower uptake 50-75% for innovative measures. Decarbonising energy use focuses on electrification and the use of biomass and biodiesel as a transition fuel. There is no uptake of hydrogen.
- Crop yields are assumed to be the same as in the Balanced Pathway, but livestock stocking density is limited to 5% increase on grasslands.
- A larger shit towards healthier diets beyond 2030, results in a 50% switch away from meat and dairy products to all plant-based products by 2050. Food waste is halved by 2030 and continues to fall to 70% by 2050.
- Annual afforestation rates reach 50,000 hectares by 2030 and 70,000 from 2035 to 2050. There is an increased focus on creating woodlands for biodiversity rather than productive forestry: planting density is reduced for broadleaves to enhance conservation outcomes (1,200-1,800 stems per hectare); the mix of slower growing broadleaves is higher at 66:34, yields of conifers remain at the current level of YC14; and the area of open ground is increased to 20%.
- More grassland is allocated to trees with 15% of the area under a silvopastoral system, while trees on cropland area remains at 10%.
- Peatland restoration and the level of sustainable management of lowland cropland matches the ambition in the Balanced Pathway.
- Energy crop planting drops to a third (10,000 hectares by 2035) of the level in the Balanced Pathway with only miscanthus planted. This results in 1 million odt and 3.4 million odt of harvested output by 2035 and 2050 respectively.

Widespread Innovation is characterised by high levels of innovation, and emissions fall to 30 $MtCO_2e$ in 2035 and by 2050, reaches negative emissions of 8 $MtCO_2e$.

Widespread Innovation is characterised by high levels of innovation with a focus on technology to deliver higher yielding food and energy crops and more productive trees. A lower tree planting rate (compared to the Wider Engagement scenario) is offset by a higher mix of conifers which delivers faster and higher carbon sequestration by 2035. Residual emissions fall to 30 $MtCO_2e$ by 2035 and by 2050 agricultural emissions are offset by the land net carbon sink, with combined negative emissions of 8 $MtCO_2e$

- Farmers adopt a high uptake of low-carbon innovation measures of between 60-80%; and a lower uptake of 50-75% for behavioural measures.
- Developments in crop breeding lead to wheat yields of 13 tonnes by 2050, and livestock stocking rates increase by 10% on rough grazing and permanent grassland.
- The same level of diet change as Widespread Engagement, except 30% of the meat is replaced with lab-grown meat and 20% by plant alternatives. Food waste is halved by 2030 and continues to fall, reaching 60% below 2007 levels by 2050.
- Afforestation rates reach 50,000 hectare five years earlier than in the Balanced Pathway in 2030. The focus is on more productive forestry with a higher mix of faster growing conifers (67:33) with higher yields.

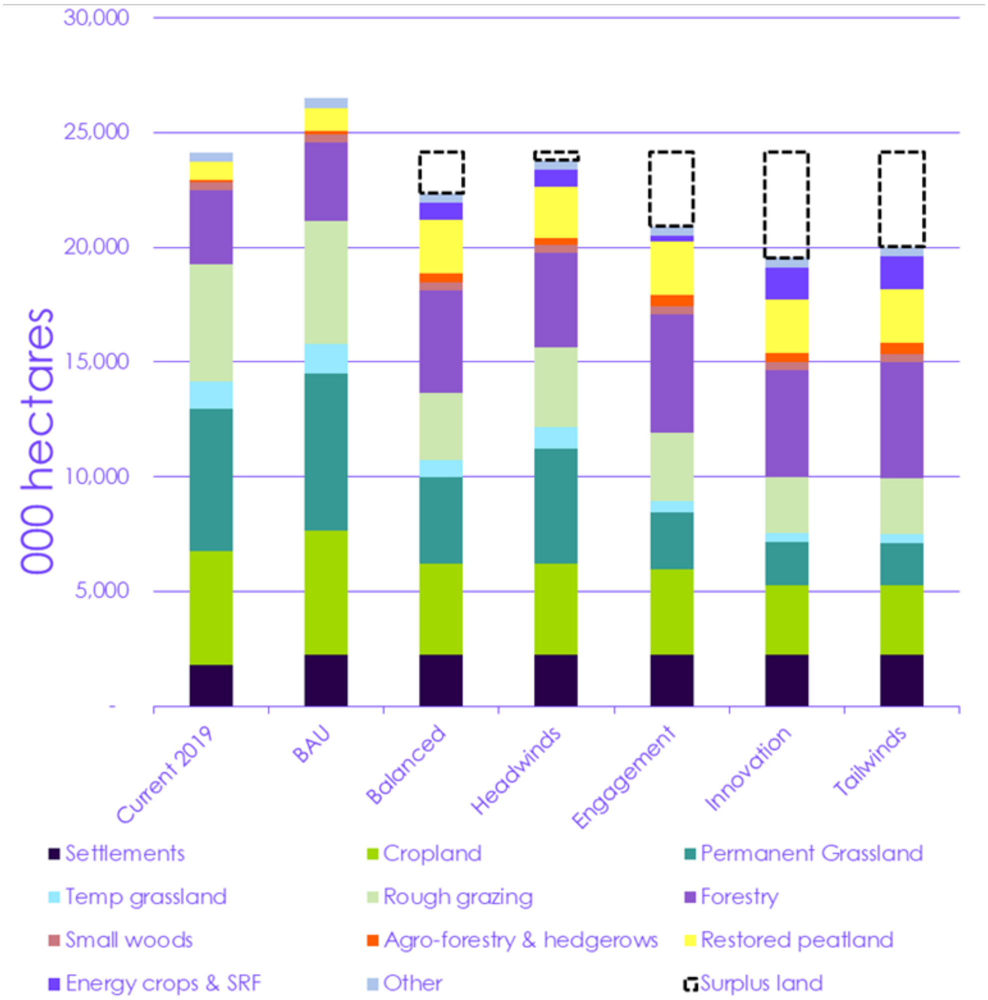
Breeding allows for the planting of conifers with an average YC18 and broadleaves with YC8 from 2030. This offsets the lower planting rates (50,000 hectares a year from 2030) and delivers quicker and higher savings by 2035 and 2050 compared to the Widespread Engagement Scenario.

- Agroforestry is applied to 10% of farmland, and hedges increase by 30% by 2050, with 10% managed.
- There is more reliance on sustainable management of lowland cropland peat driven by technological solutions that allow for better management of the water table. This is applied to 50% of lowland cropland. Only 25% of the area is rewetted for paludiculture and we assume no restoration to near-natural condition.
- Energy crop planting doubles by 2035 and reaches 1.4 million hectares by 2050. Developments in innovation allow for miscanthus and SRC yields to increase by 33% to 20 odt per hectare by 2050. This results in the highest level of harvested products (4 million odt) by 2035.

Tailwinds delivers the highest level of ambition, nearly 50% higher than in the Balanced Pathway by 2035.

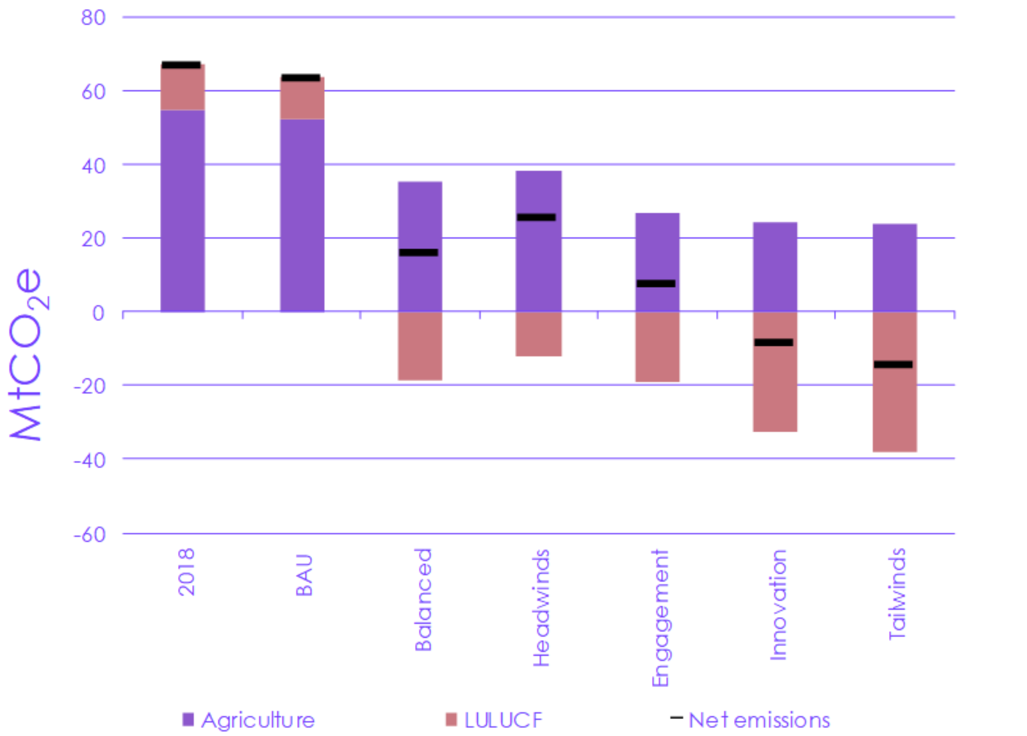
Tailwinds represents the highest level of ambition. Measures are aligned to the Wider Innovation scenario, except for food waste where there is a higher level of ambition with a 70% reduction on 2007 levels reached by 2050. This scenario delivers the highest level of emissions savings which are 49% higher than in the Balanced Pathway by 2035. Residual emissions are 28 $MtCO_2e$ by 2035, falling to below zero by 2046 and -14 $MtCO_2e$ in 2050.

Figure 7.10 Current land use and under our Sixth Carbon Budget scenarios by 2050



Source: CEH(2020) and CCC analysis.

Figure 7.11 Residual GHG emissions in agriculture and land use in 2050



Source: BEIS (2020) *Final UK greenhouse gas emissions national statistics 1990-2018*; CEH (2020); SRUC (2020); CCC analysis.
Notes: Using the Global Warming Potential of AR5 for methane.

iv) Costs and Benefits

Our analysis covers private costs and benefits and wider social benefits of increased recreation, improved air quality, improved health and flood alleviation.

Our assessment of costs and benefits updates work we commissioned from Vivid Economics and new work from SRUC.[49] It covers all private costs and benefits and wider social benefits of increased recreation, improved air quality, improved health and flood alleviation.

There could be additional costs, both financial and non-financial, that has not been possible to include in our analysis:

- Costs of R&D and innovation to develop higher yielding crops that do not require additional inputs and are resilient to climate impacts. If these costs are passed onto farmers, they may lead to an increase in net costs.
- There are some costs to farmers from implementing low-carbon practices on their land. Where possible, costs have been considered e.g. capex of anaerobic digestion systems and changing livestock diets. There will be other non-financial barriers to overcome which could incur costs (e.g. providing information to farmers and re-education and re-skilling).
- Costs of moving horticulture indoors could involve costs of buildings and operational expenditure e.g. heating and lighting. This will be set against savings from using land, some lower input costs (e.g. fertiliser and pesticides) and higher yields.

- There could be some disruption costs associated with behaviour change e.g. for food producers to develop new plant-based foods and for consumers to change shopping and eating habits. Reducing food waste is cost saving to households and the food supply chain. WRAP estimate the value of food wasted by UK households and across the food supply chain has a value of £19 billion per year. There could be some added costs associated with trying to reduce food waste e.g. data driven approaches to optimise use by dates and technologies to monitor how much food is wasted, although these are expected to be much smaller than the cost savings made.
- The Widespread Innovation scenario assumes that meat products are partly substituted by lab-grown alternatives. These are currently at early stage of development and are more expensive than animal products. However, there is evidence that these costs are falling with Mosa Meats, a producer of lab-grown meat, reducing the costs of culturing the cells by 80% in 2020.

As set out in our accompanying Policy Report: *Policies for the Sixth Carbon Budget & Net Zero*, achieving these scenarios will require co-ordinated effort across sectors, covering farmers, the wider food supply industry and consumers, and a strong policy framework which addresses financial and non-financial barriers. There will need to be a strong Monitoring, Reporting and Verification (MRV) system to verify actions across the UK and trade policies that protect risks of carbon leakage from trade in agricultural products.

Wider benefits

Our scenarios capture some of the wider benefits from some measures – recreational benefits of woodland, air quality improvements, flood-risk alleviation and health improvements from increased physical activity. The approach was developed by Vivid Economics and we have updated this analysis to reflect the ambition in our revised Sixth Carbon Budget Pathways (Box 7.9).

Box 7.9
Valuation of non-market benefits of land uses

Recreational benefits
An Outdoor Recreation Valuation tool (ORVal) produced by the University of Exeter was used to model the number of additional visits to woodland that the planting of a new forest would generate. It was assumed that new visits do not occur until 10 years after planting, and annual visits increase as trees approach maturity. A £/visit willingness to pay for these visits was used from a large-scale cross European Union stated preference survey assessing how much people would be willing to pay to visit woodland.

Air quality
Ammonia is emitted during the storage and spreading of manures and slurries and from the application of inorganic fertilisers, and can contribute to particulate pollution in urban areas, leading to increased cardiovascular and respiratory disease.

A study commissioned by the ONS from the Centre for Ecology and Hydrology estimated the reduction in hospital admissions (from respiratory and cardiovascular conditions) from natural vegetation removing pollutants from the air. This model was adapted for use in this study. However, given that the forests in this study are predominantly located in peri-urban and rural areas, the population density is relatively low so the benefits are smaller than in studies which look at locating trees in urban areas.

Flood risk alleviation
Woodland in the upper catchments of rivers can help to alleviate flood risk by slowing down the flows of water, though the exact benefits depend on a number of factors including location and planting density. Furthermore, targeting woodland planting onto the most sensitive soils or in key locations can intercept and help absorb surface run-off generated from the adjacent ground. This is valued using a recent report by Forest Research that looked at the costs involved in holding the amount of water held in all UK woodlands in UK reservoirs (a replacement expenditure approach). This UK value is then scaled down to a per hectare basis.

Health improvements from increased physical activity
Natural environments are often used for walking, running and playing sports, leading to physical health benefits for the visitors. These benefits can lead to improved long-term health outcomes, which is measured in terms of a relative reduction in the risk of premature death. The value of this relative reduction in the risk of premature death has been calculated in many research papers, using surveys which elicit the value that individuals are willing to pay to improve their quality and length of life. In order to prevent an overestimate of physical health benefits, it is assumed some visitors to woodland would have engaged in a different form of exercise if they hadn't exercised in the woodland, so conservatively, only 10% of the exercise from recreation in the woodland is attributed to the creation of the woodland.

Source: Vivid Economics (2020); CCC analysis.

Due to lack of evidence, the quantitative benefits of biodiversity and water quality are not included in this analysis. While there is evidence that the creation of new woodland habitats support biodiversity broadly, there is no widely accepted way to value biodiversity[50]. Other studies point to the benefits that land use change can have in improving water quality, increasing pollinator numbers, and reducing soil erosion. There was insufficient quantitative evidence to support their inclusion in our analysis, though these could be important:

- There is evidence of the high biodiversity value of restored peatlands from species such as sphagnum moss, invertebrate and bird species. [51] Some studies indicate that drain or gully blocking can lead to an increase in indicator species like sphagnum moss and the recovery of aquatic macro-invertebrate fauna.

- Agroforestry and hedgerows are likely to provide biodiversity benefits (e.g. by providing habitats for insects, birds and small mammals), reduced water pollution, improved soil health and for grazing livestock shelter from wind and shade from the sun. Over 600 plants, 1,500 insects, 65 birds and 20 mammals species utilise UK hedgerow habitats.[52] Numerous studies have shown the removal of hedgerows and the abandonment of hedge management on farmland is likely to have adversely affected different species groups, for instance yellowhammers (a declining species) in southern England.[53]

- We have not included estimates of the health impacts of diet change in our analysis as these are uncertain. However, a study by Ricardo for the Committee in 2013 suggested the health impacts of reducing red meat consumption by 50% would represent 0.5% of GDP (around £1 billion), with other estimates suggesting reducing average meat consumption to two to three servings per person per week could reduce NHS costs by £1.2 billion per year. [54]

There are also wider societal risks, particularly in relation to planting bioenergy crops that could have negative impacts on biodiversity, soil health, water quality and invasive species.

These risks are higher when planting maize and on grasslands. Our scenarios look to mitigate these risks by planting only perennial energy crops and only on cropland, while SRF is grown on grasslands.

Half the low-carbon farming measures in our scenario have a major benefit for improving air and water quality.

Our scenarios also include a high take-up of low-carbon farming practices. These could deliver benefits to biodiversity and soil quality, while there could also be some risks. Based on a review of evidence from Defra's on-going 'Delivering Clean Growth through Sustainable Intensification' project, we assessed the wider environmental considerations of the 18 low-carbon measures in the Balanced Pathway (Table 7.3):

- The biggest benefits are for air and water quality, with nine of the 18 measures delivering major impacts. These include increasing milk frequency of dairy cattle, improving livestock health and covering slurry tanks with impermeable covers.
- There is less significant benefit to biodiversity and soil quality, with only two measures deemed to have a major impact (grass leys and cover crops).
- We also identified negative trade-offs from three of the measures, which could potentially worsen air quality (anaerobic digestion pigs and cattle), and water quality (from the adoption of high-starch diets).

Table 7.3
Qualitative assessment of wider environmental benefits from low-carbon farming practices

Low-carbon farming practices	Water quality	Air quality	Biodiversity	Soil
Breeding measures				
Genomics	Minor	Minor	-	-
Current breeding	Major	Major	-	-
Low methane	Minor	Minor	-	-
GM cattle	Major	Major	-	-
Increase milk frequency	Major	Major	-	-
Livestock diets				
High sugar grasses	Major	-	-	-
Nitrate additives	Minor	Minor	-	-
Precision feeding	-	Major	-	-
High starch diet	Negative	-	-	Negative
3NOP	Minor	Minor	-	-
Livestock health				
Cattle	Major	Major	Minor	-
Sheep	Major	Major	Minor	-
Soil measures				
Grass legume mix	Major	-	Major	-
Grass leys	-	-	-	Major
Cover crops	Major	Major	-	Major
Waste management				
AD pigs	-	Negative	Negative	-
Ad cattle	-	Negative	Negative	-
Cover slurry tanks	Major	Major	-	-

Source: CCC analysis based on Defra Sustainable Intensification Project.

b) Delivering the pathways for the Devolved Administrations

We have also quantified the emissions savings in each scenario for each of the devolved administrations.

The pathways for the devolved administrations (DAs) have been derived by a applying the analytical approach outlined above to more detailed data in each DA for some key metrics:

- Agricultural baseline emissions projection is developed for each DA based on their share of UK 2018 outturn emissions from the 2020 GHG inventory. This is disaggregated into the main source of emissions (e.g. enteric fermentation and soils) by individual administration. Baseline projections in the LULUCF sector are derived from the CEH work for this report, which reflect net emissions in each DA under the current GHG inventory, and the inclusion of all peat emissions. The baseline projects forward the average level of afforestation achieved in each DA between 2014 and 2018, while for Scotland we include the firm Scottish Government commitment to restore 250,000 hectares of peat by 2030.

- In the agriculture sector, our modelling of low-carbon farming measures takes account of the abatement potential based on the current use of land for growing crops and rearing livestock in each DA. DA specific abatement costs for each measure were derived.

- Abatement savings from energy use in agriculture was derived from the UK level of abatement, which was split according to each DA's share of emissions in 2018 under the 2020 GHG inventory. The abatement options and costs are assumed to be the same as for the UK.

- The outputs of our modelling of land released through productivity and behaviour changes are based on DA specific data for current use of agricultural land, including grassland and cropland. Outputs of agriculture in terms of types of crops produced, yields, and livestock numbers are also split by DA based on latest data. The UK ambition on yields, livestock intensification and consumer behaviour change are assumed to apply equally across each DA.

- The level of ambition on how to use land for measures to sequester carbon – afforestation, peatland restoration and energy crops – are based on how much land is available for these activities and in some cases on levels of ambition that have been announced by the relevant governing bodies. This can result in significant differences in the level of each measure across the DAs. For example, afforestation rates are higher in Scotland due to the availability of land.

Estimates of costs and benefits are partly split by DA and partly use UK data. Our modelling distinguishes the level of take-up of different technologies and options by DA, with some costs associated with these are DA-specific (e.g. land acquisition/opportunity costs), while others are drawn from UK averages (e.g. costs of decarbonising tractors and costs of peatland restoration for different types of peat).

c) Approach to uncertainty

In developing our advice, we have sought to consider the key uncertainties which could influence the path for emissions reduction in agriculture and land use in the UK. We explore these uncertainties primarily through our use of scenario analysis:

- The exploratory pathways achieve emissions reduction in different ways, illustrating the range for how they can be achieved. We use these scenarios to guide judgements on the achievable and sensible pace of decarbonisation in the face of uncertainty, and to understand how less success in one area can be compensated for elsewhere.
- The Tailwinds Scenario assumes considerable success on both innovation and societal/behavioural change and represents the most ambitious scenario and assumptions on scaling up sequestration measures and evidence on consumer behaviour change.
- Our Balanced Net Zero Pathway is designed to drive progress through the 2020s, creating options that keep the three 'exploratory' scenarios open.

Other specific risks that we highlight are around climate impacts on agriculture and the level of peatland emissions:

Climate risks. In its 2017 Climate Change Risk Assessment (CCRA), the Adaptation Committee highlighted the risks that climate change poses to the natural world:

- Changes in climate are already impacting on natural systems in the UK and there is a substantial risk to vital goods and services provided by the natural environment and society.
- These risks are heightened because the nature environment is already stressed.
- There are potential opportunities from modest climate change through extended growing seasons and improved productivity.

If climate risks dominate and crops yields decrease, the Balanced Pathway can still be met but would require a larger shift in diets.

In our assessment of future UK crops yields, we took account of these risks and opportunities to improve yields through innovation and good agronomy (Table xx). We also constructed a sensitivity under which climate risks dominate future yields, so that yields decrease to around 6 tonnes/hectare for wheat (and equivalent change for other crops) by 2050 compared with 8 tonnes/hectare currently.

- In the Balanced Pathway maintaining constant per capita food production with higher crop yields releases 1.2 million hectares by 2050. In the crop sensitivity scenario, this requires 1.8 million hectares more land due to lower yields – increasing cropland area by 37%, compared with today.
- Lower crop yields imply that to have enough land to deliver both the food production objective and the mitigation measures in our Balanced Pathway, more land would need to be released through other measures. If this was achieved through diets alone, it would require a 45% switch away from meat and 20% from dairy by 2050.
- The emissions reduction pathway we set out could still be achieved in a situation where climate risks dominate. But it is important that higher levels of diet change remain in scope in 2030 and are reviewed with evidence on how agriculture responds to climate impacts.

Better evidence is needed to improve our understanding of peat condition, depth and location under the different land uses.

Peatland emissions. Our estimate of emissions from peatland under different land uses is based on current understanding. UK emissions range between 18.5 and 24.5 $MtCO_2e$, depending on the method used to estimate forestry peat. Our analysis uses the higher figure, which is based on Tier 2 emissions factor for forestry peat. However, the confidence interval ranging from less than 10 $MtCO_2e$ to more than 40 $MtCO_2e$ (using AR4 for methane) highlights the large uncertainties of peatland emissions.[55] (Box 7.10).

Box 7.10

Uncertainties in peatland emissions estimates

The uncertainties in peatland emissions reflect the lack of robust activity data regarding the condition, location and extent of peatland under differ land use types. For example:

- Wasted peat is soil that is no longer deep peat (i.e. organic soil of more than 40 cm in depth) due to intensive use, mainly for crop production. Due to insufficient data however, wasted peat is assumed to emit the same level of emissions as deep peat.
- The evidence on upland peat is incomplete with the peat condition and depth in some areas not properly mapped.

Other uncertainties relate to measuring abatement savings over time and the impact of climate change:

- Under the current IPCC methodology, CO_2 emissions from restoration is assumed to fall to zero in the year of restoration. This does not reflect real-life conditions, where emissions would decline over time as the peat recovers following restoration.
- The impact of projected changes in climate on emissions from degraded peatlands is unknown. There is more confidence that near-natural peatlands will be more resilient to climate change and are likely to emit less CO_2 than degraded peatlands under all climate scenarios.[56]

A programme of work will look to improve the evidence base for these uncertainties, which will be used to update emissions estimates and abatement savings in the GHG Inventory. These include:

- On-going work to better quantify the area of wasted peat in England, while field measurements will be used to develop new emission factors. Preliminary findings from the BEIS commissioned project is expected next year.
- Nature Scotland is funding the establishment of a measurement site to measure emissions over an afforested area of peat, which will help to reduce uncertainties regarding the impacts of forestry on peat.
- Defra's sustainable lowland peat project is developing evidence on the abatement savings from a range of options that will allow for on-going crop production (see section 2 (e) above).
- Defra plan to commission work to develop an updated peatland map, which will determine peat location, depth and condition. It will enable improved spatial prioritisation of restoration work and more accurate estimation of GHG emissions. The project is expected to start in 2021.

We will provide an update on the work in next year's Progress Report.

Source: CCC analysis.

Other areas of uncertainty that we have not quantified, but are important to consider in designing policy to meet the pathway:

- The framework we have developed in our analysis of emissions pathways is necessarily stylised and relies on delivering a complex set of behavioural changes and interactions among consumers, the food supply sector and farmers. This transition is complex and reaches across the diverse farming sector, geographies and other actors. There are risks around how the timing and co-ordination of these actions are implemented in practice and in a way that is delivers a fair transition across all players.
- In order to deliver emissions reduction in the UK, famers need to respond to changes in UK diets by changing the type of food produced. This means reducing livestock production and increasing crops, if they can be grown. There is a risk that farmers respond to a change in UK demand by increasing exports of meat products rather than switching production to crops. If this happens UK emissions will not fall along the pathway we set out (although there may be reductions in emissions in other countries, depending how overseas demand and production responds).
- UK farmers are largely dependent on global commodity prices, which affect decisions on what to grow. These are historically volatile, with prices dependant on climate and global supply and demand. Our scenarios do not take account of future impact on prices, as they are difficult to predict with any certainty, but are likely to impact on decision making in practice.
- The COVID-19 crisis has impacted farmers through a fall in beef and lamb prices, driven by social distancing rules impacting on food demand from cafes and restaurants. Milk demand also reduced at a time when milk production was at a peak with cows grazing outside in the spring, which had a disproportionate effect on farmers. The sector was also affected by the travel restrictions impacting on the supply of seasonal workers. It is unclear how lasting these impacts could be. Going forward there will be uncertainties relating to the transition to the Environmental Land Management System (ELMs) of payment for public good. This and other policies put in place need to recognise the essential role of farmers as stewards of the UK's land while encouraging real change.
- The impact of COVID-19 has also focussed people's attention on essential needs, including food and the security of food supplies as well as the importance of green spaces and nature and access for people's physical and mental health. Research in 20 European countries found that the COVID-19 pandemic has led to a positive shift in public awareness of nature-related topics.[57] The Citizen's Assembly on Climate Change highlighted the role for a managed diversity of land that included peatland and forests. This, together with new research highlighting the biodiversity loss across the world and the importance of biodiversity in underpinning the many services that land and nature provides,[58] may strengthen public support for a recovery programme aimed at nature recovery and sustainability.

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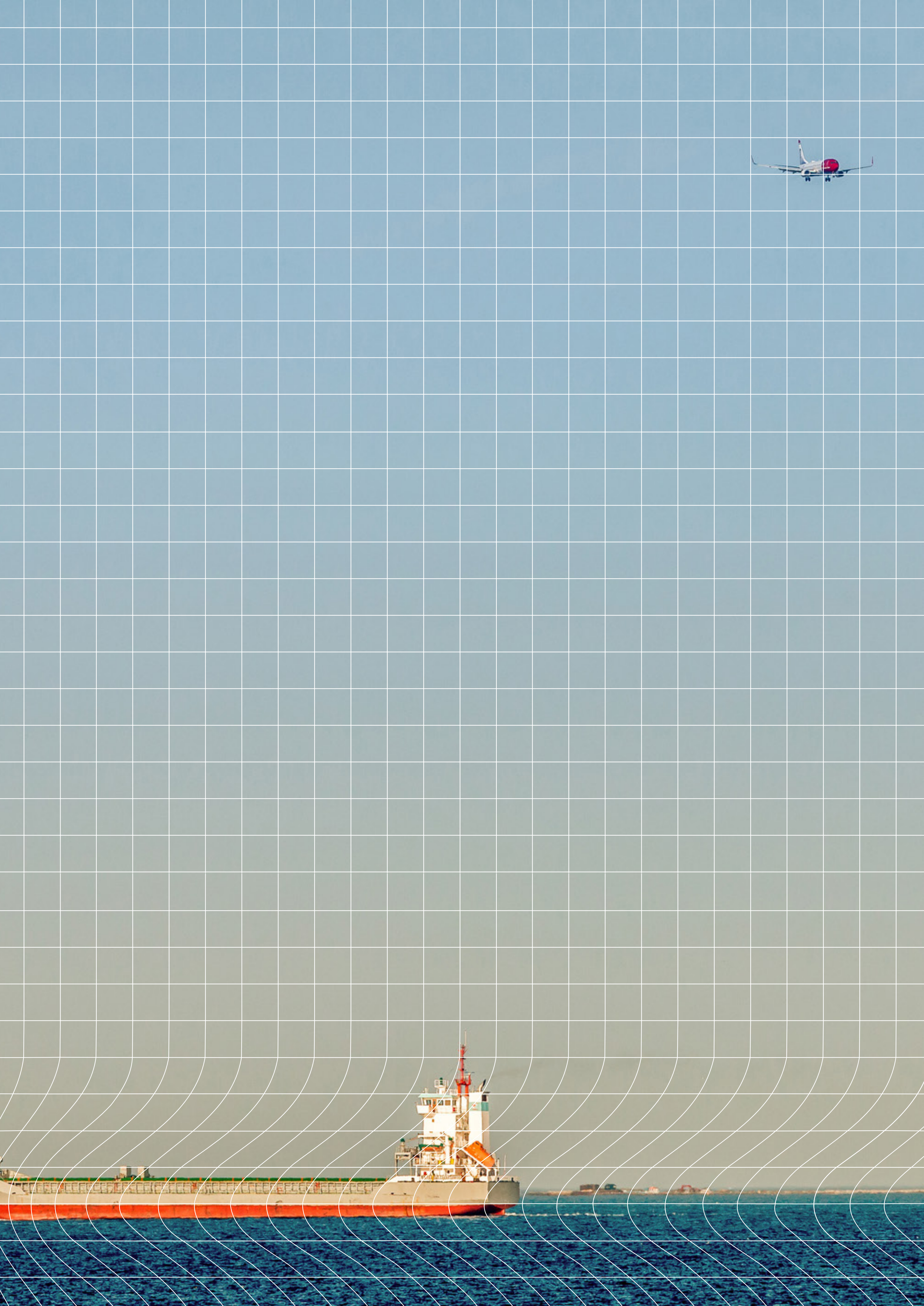
Chapter 8

Aviation



Introduction and key messages

This chapter sets out the method for the aviation sector's Sixth Carbon Budget pathways.

The scenario results of our costed pathways are set out in the accompanying *Advice report*. Policy implications are set out in the accompanying *Policy report*.

For ease, these sections covering pathways, method and policy advice for the aviation sector are collated in *The Sixth Carbon Budget – Aviation*. A full dataset including key charts is also available alongside this document.

The key messages from this chapter are:

- **Background**. Aviation emissions accounted for 7% of UK GHG emissions in 2018 and were 88% above 1990 levels. Emissions have been relatively flat from 2008-2018, with increasing international travel being offset by some improvements in efficiencies and by falling military and domestic aviation emissions. 2020 has likely seen a drop in GHG emissions of over 60% from 2019, due to the impact of COVID-19, with a return to pre-pandemic passenger levels not expected until 2024.[1]
- **Options for reducing emissions**. Mitigation options considered include demand management, improvements in aircraft efficiency (including use of hybrid electric aircraft), and use of sustainable aviation fuels (biofuels, biowaste to jet and synthetic jet fuels) to displace fossil jet fuel.
- **Analytical approach**. Our starting point for this analysis has been the 2019 *Net Zero* report, and the underlying DfT demand, efficiency and emissions modelling.

  We have adapted and updated this analysis to fit to a new set of demand scenarios (consistent with those considered by the Climate Assembly), before introducing significantly higher shares of sustainable aviation fuels than previously considered.

  This includes new evidence on the costs and emissions savings of sustainable aviation fuels, fitting with our Fuel Supply analysis, and the added capital costs of efficiency improvements.
- **Uncertainty**. We have used the scenario framework to test the impacts of uncertainties, to inform our balanced Net Zero Pathway. The key areas of uncertainty we test relate to sustainable aviation fuel supplies and costs of synthetic jet fuel, the mix of SAF options, the profile for expansion in passenger demand over time (with mid-term or no net expansion of airports), and whether there will be long-term structural change in the sector due to COVID-19. Out of all the CCC's sectors, Aviation has been most impacted by COVID-19, and continues to face the highest uncertainties about the future size of the sector.

We set out our analysis in the following sections:

1. Sector emissions
2. Options for reducing emissions
3. Approach to analysis for the Sixth Carbon Budget

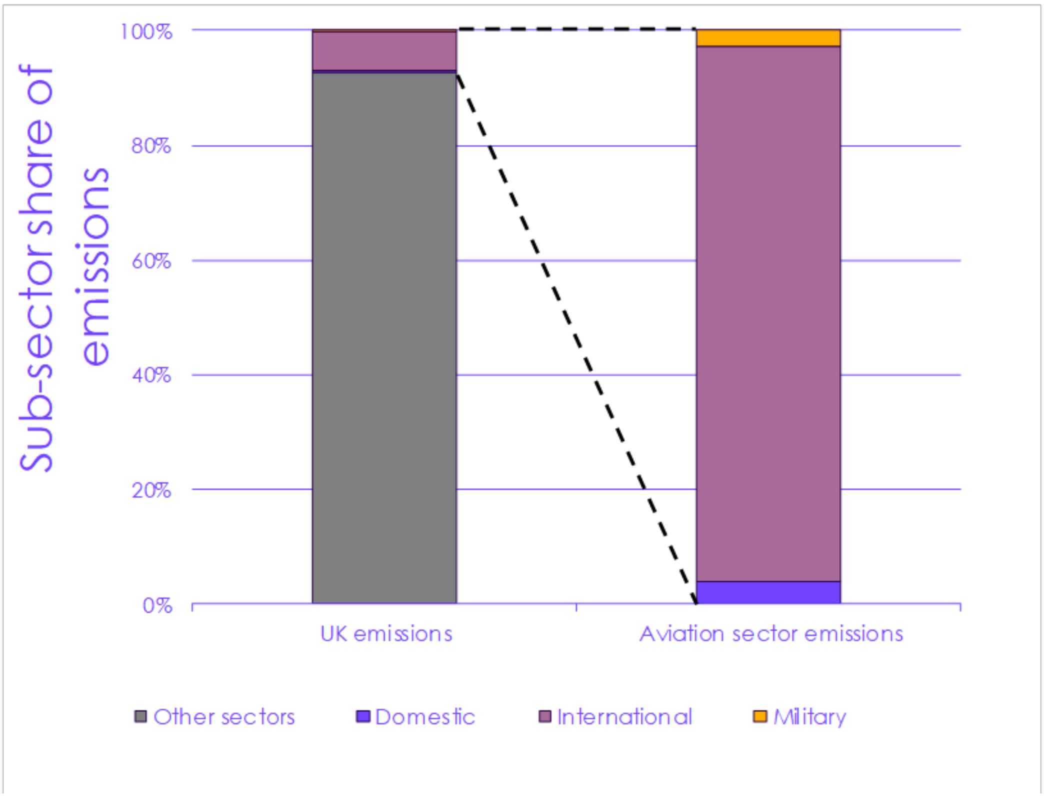
This section outlines the recent trends in aviation emissions and their sources. For more detail, see our 2020 Progress Report to Parliament.[2]

a) Breakdown of current emissions

Based on the most recent official UK emissions data, total UK aviation emissions increased by 0.8% from 2017 levels to 39.3 $MtCO_2e$/year in 2018. Within this, emissions from international flights increased by 1.1% to 36.7 $MtCO_2e$/year, emissions from domestic flights fell by 5.9% to 1.5 $MtCO_2e$/year, and emissions from military aviation fell 0.6% to 1.1 $MtCO_2e$/year. Aviation therefore comprised 7% of UK GHG emissions in 2018, and within this international aviation dominates at 93% of UK aviation emissions (Figure 8.1).

To be consistent with other sectors and the Climate Change Act framework, these GHG emissions do not include non-CO_2 impacts of aviation, which are discussed in Chapter 8, section 4 of the main *Advice Report*.

Figure 8.1 Breakdown of aviation sector emissions (2018)



Source: BEIS (2020) *Final UK greenhouse gas emissions national statistics 2018*.
Notes: Total UK emissions in 2018 were 539 $MtCO_2e$/yr (AR5 basis, peatland revisions and IAS included). UK aviation sector emissions in 2018 were 39.3 MtCO2e/yr.

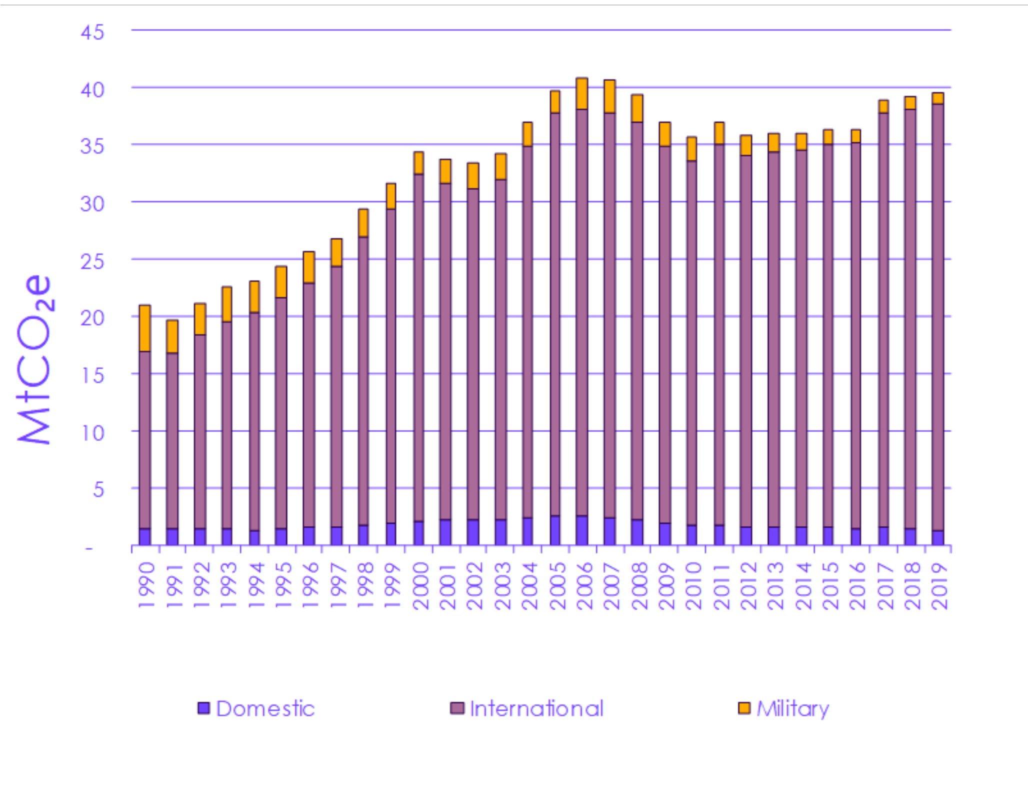
We have also estimated UK aviation emissions for 2019 at 39.6 $MtCO_2e$/year, a 0.9% increase on 2018 levels. This combines 11% falls in domestic and military emissions with a 1.7% increase in international aviation emissions.

However, given the COVID-19 pandemic and its impact on the aviation sector, and the need to reflect this in our analysis in the near-term, we have also estimated a fall in 2020 GHG emissions of over 60% from 2019 levels (and then a recovery to 2024), as detailed below in section 3(e). The emissions estimates from 2019 onwards will revised once official BEIS final GHG emissions data is published.

b) Emissions trends and drivers

The breakdown of aviation emissions since 1990 is shown in Figure 8.2. Overall, emissions from domestic and international aviation in 2018 were 124% above 1990 levels, and military aviation emissions have fallen 71% from 1990 levels.

Figure 8.2 Breakdown of aviation sector emissions (1990-2019)



Source: BEIS (2020) *Final UK greenhouse gas emissions national statistics 2018*; BEIS (2020) *Provisional UK greenhouse gas emissions national statistics 2019*; BEIS (2020) *Energy Trends*; CCC estimates for 2019.

Aviation emissions rose strongly throughout the 1990s and early-to-mid 2000s, due to increasing passenger demand, with only minor falls seen around 1990 and 2000 due to economic down-turns.

Emissions fell significantly during 2007-2010 due to the financial crisis, then stayed relatively flat in the early 2010s, but have been rising again in recent years.

UK aviation emissions in 2018 were therefore the same as in 2008, as falls in domestic and military aviation emissions have been balanced by a rise in UK international aviation emissions. Over the same 2008-2018 period, the total number of UK terminal passengers rose by 24% to reach 292 million in 2018, with a further 2% increase seen in 2019.

The increase in emissions has been more modest than growth in passengers due to increased plane loadings, decreases in average flight distance (due to faster growth in flights to the EU than other international destinations) and some improvements in fleet efficiency.

2. Options for reducing emissions

Several different emissions reduction options have been explored within the Aviation sector. These include:

- **Demand management**. A reduction in the annual number of passengers versus a counterfactual with unlimited passenger demand growth. Demand management policies could take several forms, either reducing passenger demand for flying through carbon pricing, a frequent flyer levy, fuel duty, VAT or reforms to Air Passenger Duty, and/or restricting the availability of flights through management of airport capacity. Our analysis only assumes a demand profile is achieved, and does not model the policies required to achieve these profiles.

- **Aircraft fleet-efficiency improvements**, achieved via a combination of airspace modernisation, operational optimisation, aircraft passenger loadings, aircraft design and new engine efficiency improvements, as well as introduction of hybrid electric aircraft (significant falls in jet use, but adding some use of electricity via on-board batteries and motors). Our analysis uses fleet fuel tCO_2/passenger values from DfT modelling, and does not model individual improvements from the list above.

- **Sustainable aviation fuels (SAF)**. These are "drop-in" replacements for fossil jet fuel, meeting international fuel specifications (and currently allowed to be blended at up to 50% by volume), and have nil accounting CO_2 emissions on combustion. SAF production routes considered include:

  - Biomass to Fischer-Tropsch (FT) biojet, with or without CCS;
  - Biogenic waste fats/oils to Hydroprocessed Esters and Fatty Acids (HEFA) biojet;
  - Biogenic fraction of waste* to Fischer-Tropsch (FT) biojet, with or without CCS; and
  - Synthetic jet fuel produced via Direct Air Capture (DAC) of CO_2 and low-carbon H_2.

  Our analysis uses these four SAF options to displace fossil jet fuel, and each SAF option has its own deployment and cost profile, based on the availability of the feedstocks, efficiencies, input energy, capital and operating costs. Each route is discussed in more detail in the Fuel Supply chapter.

* Note that the non-biogenic fraction of waste converted to FT jet will still have fossil accounting CO_2 emissions on combustion in aviation, and so is included within fossil jet fuel figures, not as SAF.

a) Summary of scenario choices

As a reminder from Chapter 3, section 7 of the *Advice Report*, the measures discussed in section 2 above are combined into the different scenarios as set out in Table 8.1.

Table 8.1
Aviation scenario composition

	Passenger demand growth by 2050 from 2018 levels	Average efficiency improvement 2018-2050 (%/year)	Use of biomass FT jet (TWh, % of liquid fuel demand in 2050)	Use of HEFA biojet (TWh, % of liquid fuel demand in 2050)	Use of bio-waste FT jet (TWh, % of liquid fuel demand in 2050)	Use of synthetic jet (TWh, % of liquid fuel demand in 2050)	Use of fossil jet (TWh, % of liquid fuel demand in 2050)
Balanced Net Zero Pathway	**+25%, with no net expansion**	**+1.4%**	**14 (11%)**	**8 (6%)**	**-**	**10 (8%)**	**94 (75%)**
Headwinds	+25%, with expansion	+1.4%	14 (11%)	11 (9%)	-	-	101 (80%)
Widespread Engagement	-15%, no expansion	+1.6%	14 (16%)	4 (4%)	5 (5%)	-	61 (74%)
Widespread Innovation	+50%, with expansion	+2.1%	23 (19%)	9 (7%)	-	30 (25%)	58 (49%)
Tailwinds	-15%, no expansion	+2.1%	23 (33%)	12 (18%)	-	30 (44%)	4 (5%)
Baseline	+64%, with expansion	+0.7%	-	-	-	-	205 (100%)

Our baseline is taken direct from DfT modelling, with high demand growth (64% growth in passenger number by 2050, from 2018 levels), low efficiency improvement (0.7%/year), no hybrid electric aircraft and no SAF deployment.

The exploratory scenarios use different mixes of the options set out in section 2 to reduce emissions below baseline emissions:

- **Headwinds** follows the approach in Net Zero 2019, with 25% passenger growth by 2050, 1.4%/year efficiency improvement (in-line with historical averages), and 14 TWh/year of biomass to FT jet. We have also added 11 TWh/year of HEFA biojet, as surface transport shifts to EVs, leaving waste fats/oils resources available to be converted into HEFA biojet instead of biodiesel.
- **Widespread Engagement** assumes a reduction in aviation demand of 15% from 2018 levels, based on the lowest of the Climate Assembly scenarios. This reflects a scenario in which people are willing to embrace greater changes to behaviour. Efficiencies are marginally higher than in Headwinds. Biomass to FT jet remains at the same level, whereas significantly lower livestock numbers and a phasing out of biofuel imports leads to lower HEFA biojet use. However, in this scenario, residual wastes are assumed to be increasingly diverted from energy-from-waste plants, with 70% of the UK's residual waste converted into 5 TWh/year of biojet (plus a similar fossil fraction) by 2050, thereby contributing an additional 5% of aviation fuel demand from waste biojet.

- **Widespread Innovation** assumes demand growth of 50% from 2018 levels, based on the highest demand amongst the preferred Climate Assembly scenarios. Efficiencies are much higher, based on the DfT scenario selected. More biomass is assumed to be diverted to FT biojet, along with HEFA biojet making up ~25% of supply, and the other 25% of the fuel mix is assumed to be made up of synthetic jet fuel. We did not increase the blending of synthetic jet fuel above 25% due to the high costs of synthetic jet fuel, and the high penetration of biomass to hydrogen in the Widespread Innovation scenario (where it would be more efficient to make biojet direct from the biomass, rather than via a hydrogen intermediary). However, the overall choices fit with the overall scenario design philosophy of maximal technical change.

- **Tailwinds** combines the most stretching of the scenarios above – a reduction in demand, high efficiency, and the maximal resource allocations for the biojet and synthetic jet fuel from the other scenarios. Waste to jet has not been included, as the remaining energy-from-waste (EfW) plants in our analysis all retrofit CCS before 2050, ensuring 95% capture of the fossil & biogenic carbon. However, putting the residual waste instead into new jet production plants with CCS would likely lead to a very similar outcome in terms of GHG emissions.*

Our scenario for the Balanced Net Zero Pathway takes elements from each of the above pathways:

- **Demand growth**: Our demand growth by 2050 matches Headwinds at 25%, although the passenger growth profile is more gradual due to an assumption of no net capacity expansion at UK airports in this scenario. This arises as a function of 2050 passenger numbers (365 million passengers) being within current UK airport capacities (at least 370 million passengers), and the need to ensure the UK achieves Net Zero by 2050 with aviation still one of the largest emitting sectors. We therefore do not assume a surge in emissions occurs in the early 2030s, as happens with the airport expansion modelled in the Headwinds and Widespread Innovation scenarios. Airport expansion could still occur under the Balanced Pathway, but would require capacity restrictions elsewhere in the UK (i.e. effectively a reallocation of airport capacity).

Box 8.1
Climate Assembly scenarios

The Climate Assembly debated five aviation scenarios, with changes in demand from 2018 to 2050 of -15%, +20%, +25%, +50% and +65%. Growth of 65% growth was highly unpopular - a majority wanted to see a 25-50% growth in flights, with the higher end of the range acceptable if technology was developed to mitigate the additional emissions. However, the weighted average of scenario Borda votes was +24% growth, and the report also noted that a majority voted for +25% growth or less. This gives added confidence that the required demand management to keep the Balanced Net Zero Pathway to only 25% growth by 2050 would be acceptable to the UK general public.

Source: Climate Assembly UK (2020); CCC analysis.

* This assumes that jet production is maximised and that other co-products (e.g. diesel, LPG) also still displace fossil fuels (increasingly difficult to 2050 as other sector counterfactuals decarbonise); and that EfW plants with CCS are displacing grid electricity with zero emissions by 2050 (rather than displacing fossil gas with CCS plants).

- **Efficiency**: The Balanced Net Zero Pathway takes the same efficiency assumptions as in the Headwinds scenario, in line with historical average improvement.

- **SAF**: Use of SAF matches Headwinds and Widespread Engagement for biomass to FT jet, and similar assumptions are taken on HEFA biojet (with slight differences due to waste fats/oils availability). Our Balanced Net Zero Pathway also assumes some synthetic jet fuels might be available in 2040s, at one third of the level deployed in the Widespread Innovation scenario, due to the higher costs of hydrogen and Direct Air Capture in the Balanced Net Zero Pathway compared to the Widespread Innovation scenario. Similar to the Tailwinds scenario, we have not allocated residual waste to jet fuel in this scenario.

The resulting GHG emissions in the Balanced Pathway grow during 2021-2023 with the return in passenger numbers post-COVID, before flat demand, efficiency measures and the start of SAF deployment lead to falls in emissions to the early 2030s. The more back-ended passenger growth in the Balanced Pathway (compared to Headwinds) has passenger numbers starting to grow from the mid-2030s, meaning that emissions continue to decline to 2040, as this later passenger growth is able to be accommodated by further improvements in efficiency and the continued uptake of SAF (compared to emissions increasing in Headwinds in the early 2030s with earlier passenger growth). The Balanced Pathway therefore only sees growth in passenger numbers towards 2050 once SAF is commercially proven and contributing at scale (in this scenario, there is 8% SAF used in 2035, increasing at slightly above 1 percentage point a year). From 2040, DfT modelling then introduces a new generation of aircraft (including the start of hybrid electric aircraft) that lead to further falls in emissions, with continued SAF uptake and passenger numbers continuing to increase to 2050.

Aviation measures reduce sector emissions to 23 $MtCO_2e$/year by 2050 in the Balanced Pathway, and all scenarios have positive emissions. The aviation sector will therefore require significant amounts of GHG removals to be developed to offset an increasing proportion of the sector's (declining) gross emissions to 2050, and aviation is therefore likely to be a key driving force behind the long-term deployment of engineered removals.

b) Sector classifications

Note that with our current sector classifications, some emissions reduction options have been counted outside of the CCC's Aviation sector, even if these emissions reductions are achieved via aviation policy and could count towards a separate Net Zero goal for the sector. For example:

- Sequestering biogenic CO_2 by installing CCS on UK biojet production facilities is counted within the CCC's engineered GHG removals sector, as a form of bioenergy with CCS (BECCS).

- Airlines paying for Direct Air Capture with CCS (DACCS) in the UK, in order to offset their remaining aviation gross emissions, is also counted within CCC's engineered GHG removals sector.

- Airlines paying for tree planting in the UK, in order to offset their remaining aviation gross emissions, is counted within CCC's Land Use, Land Use Change & Forestry (LULUCF) sinks sector.

These do not constitute recommendations on emissions accounting, merely what we have assumed for this analysis. These 'negative emissions' options are discussed in greater detail in the LULUCF and engineered GHG removals chapters.

This CCC sector classification also means that whilst some SAF fuels can be strongly carbon-negative on a lifecycle basis at the point of use (e.g. if there is upstream biogenic CCS involved in their production), our Aviation sector analysis only considers the direct accounting CO_2 emissions from the use of SAF in the sector, i.e. nil and not negative. If an alternative accounting methodology were followed, the negative emissions from upstream biogenic CCS could be counted within the Aviation sector emissions, but then these upstream negative emissions would have to be excluded from the GHG removals or LULUCF sinks sector to avoid double-counting. Overall, these discussions reflect emissions accounting classifications and do not affect aggregate UK emissions.

The residual aviation emissions in the Widespread Innovation scenario are used to calculate the Direct Air Capture with CCS requirement (14.5 $MtCO_2$/year) in both the Widespread Innovation scenario and the Tailwinds scenario. DACCS costs, energy inputs and deployment profiles are discussed in the GHG removals sector.

c) Analytical steps

The aviation analysis for the Sixth Carbon Budget advice consists of the following steps:

- **Coverage.**
  - Aviation is split into three sub-sectors: domestic, international and military.
  - Emissions cover CO_2, N_2O and CH_4.
  - Coverage is for UK, Scotland, Wales and Northern Ireland.
- **Abatement measures** are split into three types: demand, efficiency (including hybrids) and SAF.
  - Domestic and international passenger demand and fuel use trajectories to 2050 are sourced from DfT aviation modelling, thereby incorporating DfT efficiency assumptions.
  - Trajectory start points were adjusted for 2015-2019 actual NAEI[3] and CCA data[4], and estimated COVID-19 impacts in 2020-23 (discussed below), and trajectories then re-scaled to meet passenger growth targets for 2050 (discussed above).
  - The domestic share of DfT fuel use increases from 3.4% today to 3.9% by 2050. Military fuel use is derived separately from NAEI[3] and held fixed to 2050. Freight flights are included within DfT trajectories, so are implicitly assumed to scale with CCC passenger profiles.
  - SAF deployments from the CCC's Fuel Supply sector modelling are used to calculate residual fossil jet demands, with the same SAF % blend assumed to be used in each sub-sector (including in military aviation).
  - Direct accounting CO_2, CH_4 and N_2O emissions are calculated based on fuel use, then split into sub-sectors and DAs (discussed below).

- Energy inflows to the sector (SAF = bioenergy, non-bio waste and hydrogen derived fuels, fossil jet and electricity from hybrid planes) are split into sub-sectors and DAs. It is assumed that 50% of the hybrid aircraft electricity use is in the domestic sub-sector.

- **Costs.**

    - Re-scaled DfT departing seat-km data is used to calculate operating cost savings from efficiency measures and increased annualised aircraft capital costs (which are de-annualised to in-year investments), based on ATA data which assumes a 20 year economic lifetime, 10% residual value and a 4.5% interest rate[5]. No cost data was available for the military aviation sub-sector. Marginal added costs of SAF above fossil jet are also calculated for all sub-sectors.

    - Costs are then split into sub-sectors and DAs to calculate £/tCO_2e abated by each measure, using CCC's 3.5% social discount rate.

Further assumptions used in the analysis include:

- In 2018, 99.91% of fuel used in the UK aviation sector was aviation turbine fuel (avtur or jet), and 0.09% of fuel used was aviation spirit (avgas). CCC have used the term "jet" or "jet fuel" to include all the fuel used in UK aviation. Our analysis uses the 2018 weighted average of avtur and avgas, with constant fuel density, calorific value and carbon content values from Defra.[6]

- NAEI factors are also applied to scale combustion CO_2 to combustion CH_4 (with separate factors for domestic, international and military sub-sectors), and a constant factor to scale combustion CO_2 to combustion N_2O (applied for all sub-sectors).[7] SAF fuels are assumed to continue to have the same combustion CH_4 and N_2O emissions per kWh as fossil jet (only their accounting CO_2 emissions are reduced).

- Jet fuel costs are not part of the BEIS/HMT Green Book Long-run variable costs of energy supply (LRVCs) dataset. However, based off IATA[8], financial market and refining datasets, the jet crack ($/bbl) above crude oil price is historically very similar to the diesel crack ($/bbl). The Green Book diesel LRVCs (p/litre) were therefore used and converted into p/kWh values for fossil jet fuel.

d) Devolved administrations

The 2018 share of emissions from the NAEI is used to apportion UK emissions to emissions at devolved administration (DA) level. Separate splits are used for domestic, international and military aviation:

- Domestic: 32.8% Scotland, 0.80% Wales, 13.1% NI, 53.2% England

- International: 4.3% Scotland, 0.29% Wales, 0.55% NI, 94.9% England

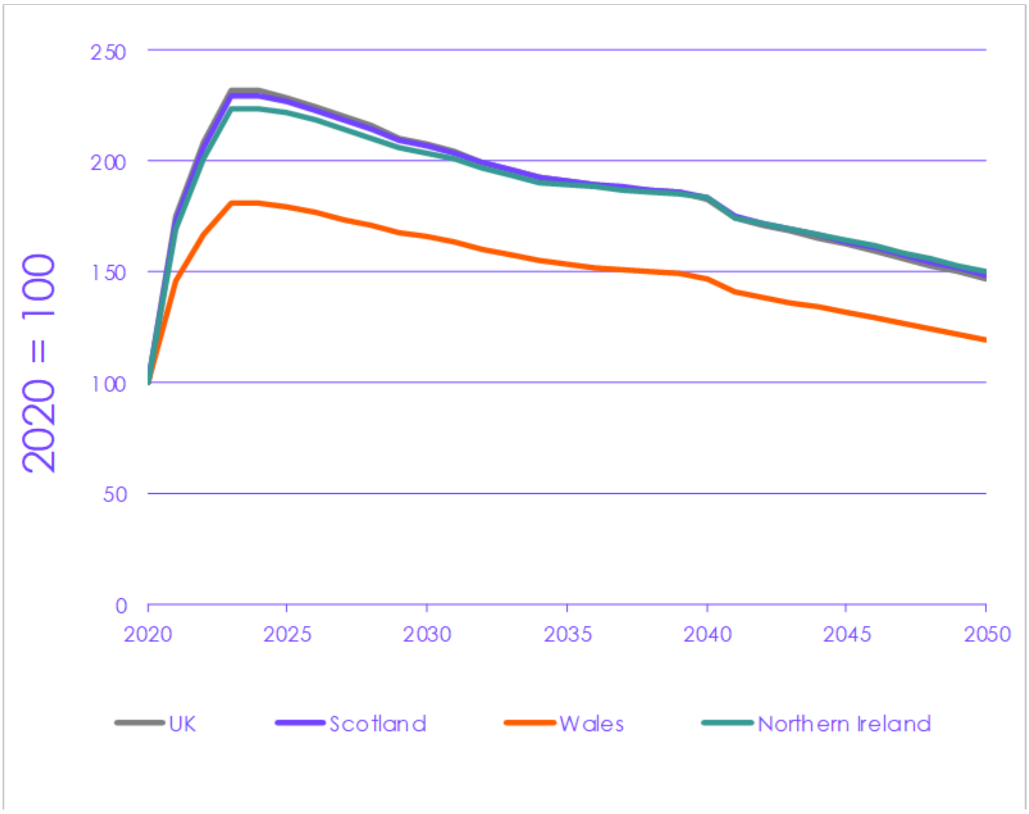
- Military: 7.4% Scotland, 3.4% Wales, 2.2% NI, 86.9% England

These DA splits are held fixed over time in all scenarios, except for in the Baseline, Headwinds and Widespread Innovation scenarios, where expansion in London airports from 2030 to 2033 is assumed (delayed from DfT modelling which assumes this happens from 2026):

- This expansion leads to domestic DA splits reaching 28.7% Scotland, 0.73% Wales, 10.9% NI, 59.7% England by 2033, before a linear return to 2018 DA splits is assumed by 2050.
- International DA splits reach 3.8% Scotland, 0.27% Wales, 0.48% NI, 95.4% England by 2033, before a linear return to 2018 DA splits is assumed by 2050.
- No change assumed in military aviation DA splits.

As show in Figure 8.3, Welsh aviation emissions to not rebound post-COVID as much as other DAs relative to the 2020 base year, due to the outsized influence of military aviation emissions in Wales, where fuel use has been assumed to be held flat from 2019. Scotland and NI have much smaller military sub-sectors relative to their combined domestic and international emissions, and so their emissions profile matches the UK profile with the COVID-19 recovery.

Figure 8.3 Comparison of emission pathways for the UK, Scotland, Wales, Northern Ireland



Source: CCC analysis.
Notes: Aviation sector GHG emissions for the Balanced Net Zero Pathway, split into DAs, and re-based from 2020 levels (which is at the bottom of the COVID-19 dip, hence strong growth in the following years).

e) Uncertainties

Given aviation will be one of the largest-emitting sectors in 2050 (23 $MtCO_2e$/year in the Balanced Pathway), the following uncertainties could change UK emissions in 2050 by many $MtCO_2e$/year and impact Net Zero:

- **COVID-19**. Out of all the sectors, aviation has been most impacted by COVID-19, and continues to be severely impacted. There remain major uncertainties as to the size of the aviation industry that will emerge post-COVID, particularly as the pandemic continues to spread globally and many countries return to forms of stricter lockdowns in late 2020. CCC have estimated a drop in UK flights and emissions during 2020-2023 as shown in Table 8.2, with a return to previously projected to demand levels from 2024 in most scenarios.
  - Data for 2020 is based on CAA flight data to date, and OAG scheduling trackers showing UK flights in mid-October at ~30% of last year's levels. We have then assumed flat demand over winter 2020/21, before increases from 2021. Values chosen for 2021-23 are estimates, but align with IATA forecasts for a recovery by 2024, i.e. a return to the chosen pathways from 2024 onwards.
  - In the Widespread Engagement and Tailwinds scenarios we assume a structural shift in demand due to behaviour change (e.g. due to video-conferencing) and have estimated this potential impact via halving business travel (which previously comprised 20% of UK passengers) by 2024. These two pathways ultimately end up at a 15% fall in passenger numbers from 2018 levels by 2050, but most of the change in demand is assumed to happen over the next 4 years.
  - The pandemic may result in a near-term marginal improvement in fleet efficiency, due to earlier retirement of older aircraft (e.g. Boeing 747s), although lower passenger loadings could offset this on a tCO_2/passenger basis, and so has not been modelled. Lower demand could also decrease or delay purchases of newer, more efficient aircraft.

Table 8.2
Aviation COVID-19 impacts, as a % of expected pathway emissions

	2019	2020	2021	2022	2023	2024+	Notes
Headwinds	100%	39%	70%	85%	95%	100%	Recovers to expected pathway
Widespread Engagement	100%	39%	67%	76%	86%	90%	Half of business customers do not return
Widespread Innovation	100%	39%	70%	85%	95%	100%	Recovers to expected pathway
Balanced Net Zero Pathway	100%	39%	70%	85%	95%	100%	Recovers to expected pathway
Tailwinds	100%	39%	67%	76%	86%	90%	Half of business customers do not return
Baseline	100%	39%	70%	85%	95%	100%	Recovers to expected pathway

- **GDP/economic outlook.** We have not attempted to calculate a long-term reduction in aviation demand due to structural changes to the economy or long-term level of GDP due to COVID-19 (flights have historically correlated to GDP). We have also not considered any reductions in supply via e.g. failures of airports, airlines or engine manufacturers. Lower long-term fossil jet fuel prices and slowed aircraft sales and development cycles could lead to smaller efficiency gains than previously projected, although this has also not been modelled.
- **Efficiency** measures are expected to be cost saving in all scenarios, and under a range of fossil fuel costs and passenger demands. However, costs have not been modelled by DfT, and the DfT model is not an aircraft stock/sale model.

  We have therefore had to infer added investment costs in each year from representative ATA aircraft Class data, applied to DfT seat-km/year outputs, and de-annualising using annual changes. There are therefore some years with particularly large or small (or even very occasionally negative*) capital costs, due to the limitations of the datasets.
- **Future aircraft**.
  - The uptake of electric hybrid aircraft in the DfT modelling is relatively modest (around 9% of aircraft kilometres by 2050, consuming 6-7% of jet fuel). The DfT model assumes that full electric planes will not be commercialised by 2050, and it does not have a role for hydrogen turbine or hydrogen fuel cell planes by 2050 either. There could be break-throughs in these aircraft options, although the time taken to design, build, test, scale-up, certify and manufacture new aircraft propulsion systems (and the new aircraft bodies to accommodate them and their energy stores on-board) is significant – at least several decades.
  - Even if one of these options were commercialised in the 2040s, it would be challenging to immediately achieve a large % share of aircraft sales, and given the 20-30 year lifetimes of aircraft, this will not lead to a significant fleet penetration by 2050. These full electric or hydrogen options have energy storage limitations, and would be most suited for domestic or short-haul flights and/or smaller airplane classes, which make up a relatively small share of UK aviation emissions.
  - Combined, these range, aircraft class and development timings mean that 2050 penetrations of these options are likely to be limited, or they could occupy small niches by 2050 – although neither is likely to significantly improve the overall UK emissions profile. Long-haul flights dominate UK aviation emissions and are likely to stay using a hydrocarbon fuel until 2050 or beyond, hence the need for SAF.

* A negative capital cost is possible, and would indicate a net sale of assets in the year. This only occurs where there is a particularly large divergence in demand from the Baseline scenario, at which point the sector may down-size.

- **SAF** is expected to be an added marginal cost, and this marginal cost will depend heavily on the counterfactual fossil jet cost, the cost of feedstocks (especially for synthetic fuels using hydrogen and DAC CO_2), and the future improvement in processing plant costs (including the addition of CCS to FT routes which will significantly increase fuel GHG savings). Our scenarios explore different hydrogen and DAC costs, but hold costs of biomass, waste and waste fats/oils fixed over time (prices may well rise over time, but CCC analysis is only focused on resource costs). Processing costs are assumed to fall over time (as they are largely determined by global progress in SAF scale-up), and do not vary between scenarios. However, the earliest, high-risk projects, or smaller UK projects, or projects further from feedstocks or CO_2 sequestration sites, might be significantly more expensive than modelled. SAF costs are therefore have some level of uncertainty.
- **Impact of demand policies.** Although we have assessed how much efficiency and SAF costs would subtract/add to an indicative trans-Atlantic ticket price, our analysis is only taking the outputs of DfT modelling, and we do not have the ability to feed the specific decarbonisation costs back in to the demand framework to calculate the impact on passenger demand. This limitation also applies to demand management policies – DfT modelling internally assumes a rising carbon price, which reduces demand from an original counterfactual scenario, but CCC again only take the outputs after this internal carbon pricing is applied to demand. The particular policies that might be utilised to manage demand could have different impacts on ticket prices (e.g. carbon pricing, frequent flier levy, VAT, fuel duty, APD reform, airport capacity management). CCC analysis has focused on the outcomes (demand, fuel and emissions), rather than prescribing or modelling the policy method for achieving the demand levels required.
- **Measure interdependencies**. Theoretically, any combination of the mitigation measures discussed in section 2 would be possible, as they separately impact demand, fuel use and fuel accounting emissions. However, scenarios that rely on high amounts of technical change or new expensive fuels will likely either require a profitable sector to fund this RD&D, customers being willing to pay more, and/or more government intervention (regulation or support). Scenarios with negative growth, if repeated globally, are likely to result in a slower uptake of new, more efficient aircraft, and less investment in SAF due to depressed fossil fuel prices. Delivery of the Tailwinds scenario would therefore be particularly challenging – a reduction in demand from 2018 levels, with maximal efficiency and 95% SAF by 2050.
- **Non-CO_2 impacts.** These impacts are discussed in Chapter 8, section 4 of the Advice Report. There remain significant uncertainties in the science and mitigation options, and therefore uncertainties regarding the policy response and any interactions with sector GHG emissions (e.g. re-routing aircraft around super-saturated atmospheric zones to avoid cirrus cloud formation could increase GHG emissions).

Endnotes

[1] IATA (2020) *Recovery Delayed as International Travel Remains Locked Down*

[2] CCC (2020) *2020 Progress Report to Parliament*

[3] National Atmospheric Emissions Inventory (2020) *UK Greenhouse Gas Inventory, 1990 to 2018: Annual Report for submission under the Framework Convention on Climate Change*

[4] Civil Aviation Authority (2020) Airport data 2019

[5] ATA & Ellondee (2018) *Understanding the potential and costs for reducing UK aviation emissions*

[6] Defra (2020) *Greenhouse gas reporting: conversion factors 2020*

[7] All the analysis is conducted on an IPCC AR5 basis with carbon feedbacks, using 34 tCO_2e/tCH_4 and 298 tCO_2e/tN_2O.

[8] IATA (2020) *Jet Fuel Price Monitor*

Chapter 9

Shipping

Introduction and key messages

This chapter sets out the method for the shipping sector's Sixth Carbon Budget pathways.

The scenario results of our costed pathways are set out in the accompanying *Advice report*. Policy implications are set out in the accompanying *Policy report*.

For ease, these sections covering pathways, method and policy advice for the shipping sector are collated in *The Sixth Carbon Budget – Shipping*. A full dataset including key charts is also available alongside this document.

The key messages from this chapter are:

- **Background**. Shipping emissions accounted for 3% of UK GHG emissions in 2018 and were 21% below 1990 levels. Emissions have been on a slow downward trend over the past two decades, with the past decade seeing reductions in domestic journeys around the UK coast and in international export shipping, plus falls in naval shipping. 2020 has seen a drop in GHG emissions, due to the impact of COVID-19, with a return to pre-pandemic levels expected in 2022.
- **Options for reducing emissions**. Mitigation options considered include improvements in vessel efficiency (including electricity), and use of zero-carbon fuels (principally ammonia made from low-carbon hydrogen) to displace fossil marine fuels.
- **Analytical approach**. Our analysis relies on UMAS shipping modelling of energy, emissions and costs for the DfT Clean Maritime Plan.[1] We have adapted this analysis for UK bunker fuels sales (instead of an activity basis) and introduced ammonia costs consistent with the new evidence from our Fuel Supply analysis.
- **Uncertainty**. We have used the scenario framework to test the impacts of uncertainties, to inform our balanced Net Zero Pathway. The key areas of uncertainty we test relate to ammonia costs, and deployment timings. Shipping has been impacted by COVID-19, and continues to face uncertainties about the future size of the sector.

We set out our analysis in the following sections:

1. Sector emissions
2. Options for reducing emissions
3. Approach to analysis for the Sixth Carbon Budget

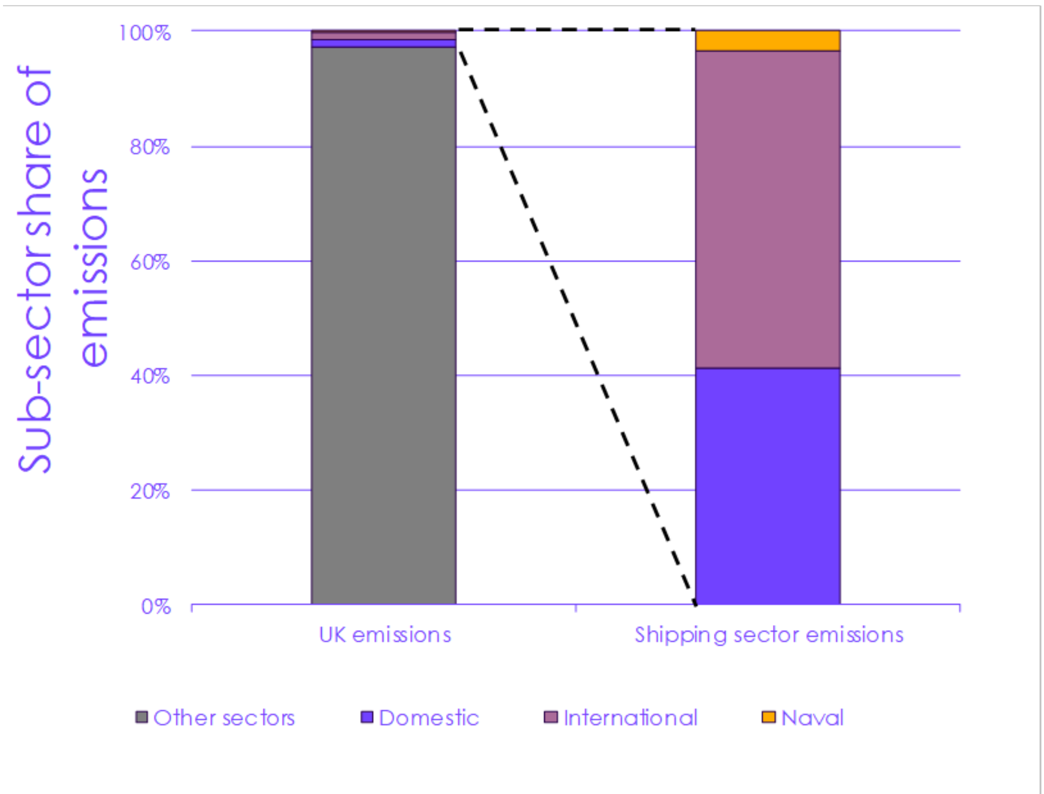
This section outlines the recent trends in shipping emissions and their sources. For more detail, see our 2020 Progress Report to Parliament.[2]

a) Breakdown of current emissions

Based on the most recent year of official UK emissions data, total UK shipping emissions increased by 0.2% from 2017 to 14.3 $MtCO_2e$/year in 2018. Emissions from international journeys fell by 0.2% to 7.9 $MtCO_2e$/year, emissions from domestic journeys increased by 0.2% to 5.9 $MtCO_2e$/year, and emissions from naval shipping increased 6% to 0.5 $MtCO_2e$/year (Figure 9.1).

Shipping therefore comprised 3% of UK GHG emissions in 2018, and within this international shipping (as measured on a bunker fuel basis) has a majority share of emissions.

Figure 9.1 Breakdown of shipping sector emissions (2018)



Source: BEIS (2020) *Final UK greenhouse gas emissions national statistics 2018.*
Notes: Total UK emissions in 2018 were 539 $MtCO_2e$/yr (AR5 basis, peatland revisions and IAS included). UK shipping emissions in 2018 were 14.3 $MtCO_2e$/yr.

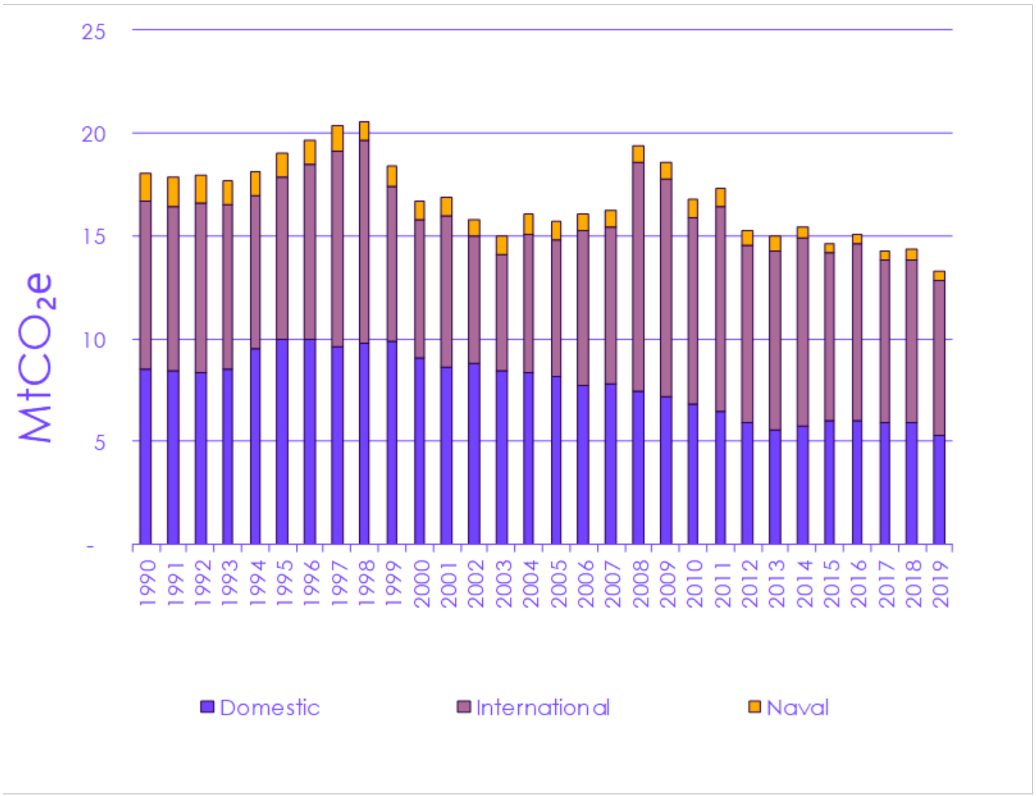
We have also estimated UK shipping emissions for 2019 at 14.3 $MtCO_2e$/year, a 7% decrease from 2018 levels. This is distributed as a 10% fall in domestic shipping emissions, a 5% fall in international shipping emissions and an 11% fall in naval shipping emissions.

However, given the COVID-19 pandemic and its impact on the shipping sector, and the need to reflect this in our analysis in the near-term, we have also estimated a fall of around 21% in 2020 GHG emissions from 2019 levels (and then a recovery to 2022), as detailed below in section 3(e). The emissions estimates from 2019 onwards will revised once official BEIS final GHG emissions data is published.

b) Emissions trends and drivers

The breakdown of shipping emissions since 1990 is shown in Figure 9.2. Overall, emissions from domestic and international shipping in 2018 were 17% lower than 1990 levels, whereas naval shipping emissions have fallen 65% from 1990 levels.

Figure 9.2 Breakdown of shipping sector emissions (1990-2019)



Source: BEIS (2020) *Final UK greenhouse gas emissions national statistics 2018*; BEIS (2020) *Provisional UK greenhouse gas emissions national statistics 2019*; BEIS (2020) *Energy trends*; CCC estimates for 2019.

Shipping emissions have generally followed a downward trend from 1990. Domestic shipping emissions increased in the 1990s, before falling from 2000 onwards. Naval emissions have fallen steadily since 1990. International shipping emissions have been more variable, with peaks in the late 1990s and late 2000s.

More recently, shipping has seen a decrease in emissions of 26% over the period 2008-2018, with a sharp fall occurring after the global financial crisis, and more modest reductions in recent years. Shipping sector emissions are determined by UK maritime fuel bunker sales, which have fallen over the period mostly due to reductions in domestic journeys around the UK coast and in international export shipping.

In terms of overall freight tonnages, dry and liquid bulk have seen significant falls (in particular, less coal and crude oil carried by ship), although container and roll-on/roll-off freight has increased.

Demand for shipping is primarily driven by freight tonnages, as a result of economic growth and import/export dependencies, plus other offshore activities such as fishing, ferries, cruises etc. International fuel bunker sales (the basis for international shipping emissions) are also not just dependent on activity levels, given the ability of many international vessels to choose where they refuel, and are also determined by relative fuel prices in the UK vs abroad.

Three main emissions reduction options have been explored within the domestic and international shipping sub-sectors. These include:

- **Fleet efficiency improvements**. Achieved via a combination of slow steaming, operational optimisation, ship hull design and new engine efficiency improvements, onboard renewable power generation (e.g. solar) and wind propulsion systems. Our analysis uses fleet fuel tCO_2/MWh values from UMAS[1] modelling for DfT and does not model individual improvements from the list above.

- **Electrification**. Electricity is used in a limited number of niche hybrid & full electric propulsion vessels (using onboard batteries and motors), and more widely used to provide shore power/' cold ironing' (ships temporally connecting to grid electricity to power onboard systems when docked in port).

- **Zero-carbon fuels**. These fuels displace fossil marine fuels, typically requiring either engine retrofits or new propulsion and energy storage systems, and have zero accounting CO_2 emissions on combustion. In our scenarios, this is assumed to be ammonia, produced from low-carbon hydrogen and air separation.

- This preference for ammonia in UMAS modelling is due to the potential to retrofit ship engines at relatively low cost, the higher energy density of ammonia compared to hydrogen (and therefore a much lower commercial penalty due to smaller fuel tanks onboard taking up less space), and the lower cost of ammonia production compared to methanol[*] (which has to be made from Direct Air Capture of CO_2 and low-carbon hydrogen to achieve the same emissions intensity). Discussion of the uncertainties associated with the choice of ammonia is provided in section 3(d) below.

- Biofuel routes were excluded, as long-term, our analysis of the best-use of bioenergy (Chapter 6) shows that use of biofuels in shipping achieves lower GHG savings compared to uses in other sectors. Transitioning shipping to a carbon-free fuel such as ammonia, rather than a biofuel that releases CO_2 on combustion, allows finite bioenergy resources to be used in other applications that sequester the biogenic carbon, leading to lower overall UK emissions. UMAS modelling also indicates that biofuel availability and use in shipping is likely to delay the transition to zero-carbon ammonia. Further discussion is provided in section 3(d) below.

Our analysis uses zero-carbon ammonia to displace a fossil fuel mix of heavy fuel oil (HFO), liquified natural gas (LNG), low-sulphur fuel oil (LSFO) and marine diesel oil (MDO). The ammonia production route is discussed in more detail in the Fuel Supply methodology (Chapter 6).

- Our analysis has not assumed differences in economic growth or shipping demands between the scenarios – a common underpinning shipping demand trajectory to 2050 is used in the UMAS modelling. There may be some changes in export/import dependencies between scenarios, e.g. tonnages of fossil fuels imported, but these have not been modelled.

[*] Methanol is deployed in UMAS modelling, but at well below 2% of total fuel use in 2050, so for analytical simplicity we have merged the UMAS methanol results with the ammonia results in presenting our zero-carbon fuel abatement.

No decarbonisation measures have been modelled in the naval sub-sector – naval shipping was not included in the UMAS modelling, and there was insufficient evidence available as to whether zero-carbon ammonia or alternatives would be suitable for naval shipping operational requirements.

a) Summary of scenario choices

As discussed in Chapter 3, section 8 of the *Advice Report*, the measures above were used in UMAS modelling for DfT's Clean Maritime Plan. We have chosen specific scenarios from the UMAS work to match the Sixth Carbon Budget scenario framework, based on different timings and speeds of zero-carbon fuel deployment, as set out in Table 9.1.

Table 9.1
Shipping scenario choices

	UMAS scenario	Use of zero-carbon fuels (TWh, % of fuel demand in 2035)	Use of electricity (TWh, % of fuel demand in 2035)	Use of fossil marine fuels (TWh, % of liquid fuel demand in 2035)	Use of zero-carbon fuels (TWh, % of fuel demand in 2050)	Use of electricity (TWh, % of fuel demand in 2050)	Use of fossil marine fuels (TWh, % of liquid fuel demand in 2050)
Balanced Net Zero Pathway	**D**	**22 (34%)**	**1 (2%)**	**42 (65%)**	**70 (91%)**	**3 (4%)**	**4 (5%)**
Headwinds	D	22 (34%)	1 (2%)	42 (65%)	70 (91%)	3 (4%)	4 (5%)
Widespread Engagement	B	0.9 (1%)	0.6 (1%)	64 (98%)	70 (91%)	3 (4%)	4 (5%)
Widespread Innovation	C	38 (58%)	2 (3%)	26 (40%)	70 (92%)	3 (4%)	3 (4%)
Tailwinds	C	38 (58%)	2 (3%)	26 (40%)	70 (92%)	3 (4%)	3 (4%)
Baseline	A	0 (0%)	0.1 (0.1%)	68 (99.9%)	0 (0%)	0.2 (0.2%)	84 (99.8%)

Our baseline is taken direct from UMAS modelling (Scenario A), which has modest efficiency improvements, extremely limited electrification and no use of zero-carbon fuels. This scenario uses increasing amounts of heavy fuel oil over time, particularly in domestic shipping (use of low sulphur fuel oil and marine diesel oil is more static). This results in average fossil fuel costs in the baseline increasing to 2030 (in line with BEIS/HMT Green Book assumptions about rising oil prices). Fossil fuel costs then decline to 2050, which increases £/tCO_2e abatement values for the other scenarios. Under the exploratory scenarios, we vary the timing and cost of the transition to use of ammonia as a fuel:

- **Headwinds** uses the same approach as in Net Zero 2019, following UMAS Scenario D, whereby improvements in efficiency and small amounts of shore power and electric propulsion are accompanied by large amounts of zero-carbon ammonia (70 TWh/year by 2050). This transition starts in 2030, mainly focused on domestic shipping in the 2030s, with the majority of international shipping transitioning to ammonia in the 2040s.

- **Widespread Engagement** has the highest-cost hydrogen, and therefore highest-cost ammonia, and so is assumed to have a delayed pathway (UMAS Scenario B), reaching the same level of sector emissions and energy use as in UMAS Scenario D by 2050. This pathway leaves it until the 2040s before implementing a sector-wide roll-out of ammonia, along with some electrification.

- **Widespread Innovation** assumes particularly low-cost hydrogen and ammonia, and so progress in shipping decarbonisation is assumed to be more rapid, following UMAS Scenario C. Full sector decarbonisation is broadly achieved by 2040, having started in 2030.

- Our **Tailwinds** scenario matches the Widespread Innovation scenario (UMAS Scenario C), as the fastest feasible pathway to sector decarbonisation, given the need to scale-up low-carbon hydrogen for ammonia production.

Our **Balanced Net Zero Pathway** takes the middle ground, in terms of a phased roll-out of ammonia over 20 years from 2030 as in the Headwinds scenario (UMAS Scenario D), to achieve sector decarbonisation by 2050.

It is expected that the Shipping sector can achieve very close to full decarbonisation in all scenarios by 2050. All scenarios have only very small residual emissions (<1 $MtCO_2e$/year) from a very limited use of fossil fuels in 2050, and around half of these residual emissions are in naval shipping, due to no decarbonisation options being modelled in this sub-sector.

b) Analytical steps

The analysis for the sixth Carbon Budget advice consists of the following steps:

- **Coverage.**
  - Shipping is split into three sub-sectors: domestic, international and naval.
  - Emissions cover CO_2, N_2O and CH_4.
  - Coverage is for UK, Scotland, Wales and Northern Ireland.
- **Abatement measures** are split into two groupings: efficiency (including electrification) and zero-carbon fuels.
  - Domestic and international fuel use trajectories to 2050 are sourced directly from UMAS modelling for DfT.[1] Methanol use values (very small) are merged with ammonia use values (very large) to create a zero-carbon fuels grouping.
  - Trajectory start points were adjusted for 2016-2019 actual NAEI[3] data, and estimated COVID-19 impacts in 2020-21 (discussed below in section 3(d)).
  - International fuel use is scaled down to a bunker fuel basis from UMAS activity basis by applying a multiplier of 0.51 (derived from 2019 data). Naval fuel use is derived separately from NAEI[3] and held fixed to 2050.
  - Emission savings due to energy efficiency are calculated using the baseline emissions minus the emissions achieved if applying the baseline average fuel carbon intensity to the scenario fuel use. Emissions savings due to zero-carbon fuels are therefore the residual savings between the scenario and baseline emissions.
  - Direct CO_2, CH_4 and N_2O emissions are calculated based on fuel use, then split into sub-sectors and by devolved administration (DA). DA splits are discussed below in section 3(c).
  - Energy inflows to the sector (as hydrogen-derived fuels, electricity and fossil fuels) are split into sub-sectors and DAs.
- **Costs.**
  - UMAS model results were used for operating cost and non-fuel cost changes from efficiency and increased capital costs (de-annualised to in-year investment where required, based off UMAS 10% interest rate and CCC's assumption of a 15 year lifetime, given UMAS model lifetimes varies between 0-30 years depending on the measure and remaining ship life).
  - Marginal added costs of zero-carbon fuels were also calculated for domestic and international sub-sectors. Costs were then split into sub-sectors and DAs to calculate £/tCO_2e abated by each measure, using CCC's 3.5% social discount rate. No cost data were available for the naval sub-sector.

Further assumptions used in the analysis include:

- Constant fuel properties over time are assumed for fuel density, calorific values and combustion emission values (CO_2, N_2O and CH_4).[4] Values are taken directly from UMAS modelling – these values are similar to, although very slightly lower than, Defra[5] conversion factors.
- Heavy fuel oil, low sulphur fuel oil and marine diesel costs were not given in the BEIS/HMT Green Book Long-run variable costs of energy supply (LRVCs) dataset. However, based off UMAS data,[6] the cost discount for heavy fuel oil compared to marine diesel oil is 40%, and the cost discount for low sulphur heavy fuel oil compared to marine diesel oil is 32%. Marine diesel oil has been assumed to be equal in cost to diesel in the Green Book dataset, with heavy fuel oil and low sulphur fuel oil costs aligned to the Green Book projections.

c) Devolved administrations

The 2018 share of emissions from the NAEI is used to apportion UK emissions to the level of the devolved administrations (DAs). Splits to DA level are held fixed over time, with different splits used for domestic, international and naval shipping:

- Domestic: 33.8% Scotland, 4.9% Wales, 3.7% NI, 57.7% England
- International: 4.3% Scotland, 4.6% Wales, 2.3% NI, 88.8% England
- Naval: 7.4% Scotland, 3.4% Wales, 2.2% NI, 86.9% England

Shipping emissions grow similarly at DA level over 2021-2022 with the return in freight tonnages and passenger numbers post-COVID, and demand continues to grow faster than efficiency improvements until 2030 (Figure 9.3). Domestic shipping then transitions to ammonia mostly in the 2030s and early 2040s, and international shipping mostly in the 2040s, which leads to almost full sector decarbonisation by the late 2040s.

Scotland decarbonises slightly faster than the UK and other DAs, due to Scotland having a larger share of domestic shipping emissions, and domestic shipping decarbonising earlier than international shipping in the Balanced Pathway.

Figure 9.3 Comparison of emissions pathways for the UK, Scotland, Wales and Northern Ireland

Source: CCC analysis.
Notes: Shipping sector GHG emissions for the Balanced Net Zero Pathway, split into DAs, and re-based from 2020 levels (at the bottom of the COVID-19 dip).

d) Uncertainties

Given shipping is one of the smaller sectors (3% of current emissions) and is expected to have decarbonised by 2050 (0.9 $MtCO_2e$/year in the Balanced Pathway), the following uncertainties may cause some changes in UK emissions in the near to mid-term. However, these uncertainties will have a decreasing impact by 2050 as the sector decarbonises, and so their impact on Net Zero is limited:

- **COVID-19**. Although not as badly impacted as Aviation, has been significantly impacted by COVID-19, and continues to be impacted. Based on WTO forecasts[7] and BEIS Energy Trends[8] data for Q1 & Q2 2020, we have estimated a drop in shipping demand and emissions during 2020, a substantial improvement in 2021, with a return to modelled UMAS pathways from 2022 (Table 9.2). However, there remain uncertainties as to the size of the shipping industry that will emerge post-COVID.

Table 9.2
Shipping COVID-19 impacts, as a % of expected pathway emissions

	2019	2020	2021	2022+	Notes
All scenarios	100%	79%	96%	100%	Recovers to expected pathway

- **GDP/economic outlook**. We have not attempted to calculate a long-term reduction in shipping demand due to structural changes in GDP due to COVID-19 (trade has historically correlated to GDP). We also have not considered any reductions in supply via failures of ports, vessel operators or ship manufacturers. Longer-term, lower fossil fuel prices could lead to smaller efficiency gains than previously projected, although this has also not been assessed.

- **Future demands**. All UMAS scenarios have the same underlying shipping demands to 2050. There is considerable uncertainty over the amount of future growth in the demand for shipping, particularly as the UK sets out to strike new trade deals globally, and as more rail infrastructure is developed within the UK (potential modal shifts to/from shipping remain unclear in the long term). We have not modelled the impact of higher shipping fuel costs (e.g. ammonia) on the demand for shipping vs other modes or their relative GHG intensities, nor the impact of decarbonisation across the rest of the economy on demands for shipping (e.g. due to reduced fossil fuel imports).

- **Air quality standards**. The strictness of standards that will be in place to 2050 in different world regions and around the UK coast are not yet known. Particularly strict air quality standards would favour the use of electricity or hydrogen over the use of ammonia in retrofitted engines (due to NOx abatement costs) or the use of biofuels. UMAS modelling does include air quality policies (IMO emissions control area, global sulphur cap), but still prefers ammonia combustion for the large majority of ship types and sizes.

- **Role of biofuels**. UMAS modelling excluded the use of biofuels in shipping. Our analysis shows that the use of biofuels in shipping is not likely to be an optimal use of bioenergy by 2050, as using a carbon-free fuel in shipping (such as ammonia) and instead using the biogenic feedstock for other applications that sequester the biogenic carbon will result in significantly lower overall UK emissions. However, in the near-term, biofuels used in shipping would displace fossil fuels.

-There are therefore a number of reasons to suggest that large-scale use of biofuels in shipping is not desirable, and that the transition to ammonia (and potentially some methanol or hydrogen) and electrification needs to be prioritised instead.

-At best, marine biofuels might have a limited niche role, due to, for example, aviation biojet plants producing some heavy end co-products that they decide not to recycle, and given the 3.5 TWh/year of fossil fuels still being used in shipping in 2050 in the Balanced Pathway that could be substituted. However, this would only comprise up to 5% of the total marine fuel supply, and this use of biofuels in shipping would be at least six times smaller than the use of biofuels in aviation – and would most likely follow SAF developments in the aviation market, not lead it.

-Biomass to marine FT fuel routes are still under development and waste fats/oils to biodiesel are relatively limited in supply. Given the lifetime of infrastructure such as fuel production plants and storage, choices made in the 2020s still need to be compatible with the long-term best use of bioenergy.

-If biofuels are assumed to be available to shipping, UMAS modelling (Scenario J) suggests that one potential consequence is to delay the transition to the use of ammonia, with a subset of the UK's domestic and international shipping fleets continuing to operate on conventional fuels even in 2050, which would lead to higher overall UK emissions.

- **Batteries**. The uptake of electric propulsion in the UMAS modelling is small (<0.2 TWh/year in the Balanced Pathway). Although battery costs reductions are assumed by UMAS, use is limited to smaller niche applications such as domestic short-distance passenger or car ferries. Significant breakthroughs in battery capacity and cost by 2050 would be required to out-compete liquid fuels in those larger ships and longer journeys that make up the majority of UK emissions.
- **Hydrogen in shipping.**
    - UMAS modelling picks ammonia in preference to hydrogen, because of the higher costs of onboard storage for hydrogen (including the additional space taken up that lowers the commercial returns for the ship). Similar to electric propulsion, hydrogen is being initially explored for short journeys where energy storage requirements are low. Breakthroughs in hydrogen storage technology with significantly improved volumetric density could be possible by 2050, although would take time to be commercialised and deploy within the fleet.
    - UMAS modelling recognises that relatively small changes in costs and efficiencies could change the commercial balance between hydrogen and ammonia, as could air quality regulations. However, at the moment, GW-scale renewable electrolysis plants are being planned in e.g. Australia[9] and Saudi Arabia[10], with export of the hydrogen as ammonia. This reflects the industry's view that despite the additional conversion losses, transporting ammonia is significantly cheaper overall than transporting hydrogen. If this market continues to develop and costs fall, ammonia stored onboard ships will become increasingly attractive as a fuel source for propulsion.

- **Methanol in shipping**.
  - UMAS modelling considers that zero-carbon synthetic methanol could be produced from low-carbon hydrogen plus CO_2 sourced from Direct Air Capture. This synthetic methanol is therefore significantly more expensive than ammonia or hydrogen, and so only appears in a few limited applications in UMAS modelling (well under 2% of total fuel use in 2050, and concentrated in domestic shipping niches). For simplicity in our analysis, we have combined this small amount of methanol with ammonia when presenting the zero-carbon fuel findings.
  - If Direct Air Capture costs were to fall significantly, such that synthetic methanol costs were much closer to ammonia costs, then the higher energy density of methanol could favour it over ammonia in a number of ship types. However, this methanol route would not likely be commercially available before 2035-2040, given Direct Air Capture technology development assumptions (Chapter 12).
- **Costs of switching to ammonia.** The additional cost from switching to ammonia will depend heavily on the counterfactual fossil fuel cost (or blended fossil fuel cost), the cost of hydrogen, and any future improvement in processing plant capital and operating costs. Our scenarios explore different hydrogen costs but hold ammonia processing plant costs fixed as this is commercialised technology. However, projects significantly smaller than 2,200 tonnes/day,[11] or projects further from hydrogen feedstocks, might be significantly more expensive than modelled. Ammonia costs therefore have some uncertainty.
- **Estimated time profile of costs.** The UMAS model is a fleet stock/sale model (explicitly covering 72% of the domestic fleet and 69% of the international fleet), but we only have access to in-year investment costs for domestic shipping in UMAS scenarios A, C and D. We have therefore had to infer added investment costs in each year from the annualised costs for international shipping in all scenarios, and domestic shipping in scenario B, assuming an average 15 year remaining lifetime on all measures – whereas the UMAS model uses 0-30 years depending on each ship, its remaining lifetime and the lifetime of the measure.
- **International accounting methodology.** Bunker fuel sales are the currently agreed basis by which countries report international shipping emissions to the UN. Were an alternative methodology developed and agreed, this would likely lead to an increase in the UK's international shipping emissions. For example, the activity basis used for the IMO's 4th GHG study (which is the same basis used by UMAS modelling, before we adjust back to bunker fuels) could approximately double UK international shipping emissions (adding 7-8 $MtCO_2e$/year during the 2020s).

Endnotes

[1] UMAS (University Maritime Advisory Services), E4tech, Frontier Economics, CE Delft (2019) *Reducing the maritime sector's contribution to climate change and air pollution. Scenario Analysis: Take-up of Emissions Reduction Options and their Impacts on Emissions and Costs*

[2] CCC (2020) *2020 Progress Report to Parliament*

[3] National Atmospheric Emissions Inventory (2020) *UK Greenhouse Gas Inventory, 1990 to 2018: Annual Report for submission under the Framework Convention on Climate Change*

[4] All the analysis is conducted on an IPCC AR5 basis with carbon feedbacks, using 34 tCO2e/tCH4, and 298 tCO2e/tN2O.

[5] Defra (2020) *Greenhouse gas reporting: conversion factors 2020*

[6] UMAS, E4tech, Frontier Economics, CE Delft (2019) *Reducing the maritime sector's contribution to climate change and air pollution. Scenario Analysis: Take-up of Emissions Reduction Options and their Impacts on Emissions and Costs - Technical Annex.* Table 5

[7] World Trade Organisation (2020) *Trade set to plunge as COVID-19 pandemic upends global economy*

[8] BEIS (2020) *Energy Trends: UK oil and oil products*

[9] The Asian Renewable Energy Hub (2020)

[10] Air Products (2020) *Air Products, ACWA Power and NEOM Sign Agreement for $5 Billion Production Facility in NEOM Powered by Renewable Energy for Production and Export of Green Hydrogen to Global Markets*

[11] 70 TWh/year of ammonia would require 15 plants at 2,200 tonnes/day scale, or a greater number of smaller plants. The Balanced Pathway assumes that 75% of low-carbon ammonia consumed by UK shipping is produced in the UK (so 11 plants in the UK at 2,200 tonnes/day scale), with 25% of low-carbon ammonia imported (made via renewable electrolysis abroad).

Chapter 10

Waste

Introduction and key messages

This chapter sets out the method for the waste sector's Sixth Carbon Budget pathways.

The scenario results of our costed pathways are set out in the accompanying *Advice report*. Policy implications are set out in the accompanying *Policy report*.

For ease, these sections covering pathways, method and policy advice for the waste sector are collated in *The Sixth Carbon Budget – Waste*. A full dataset including key charts is also available alongside this document.

The key messages from this chapter are:

- **Background**. Waste sector emissions, now including energy-from-waste (EfW) plants, accounted for 6% of UK GHG emissions in 2018 and were 63% below 1990 levels. Emissions have fallen significantly over the past two decades, due to reductions in waste being landfilled, although have not improved in the past few years due to a plateau in UK recycling and significant growth in fossil emissions from EfW plants.

- **Options for reducing emissions**. Mitigation options considered include reduced landfill methane generation (through waste prevention, recycling and banning biodegradable waste from landfill), reduced residual waste sent to EfW (through waste prevention, recycling), increased landfill methane capture and oxidation, improvements at wastewater treatment and compositing facilities, and installation of CCS on EfW plants.

- **Analytical approach**. Our analysis uses different potentials and costs in each sub-sector. The underpinning basis is BEIS' Energy and Emissions Projections. We model landfill methane falls due to landfill waste reductions and bans, before applying changes in landfill capture and oxidation rates. Industry data is used for wastewater and composting. Our EfW and CCS analysis comes from Element Energy modelling in Chapter 4, as do our assumptions on a circular economy and waste prevention potentials. Edible food waste reductions align with Agriculture sector analysis (Chapter 7). Resulting waste resource values feed into the Fuel Supply sector bioenergy & fossil waste supply analysis (Chapter 6).

- **Uncertainty**. We have used the scenario framework to test the impacts of uncertainties, to inform our balanced Net Zero Pathway. The key areas of uncertainty we test relate to landfill ban dates, recycling and waste prevention rates, and CCS roll-out timings.

We set out our analysis in the following sections:

1. Sector emissions
2. Options for reducing emissions
3. Approach to analysis for the Sixth Carbon Budget

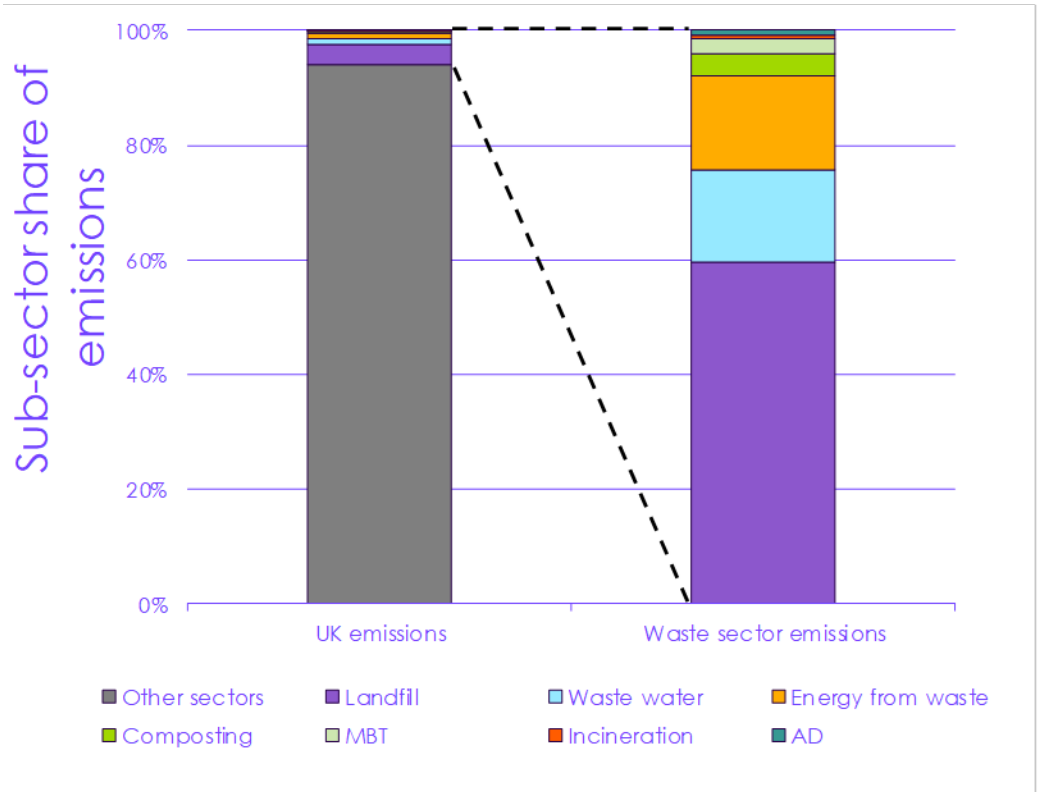
This section outlines the recent trends in waste emissions and their sources. For more detail, see our 2020 Progress Report to Parliament.[1]

a) Breakdown of current emissions

Based on the most recent year of official UK emissions data, total waste sector emissions (including energy-from-waste) increased by 3.7% from 2017 to 32.9 $MtCO_2e$ in 2018. Emissions from landfill increased by 2% to 19.6 $MtCO_2e$, emissions from wastewater were flat, and emissions from EfW plants increased 18% to 5.3 $MtCO_2e$. The waste sector, including energy-from-waste facilities, therefore comprised 6% of UK GHG emissions in 2018 (Figure 10.1). Landfill methane comprised the majority of waste sector emissions in 2018, followed by wastewater treatment and EfW plants.

Provisional GHG data for 2019 give sector emissions as 32.3 $MtCO_2e$, a 2% fall from 2018 levels. This is based on an estimate of a 2.4% fall for all CH_4 and N_2O sources, and no change in CO_2 emissions. However, these are likely to be updated.

Figure 10.1 Breakdown of waste sector emissions (2018)

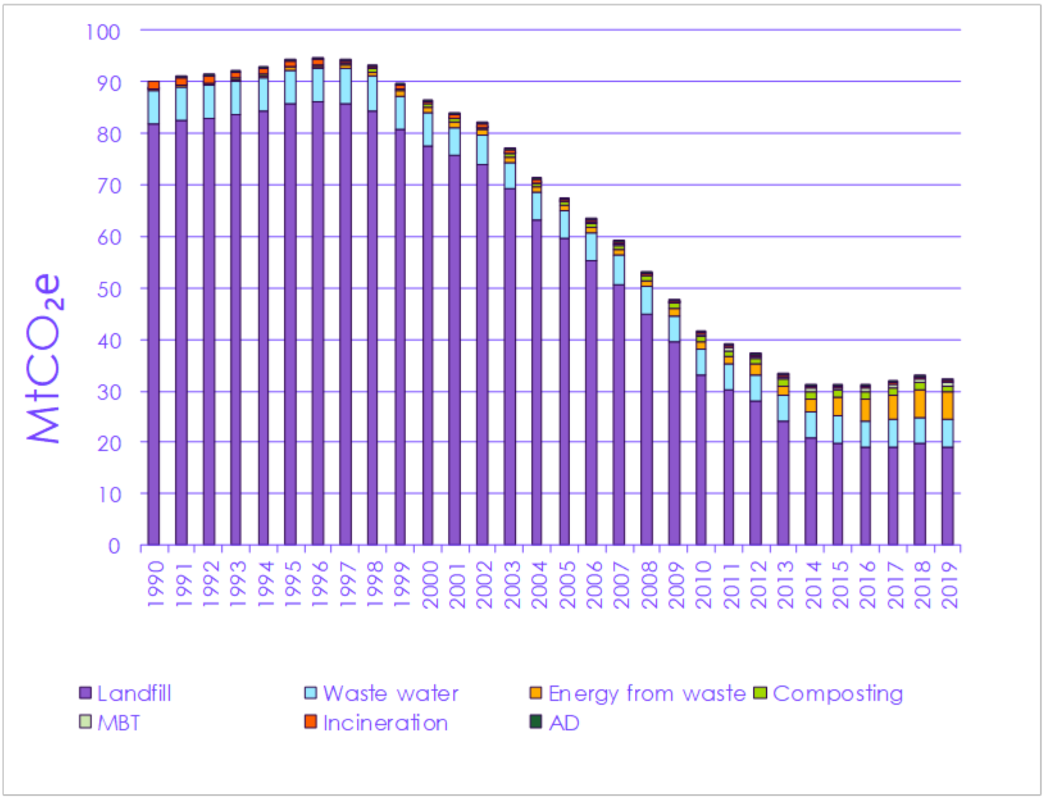


Source: BEIS (2020) *Final UK greenhouse gas emissions national statistics 2018.*
Notes: Total UK emissions in 2018 were 539 $MtCO_2e$/yr (AR5 basis, peatland revisions and IAS included). Waste sector emissions (including energy-from-waste) in 2018 were 32.9 MtCO2e/yr.

b) Emissions trends and drivers

The breakdown of waste emissions since 1990 is shown in Figure 10.2. Overall, emissions from the waste sector in 2018 were 61% lower than 1990 levels.

Figure 10.2 Breakdown of waste sector emissions (1990-2019)



Source: BEIS (2020) *Final UK greenhouse gas emissions national statistics 2018*; BEIS (2020) *Provisional UK greenhouse gas emissions national statistics 2019.*

Waste sector emissions rose with increases in landfill methane in the early 1990s, but since then have shown significant reductions. This is primarily due to falls in the amount of biodegradable waste being landfilled, driven by the UK's landfill tax diverting waste away from landfill. Landfill methane capture rates also increased significantly in the period up to the early 2010s, with policy support under the Renewables Obligation.

Wastewater treatment has seen modest improvements in emissions, as the UK population has increased but sewage treatment has shifted to improved anaerobic digestion systems. Minimal amounts of wastes (e.g. clinical & chemical wastes) are now incinerated without energy recovery.

More recently, waste sector emissions have fallen 46% over the period 2008-2018. However, progress has stalled since the mid-2010s. Landfill methane capture rates have peaked and are now declining. Recycling rates have plateaued in England, although Wales, Northern Ireland and Scotland have seen improvement in the past decade. With the significant decrease in landfilling, more local authority waste is now incinerated for energy than recycled or composted in England, and this has translated into increasing EfW emissions.

Waste sector emissions are primarily driven by the volumes of residual waste that end up in landfill or EfW facilities, which is in turn driven by UK consumption of products and food, combined with waste reduction programmes and reuse & recycling infrastructure. Wastewater emissions are more driven by population, the value of biomethane and water quality requirements.

Emissions reduction options have been explored within each sub-sector of the waste sector. These include:

- **Reduced landfill methane generation**. This is achieved via a combination of reductions in waste arisings, increased recycling rates, banning from landfill a list of key biodegradable wastes (paper/card, food waste, garden waste, waste wood and textiles) across municipal and non-municipal waste collections, as well as later bans on all landfilling of waste. Reductions in the amount of biodegradable material that is landfilled from the above actions will translate into reductions in the amount of landfill methane generated.

- **Increased landfill methane capture**, via a dispersed network of pipes inserted into the landfill, which collect landfill gas into a central location for use in generating heat, power or biomethane for gas grid injection.

- **Increased landfill methane oxidation** at the surface of landfill sites before emission to atmosphere as CO_2. This includes biocovers and biowindows, which are particularly suitable for lower-emitting sites and older sites. Most systems use compost as the filter medium.

- **Wastewater process improvements**. These measures involve the conversion of wastewater treatment plants to advanced anaerobic digestion systems (increasing the amount of biogas extracted and reducing methane emissions), as well as process optimisation improvements and leak identification using on-site emissions monitoring of CH_4 and N_2O. More innovative options include development and future installation of alternative wastewater treatment processes, such as membrane aerated biofilm reactors or partial nitrification-Anammox processes.

- **Composting forced aeration**. This involves use of pumped air to improve compost aeration and product quality, and avoid anaerobic conditions developing. It is estimated to be applicable to a third of compost facilities.

- **Reductions in residual waste sent to energy-from-waste,** achieved as above via increased recycling rates and reductions in waste arisings (including food waste), but also including changes in waste tonnages sent to landfill or exported. Waste reductions and recycling/AD/composting need to out-pace the bans on landfilling and export of wastes to avoid increased residual waste volumes being sent to EfW facilities.

- **Installation of CCS at energy-from-waste plants**, involving post-combustion carbon capture technology being installed at EfW plants and capturing 90-95% of the flue gas CO_2 for sequestration. EfW encompasses waste combustion, gasification and/or pyrolysis, for power (and heat) generation.

a) Summary of scenario choices

As a reminder from Chapter 3, section 9 of the *Advice Report*, the measures discussed in section 2 above are combined into the different scenarios as set out in Table 10.1 and Table 10.2.

Table 10.1
Waste scenario choices – waste reduction, recycling, energy-from-waste

	UK waste reduction, excluding food waste	UK per-capita edible food waste reduction		UK reuse & recycling rate		Residual waste allocated to jet fuel production		EfW plants installing CCS
	2037	2030	2050	2030	2050	2035	2050	2050
Balanced Net Zero Pathway	33%	52%	61%	68%	67%	0%	0%	100%
Headwinds	13%	52%	52%	68%	67%	0%	0%	100%
Widespread Engagement	33%	52%	71%	68%	79%	20%	70%	100%
Widespread Innovation	28%	52%	61% + 50% of inedibles	68%	67%	0%	0%	100%
Tailwinds	33%	52%	71% + 50% of inedibles	68%	79%	0%	0%	100%
Baseline	0%	27%	27%	52%	51%	0%	0%	0%

Notes: UK waste reductions are in-year versus a rising baseline of waste arisings. UK per-capita edible food waste reductions are measured (by WRAP) versus a 2007 base year for households and 2011 for business.

Table 10.2
Waste scenario choices – landfill, wastewater & composting

	Landfill bio-degradable ban	Landfill ban for all wastes	Landfill methane capture		Landfill methane oxidation		Wastewater GHG improvement		Composting GHG improvement
			2030	2050	2030	2050	2030	2050	2030
Balanced Net Zero Pathway	**2025**	**2040**	**71%**	**80%**	**10%**	**10%**	**21%**	**21%**	**23%**
Headwinds	2030	2050	68%	68%	10%	10%	21%	21%	23%
Widespread Engagement	2025	2035	68%	68%	10%	10%	21%	21%	23%
Widespread Innovation	2025	2040	80%	80%	15%	30%	21%	50%	23%
Tailwinds	2025	2035	80%	80%	15%	30%	21%	50%	23%
Baseline	None	None	60%	60%	10%	10%	0%	0%	0%

Notes: Some waste streams are banned from landfill earlier in the devolved administrations, see section 3(d) below. Wastewater improvements start ramping up from 0% in 2023, and composting improvements start from 0% in 2021.

Our baseline uses BEIS EEP 2019 modelling for "Existing Policies", with our own baseline derived for residual waste arisings and resulting EfW emissions based on the Waste sector analysis (Chapter 10).

This Baseline assumes growing waste arisings (roughly in-line with population and GDP), no further reductions in food waste from today and no other prevention, static recycling rates, and no installation of CCS on EfW plants. This leads to significant increases in EfW fossil CO_2 emissions. Regarding landfill, no landfill ban dates are set beyond those in existing DA policies, and methane capture and oxidation remain static, resulting in a slowly declining emissions trend for landfill methane. There are no improvements assumed in wastewater treatment or composting.

The exploratory scenarios assume different mixes and timings of measures to reduce waste sector emissions:

- **Headwinds** uses a similar approach to our analysis for the 2019 *Net Zero* advice, although with updates to add in new abatement measures in some sub-sectors. Changes mostly occur in the 2020s, but are more limited than in other scenarios.
    - Waste reductions align with conservative Manufacturing & Construction assumptions on product redesign, light-weighting, lifetime extensions and asset sharing.
    - Edible food waste reductions assume 2025 Courtauld Commitment[2] and 2030 UN SDG12.3 targets are met, but no further action after (this aligns with our Agriculture sector analysis).
    - Similarly, recycling is assumed to ramp-up to 56% for household and 74% for commercial & industry wastes by 2030 – this is 5 years earlier than the Waste & Resources Strategy – with no further improvement after 2030.
    - A later ban on the landfilling of biodegradable wastes in 2030, compared to 2025 in other scenarios, reflects a less ambitious rate of change in this scenario. Banning all landfill by 2050 is broadly in line with the Waste & Resources Strategy (some DAs act earlier).
    - No changes in landfill methane capture or oxidation rates are assumed, and only conservative improvements in wastewater and composting are considered to 2030. CCS is installed on EfW facilities from the late 2030s onwards.
- **Widespread Engagement** has much more ambition in terms of behaviour change than Headwinds, with more action during the 2020s and over the longer term.
    - This translates into high levels of waste prevention, aligning with the most ambitious Manufacturing & Construction assumptions, further significant reductions in food waste arisings post-2030 (this aligns with our Agriculture sector analysis), and further increases in recycling to 70% for household and 84% for commercial & industry wastes by 2050.[*]

[*] 84% reflects a likely maximum recycling rate for commercial & industry wastes, based on 16% of current non-household municipal wastes being non-recyclable, and 70% for households representing very significant progress from only ~45% in the UK today.

- Residual wastes are increasingly sent to waste-to-jet fuel plants for aviation from 2030, leading to significant falls in EfW utilisation.
    - Greater action on prevention and recycling allows a 2035 date for banning all landfill (earlier in Wales), but an earlier date would be infeasible due to further EfW facilities being required.
    - Headwinds assumptions are taken for landfill methane capture & oxidation, wastewater and composting. CCS starts being installed on EfW facilities from 2040 onwards.

- **Widespread Innovation** focuses on new technical approaches to reducing emissions.
    - Non-food waste prevention aligns with mid-level Manufacturing & Construction assumptions, food waste reduction aligns with our Agriculture sector analysis, and recycling improves as in Headwinds.
    - While edible food waste reductions do not make as much progress to 2050 as in Widespread Engagement, the inedible fraction of food waste is also assumed to be reduced by 50% (e.g. through lab-grown meat and further selective breeding).
    - A full landfill ban in 2040 coincides with EfW plants starting to install CCS. Significant increases in landfill methane capture and oxidation by 2030 are achieved, and the wastewater industry shifts to higher cost, innovative technology options after 2030.

- **Tailwinds** combines the most ambitious measures in each of the above scenarios, with the difference that CCS is installed on EfW facilities starting from the late 2020s.

Our **Balanced Net Zero Pathway** sets sub-sector assumptions from within the range of the exploratory scenarios, with some values at the more conservative end of the scenario spectrum and others at the more optimistic end, but most generally in-between. These Balanced Net Zero Pathway choices have generally been made on the basis of cost-effectiveness and technical certainty:

- Waste prevention/reduction efforts (excluding food waste) are set in line with the Widespread Engagement scenario, aligning with the assumptions made in the Manufacturing & Construction sector analysis.
- Food waste reductions assume 2025 Courtauld and 2030 UN SDG12.3 targets are met, as in all other scenarios, and then further modest reductions to 2050 are assumed (between the Headwinds and Widespread Innovation scenarios). This aligns with our Agriculture sector analysis.
- Recycling efforts focus on the 2020s, with no further improvements assumed after 2030, as in Headwinds and Widespread Innovation. Achieving a UK-wide recycling rate significantly above 70% will require significant behaviour change. This choice on recycling is balanced by the more ambitious choices on waste prevention above, recognising that waste prevention and recycling have similar impacts in terms of reducing residual waste volumes (and hence downstream landfill and EfW emissions), and that recycling rates could improve further post-2030 if maximal action on waste prevention were not achieved.

- All EfW plants are assumed to install CCS by 2050, starting from the early 2040s. No residual waste is allocated to jet fuel production, as system GHG savings are unlikely to be significantly higher than if they were used in EfW with CCS.
- Key biodegradable waste streams are banned from landfill from 2025, with landfilling of all wastes stopping in 2040, as in the Widespread Innovation scenario. Landfill methane capture rates increase to 80% as in the Widespread Innovation scenario, but this occurs by 2050 instead of by 2030. Landfill methane oxidation rates remain unchanged, as this is more uncertain and higher cost than methane capture.
- Wastewater improvements are aligned to Headwinds and Widespread Engagement, with known technology rolled out by 2030. Further improvement beyond 2030 is not assumed, due to technical development uncertainty and likely significantly higher costs.
- Composting improvements are as in the other scenarios, given their very low cost.

b) Sector classifications

Note that with the CCC's current sector classifications, a major change from previous reports is the inclusion of energy-from-waste power generation facilities emissions within the CCC's Waste sector boundary.* This reclassification has been carried out due to the interdependencies of landfill and waste reduction & recycling policies on EfW emissions, and given the increasing importance of EfW emissions that would otherwise have been subsumed within power sector emissions data. These EfW facilities generate electricity and, in some cases, also heat.

Some emissions reduction options have been counted outside of the CCC's Waste sector, even if these emissions reductions are achieved via waste sector policy. For example:

- EfW facilities with CCS will be capturing and sequestering biogenic CO_2 alongside fossil CO_2, following the mixed biogenic/fossil composition of residual waste. This sequestration of biogenic CO_2 is counted within the CCC's engineered GHG removals sector, as a form of bioenergy with CCS (BECCS).
- Water utilities may plant trees in the UK, in order to offset their gross emissions and help achieve their industry-wide 2030 Net Zero goal, but this would be counted within CCC's Land Use, Land Use Change & Forestry (LULUCF) sinks sector.

These negative emissions options are discussed in greater detail in the LULUCF and engineered GHG removals sector (Chapters 7 and 12 respectively).

This CCC sector classification also means that while some EfW electricity and heat could be carbon negative on a lifecycle basis (e.g. if using CCS with a high enough capture rate), our waste sector analysis only considers the gross accounting CO_2 emissions from the use of waste in EfW, i.e. positive or nil emissions, but not negative emissions.

* In terms of NAEI definitions, these Waste sector EfW facilities only include NAEI 1A1ai "Power stations" using "MSW", and do not include NAEI 1A1ai "Miscellaneous industrial/commercial combustion" of "MSW" which remains in the CCC's Manufacturing & Construction sector.

If an alternative accounting methodology were followed, the negative emissions from EfW with CCS plants could be counted within the waste sector emissions, but then these negative emissions would have to be excluded from the GHG removals sector to avoid double-counting. This accounting choice does not affect aggregate UK emissions.

The waste sector will not achieve full decarbonisation by 2050. Even under the most ambitious scenarios, residual emissions remain from wastewater treatment, composting and landfill fugitive methane, as well as smaller sources of emissions from EfW (the 5% of fossil CO_2 not captured via CCS), clinical/chemical waste incineration without energy recovery, anaerobic digestion and mechanical biological treatment plants.

There is therefore an expectation that the waste sector will require an amount of GHG removals to be developed to offset its gross emissions (8 $MtCO_2e$/year in 2050 for the Balanced Pathway).

c) Analytical steps

The waste sector analysis for the Sixth Carbon Budget advice consists of the following steps:

- **Coverage.**
    - Emissions considered are CO_2, N_2O and CH_4.
    - Coverage is for UK, Scotland, Wales and Northern Ireland.
    - The waste sector is split into seven sub-sectors: Landfill, Wastewater, Incineration*, Composting, Anaerobic Digestion (AD), Mechanical-Biological Treatment (MBT), and Energy-from-waste (EfW).
- **Abatement measures** are split into seven types: reduced landfill methane generation, landfill methane capture, landfill methane oxidation, waste water improvements, composting improvements, residual waste reductions and EfW CCS. There is no abatement assumed in three sub-sectors: AD, MBT and Incineration.
- **Waste arisings.** Household and commercial & industrial (C&I) waste arisings are sourced from Defra statistics[3], projected to 2050 by Ricardo as in CCC's *Biomass in a low carbon economy* report. Hazardous waste is not separately modelled, and Construction & Demolition waste is not modelled.
- **Waste reductions** ramp up to 2037, following Manufacturing & Construction sector assumptions, then are held flat. Food waste reductions are modelled separately using WRAP data[4], meeting Courtauld 2025 and UN SDG12.3 goals to 2030, before any further scenario changes to 2050.
- **Recycling** rates are then applied, ramping up to 2025 and 2030, before any further scenario changes to 2050. Waste exports are phased out by 2030.
- **Landfill tonnages** of 31 different waste streams are scaled with total remaining waste tonnages, until being banned at specified dates in each DA.

* Incineration sub-sector covers small amounts of clinical/chemical waste burnt without energy recovery. By contrast, the EfW sub-sector covers the large volumes of residual waste burnt to generate power (potentially also with heat).

- These tonnages landfilled are fed into Ricardo's MELMod model for each DA, to calculate the amount of landfill gas generated.[5]
- Landfill methane capture rates are then applied, plus an oxidation rate for the uncaptured methane, to derive fugitive methane emissions.
- Any increases in capture rates or oxidation rates are counted as abatement for these measures respectively, with the remainder of any GHG savings from the EEP 2019 baseline counted as being due to landfill bans and reduced landfilling (through waste reduction and recycling).

- **Residual waste** not landfilled is then allocated to EfW plants (or waste to jet fuel), with biogenic and fossil fractions varying over time due to the impact of landfill bans.* The baseline scenario has the largest amount of residual waste allocated to EfW plants, and so reductions in residual waste sent to EfW (due to prevention and recycling, less reductions in exports and landfilling) are accounted for as a GHG saving from the baseline. This is then before CCS is applied to EfW plants, as part of wider industrial Element Energy modelling (see Chapter 4 for details). Fossil CO_2 captured at EfW plants equate to further in-sector GHG savings, and biogenic CO_2 captured equates to GHG removals.
- **Biogas.** In addition to captured landfill gas, the following resources are calculated as biogas resources: sewage sludge (scaling with population, and the switch to advanced AD), livestock manures (scaling with Agricultural sector changes in livestock, and increasing collection rates), and food waste (with rising collection rate of the remaining waste after reductions). 2018 data is calibrated to ADBA sources.[6] Waste wood resources are estimated from Tolvik[7] data to 2022, then held flat. Used Cooking Oil is held fixed from Ricardo as in CCC *Bioenergy in a low carbon economy* report, and Tallow is scaled by Agricultural sector changes in livestock. These resources are fed into the Fuel Supply sector analysis.
- **Wastewater** and **composting**. In these sub-sectors, % improvements in GHG emissions are applied directly to the baseline from EEP 2019.
- **Energy consumption/generation**. With the exception of EfW, energy consumption in all waste sub-sectors is already fully accounted for within the Manufacturing & Construction and Non-domestic buildings sectors. However, EfW plants are not modelled within the Power sector, so the waste sector analysis includes power generation from EfW plants, using the residual waste sent to EfW and a fleet average 26% HHV electrical efficiency. The addition of CCS to EfW plants in Element Energy modelling (Chapter 4) results in a modest reduction in sector net electricity generation as well as sector consumption of low-carbon hydrogen to fuel the carbon capture equipment.
- **Costs.**
  - Data sources for costs in each sub-sector vary. Baseline investment and operating costs are only estimated for waste collection and recycling, with baseline data unavailable for other sub-sectors.

* In addition to EfW, some residual niche fossil wastes from NAEI data (4 TWh/year of 'waste', 'waste oils', 'waste solvent' and 'scrap tyres'), are allocated to manufacturing, without variation between scenarios. Similarly, NAEI also gives 0.8 TWh/year of clinical/chemical waste used in waste incineration without energy recovery, and 0.5 TWh/year waste oils in power in 2018.

- Composting aeration added costs of £11/tCO_2e from industry data, with 20-year lifetime and 6% discount rate. Landfill bio-window costs taken from Honace (2020), assuming 30 years at a 5% discount rate to derive £67/tCO_2e.[8]

- Landfill methane capture costs of £12/tCO_2e are derived from BEIS (2020)[9], using the higher end of ranges, and 28 years at 6.1% discount rate.

- Additional wastewater costs of £204/tCO_2e to 2030, and £554/tCO_2e for more ambitious improvements after 2030 in some scenarios, come from Water UK. We have inferred investments from £/tCO_2e values using a 25-year asset lifetime and 3.5% industry discount rate, and assuming no change in operating costs. These municipal wastewater costs are applied to industrial wastewater treatment, given the lack of industrial wastewater data.

- Costs of waste collection and recycling derived from Defra's 2019 Impact Assessment[10], but compressing costs in time and scaling up total costs in line with increased recycling rates in our scenarios compared to English 2035 targets in Defra's "Option 3M" scenario. In the absence of other data, costs are assumed to scale up to cover the non-municipal waste sector, and scale down to devolved administrations (DAs) based on their smaller total tonnages and waste recycling ambitions (targets minus higher starting recycling rates). Further detail on DA recycling rates is given in section 3(d).

- The added costs of reduced landfill methane generation through higher recycling rates are £15-30/tCO_2e, depending on DA and scenario, which matches with the Defra IA.

- The costs of avoided EfW emissions from lower residual waste arisings are taken to be nil, given these waste collection and recycling costs are already accounted for in deriving landfill savings.

- The costs of installing CCS on EfW plants are calculated by Element Energy modelling, factoring in energy inputs and the location/distance to sequestration points, and are typically £140-260/tCO_2e.

The reason waste sector emissions cannot be reduced further than in our scenarios is due to a combination of technical potentials, current scientific uncertainty and cost.

- Maximum recycling rates are uncertain, and we assume a blended household/C&I rate up to just under 80% would be possible. We do not have scenarios with 100% recycling, as national rates of 70% are yet to be achieved anywhere in the world, and currently around 16% of UK waste is non-recyclable. Recycling rates also need to be seen in their context in the waste hierarchy - when recycling rates in our scenarios are combined with waste reduction efforts, the result is a 72-87% reduction in post-recycling waste tonnages in 2050 compared to the baseline (with the Balanced Pathway achieving 79% by 2050).

- Existing landfill characterisation is poor. We have ruled out going above 80% landfill methane capture, or 30% oxidation of fugitive landfill methane, on the basis that it is not clear yet whether this is technically possible, or what the associated costs would be. There is also huge heterogeneity in landfill sites, making it hard for any single solution to be generally applicable.

- Reducing wastewater treatment process emissions is highly capital-intensive, with average abatement costs rising to £400/tCO_2e when including the more novel technologies in Widespread Innovation. We limit costs in our scenarios, meaning that only a 50% reduction in methane and nitrous oxide emissions by 2050 is explored. Technology that could improve beyond 50% is only speculative at present.

d) Devolved administrations

The 2018 share of emissions from the NAEI and Element Energy modelling of the EfW fleet is used to apportion UK emissions to the devolved administration (DA) level. The following splits are used in the Baseline scenario, and held fixed over time:

- Landfill methane: 9.1% Scotland, 6.9% Wales, 4.3% NI, 79.8% England
- Wastewater, incineration, composting, AD & MBT: 6.5% Scotland, 4.7% Wales, 3.3% NI, 85.5% England
- EfW: 3.9% Scotland, 4.4% Wales, 2.0% NI, 89.8% England

In the exploratory scenarios and Balanced Pathway, landfill methane reductions are modelled for Wales, Scotland, England and Northern Ireland, based on waste reductions, recycling and landfill bans of different streams in each jurisdiction.

Household recycling data is reported annually by Defra, for the UK and devolved administrations (DAs).[3] Our analysis of recycling costs therefore starts from known 2018 household recycling rates of 45% in England, 43% in Scotland, 54% in Wales and 48% in Northern Ireland. From a combination of NAEI emissions data, industry expert approximations[11], surveys of recycling facilities[12] and older literature[13], we have inferred starting C&I recycling rate positions of 55% in England, 54% in Scotland, 58% in Wales and 43% in Northern Ireland. As discussed in section 3(e) below, C&I recycling rates are extremely uncertain.

In all our scenarios, we assume Scotland and Wales achieve their target 70% recycling rate by 2025. We assume England achieves 68% by 2030 (based on a 56% household waste recycling rate and 74% C&I waste recycling rate being achieved – this is Defra's 'Option M' scenario from their 2019 Impact Assessment,[14] brought forward by 5 years from 2035, with the non-household municipal recycling rate of 74% extended to all C&I waste). We assume that Northern Ireland also achieves the same recycling rates as England.

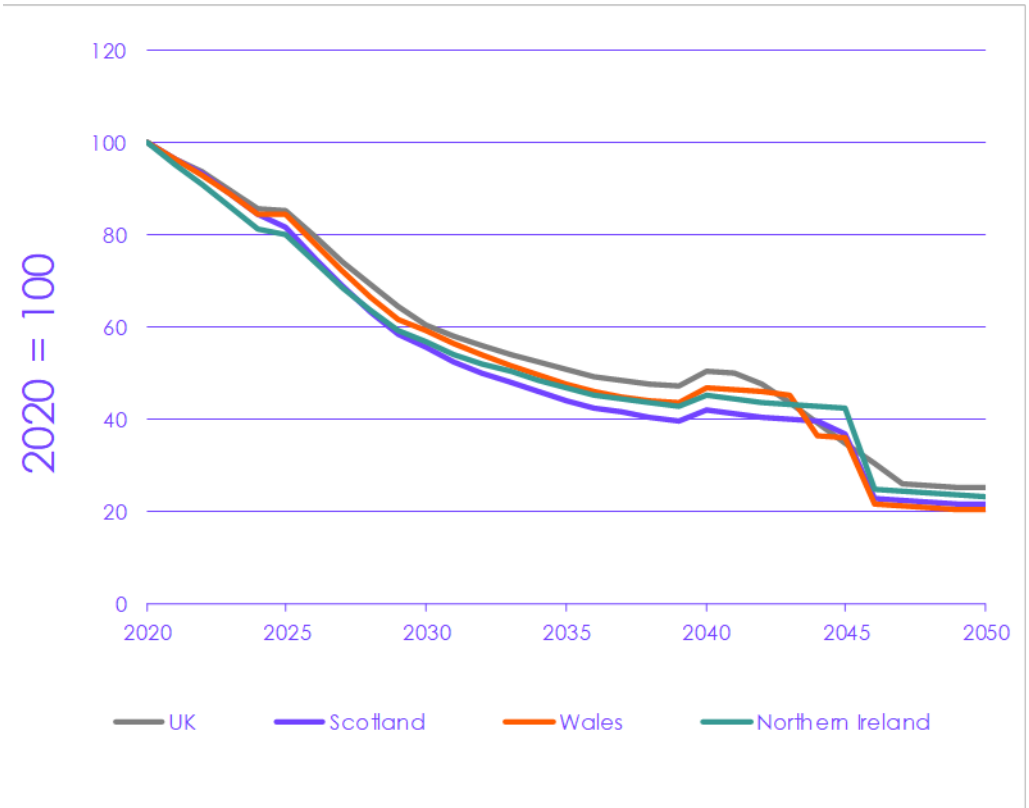
For bans on landfilling of waste streams, the following assumptions are made as inputs to Ricardo's MELMod landfill methane model:

- In England, scenarios follow the assumptions in Table 10.2.
- Scotland is assumed to ban landfilling of biodegradable municipal wastes from 2025, and follow the assumptions in Table 10.2 for non-municipal biodegradable waste (2025, or 2030 in Headwinds). Full landfill bans follow the assumptions in Table 10.2.
- Wales is assumed to ban the landfilling of all wastes from 2025.
- Northern Ireland scenarios follow the assumptions from Table 10.2, with the exception of municipal food waste which is already banned from landfill.

The DA splits for landfill methane emissions therefore vary over time, given the differing assumptions above. DA splits of EfW emissions also vary over time, since although residual waste resource estimates fed into the Element Energy modelling are at a UK level (aggregating waste reductions, recycling and DA-specific landfill bans of different waste streams), the Element Energy modelling chooses to deploy CCS in different regions at different times.* DA splits for wastewater, incineration, composting, AD & MBT are assumed to be held fixed over time in all scenarios.

As shown in Figure 10.3, the DA waste sector emissions decarbonise slightly faster than the UK as a whole, due to implementing higher recycling rates and earlier bans on landfilling of biodegradable material than in England, which leads to lower landfill methane and EfW emissions. 2040 sees a slight increase in emissions, due to banning of landfill pushing extra waste into the EfW market (in reality, this might be a phased transition to avoid these increases, or only conducted once CCS is deployed on EfW). The step-changes observed in the mid-2040s across the DAs are due to CCS modelling assumptions (Chapter 4) installing CCS on a region of EfW plants at one time. Given the smaller number of EfW plants in the DAs, this leads to steps, rather than the smoother curve seen for the UK from 2040, given the larger number of plants and regions to retrofit CCS than in the DAs.

Figure 10.3 Comparison of emission pathways for the UK, Scotland, Wales, Northern Ireland



Source: CCC analysis.
Notes: Waste sector GHG emissions for the Balanced Net Zero Pathway, including Energy from Waste (EfW) facilities, split into DAs, and re-based from 2020 levels.

* A future modelling refinement would be to consider DA-specific residual waste arisings (after DA prevention and recycling) as the resource available for EfW use in each of the DAs, although given the convergence in recycling rates assumed from 2030 across the UK, the current modelling assumption will not give a significantly different outcome for the CB6 period.

e) Uncertainties

Given waste will be still have residual gross emissions in 2050 (8 $MtCO_2e$/year in the Balanced Pathway), the following uncertainties may cause some changes in UK emissions in the near to mid-term, although these uncertainties will generally decline as sector emissions decline over time. The impact of waste uncertainties on Net Zero is therefore likely to be modest:

Uncertainties in the scenario analysis fall into the following main categories:

- **COVID-19**. Waste collection services have generally continued uninterrupted throughout the pandemic. However, with the increase in working and eating from home and increased online purchases, there has been a notable shift in waste arisings and recycling demands, with significant increases in household waste, and significant decreases in commercial & industrial wastes. This has presented challenges to Local Authorities. However, at a national level, given the main impact has been a shift in activity, we have not estimated any changes in waste arisings, recycling rates or emissions directly as a result of the pandemic. There remain uncertainties as to the final composition of the waste industry that will emerge post-COVID, due to the balance of household vs. commercial activity.
- **GDP/economic outlook.** We also have not attempted to calculate a longer-term reduction in waste arisings due to structural changes in GDP due to COVID-19.
- **Future arisings**. All scenarios have the same underlying baseline waste arisings to 2050, before waste reduction and recycling measures are applied, although there is some uncertainty over the amount of future growth in baseline waste arisings, particularly as the UK sets out to strike new trade deals globally and the long-term size of the manufacturing base in the UK is still uncertain. We have not modelled the impact of higher waste disposal costs on the amount of waste generated.
- **Water quality standards**. The strictness of standards that will be in place to 2050 in the UK are not yet known. Particularly strict water quality standards could favour or disincentivise the use of certain advanced waste water treatment processes over conventional processes.
- **Inventory uncertainties.** There are discussions ongoing about changes to NAEI's waste water inventory, to reflect improved data. There is also some uncertainty about landfill methane capture rates (and hence fugitive emissions vs. landfill gas for energy generation), given a discrepancy in the landfill gas power generation efficiencies assumed by NAEI and DUKES teams. Given the dominance of CH_4 and N_2O emissions in this sector, choices about GWPs will also have a particularly large impact.[15]
- **Commercial and industrial (C&I) waste.** Data on C&I waste arisings is uncertain, and UK data is only published every 2-3 years by Defra.[16] Even more uncertain is the overall recycling rate that applies to C&I waste – this data is not collected (some partial data is available for non-household municipal waste and packaging recycling). We have had to infer a current UK C&I recycling rate of 55% based on the $MtCO_2e$/year emissions from residual waste sent to EfW and Manufacturing, NAEI waste calorific values, and Defra data for UK C&I waste arisings, household waste arisings and household recycling estimates. Given the uncertainties in each of these factors, the actual UK C&I recycling rate may be between 40-60% (approximations in the literature for the DAs also fall within this range).

Since C&I wastes compromise the majority of UK waste, this data gap could significantly impact future sector emissions and costs, and therefore needs addressed.

- **Application of costs.** Costs for several of the waste sub-sectors are estimates based on literature sources or industry views, and are indicative of action in the sub-sector. There is likely to be a broad range of costs around our estimates, given differences in site size, location, existing equipment, cost of capital and lifetimes.
- **Modelling simplifications**: For simplicity, the modelling of various waste stream landfill bans in the four countries of the UK has been carried out by cutting off landfilling in the chosen year. In reality, there is likely to be a phase-out of landfilling in the years ahead of the ban, and potentially some small amount of non-compliance in the years after the ban, which would lead to a much smoother profile of residual waste availability – rather than the current spikes observed in e.g. 2025 and 2040 in the Balanced Net Zero Pathway. These spikes should be avoided, by significantly increased waste reduction and recycling/AD/composting efforts ahead of the landfill bans.

Endnotes

[1] CCC (2020) *2020 Progress Report to Parliament*

[2] WRAP (2020) *The Courtauld Commitment*

[3] Defra (2020) *UK statistics on waste*

[4] WRAP (2020) *UK progress against Courtauld 2025 targets and UN Sustainable Development Goal 12.3*

[5] MELMod for the UK GHGI/NAEI for 2018, produced by Ricardo Energy and Environment on behalf of Defra

[6] ADBA (2020) *Biomethane: the pathway to 2030*

[7] Tolvik (2020) *UK Dedicated Biomass statistics - 2019*

[8] Honace (2018) *Landfill aftercare scoping study*, for Defra

[9] BEIS (2020) *Electricity generation costs*

[10] Defra (2019) *Consistent municipal recycling collections in England: Impact Assessment*

[11] Scottish Government (2019) *Waste markets study: full report*, based on Eunomia estimate

[12] WRAP Cymru (2020) *Commercial and Industrial Waste in Wales*

[13] WRAP Northern Ireland (2011) *Northern Ireland Commercial & Industrial (C&I) Waste Estimates*

[14] Defra (2019) *Consistent municipal recycling collections in England: Impact Assessment*

[15] All the analysis is conducted on an IPCC AR5 basis with carbon feedbacks, using 34 tCO_2e/tCH_4, and 298 tCO_2e/tN_2O.

[16] See ref 287.

Chapter 11

F-gases

Introduction and key messages

This chapter sets out how we developed scenarios for F-gas emissions to inform the Committee's advice on the UK's Sixth Carbon Budget. It builds on evidence used in 2019 for our *Net Zero* advice on cost-effective abatement measures that go beyond existing EU regulations.

Fluorinated gases (F-gases) are released in very small volumes relative to other greenhouse gases (GHGs), but can have a global warming potential (GWP) up to 26,000 times greater than carbon dioxide. They are used across many sectors of the UK economy as refrigerants, aerosols, solvents, insulating gases, or blowing agents for foams, and they can also be emitted as fugitive emissions from other manufacturing processes. Due to their highly damaging impact on the climate, F-gases should be restricted to the very limited uses where there are no viable alternatives.

The key messages from this chapter are:

- **Background**. F-gas emissions accounted for 3% of UK greenhouse gas emissions in 2018 and were 9% below 1990 levels. Emissions in 2018 were 37% below the year of highest emissions in 1997, as abatement technologies at halocarbon production plants have cut F-gas leakage by over 99%. The largest source of emissions is now the refrigeration, air-conditioning and heat pump (RACHP) sector, where emissions are released due to refrigerant leakage from appliances during use and when they are disposed.
- **Baseline emissions**. There already exists a strong international framework for reducing F-gas emissions, through the Kigali Amendment to the UN Montreal Protocol. The UK was previously subject to the 2014 EU F-gas Regulation and 2006 Mobile Air Conditioning (MAC) Directive and is transitioning to equivalent standards. Our baseline assumes that the UK maintains a regulatory framework at least as strong as the EU F-Gas Regulation that can deliver an 80% reduction of F-gas emissions in 2050 compared to the 1995 baseline.
- **Deeper emissions reduction pathways.**
  - Our scenarios explore action to further reduce emissions in the RACHP sector, as well as a transition to medical inhalers that have a lower global warming impact. In our Widespread Innovation scenario, we explore more speculative abatement measures in more niche F-gases subsectors such as the use of foams.
  - These scenarios may require stronger regulation (for example in the RACHP sector), technical shifts to lower-GWP aerosols and behavioural changes amongst end-users (e.g. between clinicians and patients). These measures can deliver an additional 1-2 MtCO2e abatement by 2050 compared to the 1995 baseline.
- **Costs and benefits.** Actions to reduce F-gas emissions are expected to be broadly cost-neutral. Many of the technologies required exist already and are cheaper than high-GWP alternatives.

- **Delivery**. The UK Government has already taken a crucial step towards reductions in F-gas emissions, by adopting standards at least as stretching as the EU F-gas Regulation. Beyond this, there will be a need to increase training, certification and monitoring of non-compliance in the RACHP sector, introduce alternatives to Metered Dose Inhalers (MDIs), and consider regulatory approaches to deliver further reductions in the RACHP sector.

We set out our analysis in three sections:

1. Sector emissions
2. Options to reduce emissions
3. Approach to analysis for Sixth Carbon Budget pathway

This section outlines the recent trends in F-gas emissions and their sources. For more detail, see our 2020 Progress Report to Parliament.[1]

a) Breakdown of current emissions

F-gas emission levels were 15 $MtCO_2e$ in 2018, accounting for 3% of total UK GHG emissions (Figure 11.1). Emissions were 14% below 1990 levels and 37% below the peak in 1997.

F-gases are released in small volumes. However, they are very effective at trapping heat and can remain in the atmosphere for many centuries after their release. As a result, they have a high climate impact per molecule, which is reflected in the high Global Warming Potentials (GWP) used in international emissions accounting.

The climate impacts of all greenhouse gases are compared to CO_2, which has a GWP defined as 1. Future methodology changes to the GWPs* of different F-gases will tend to increase estimates of their warming potential, meaning that compared to the current UK greenhouse gas inventory, estimated total F-gas emissions will be revised upwards by around 1-2 $MtCO_2e$ per year.

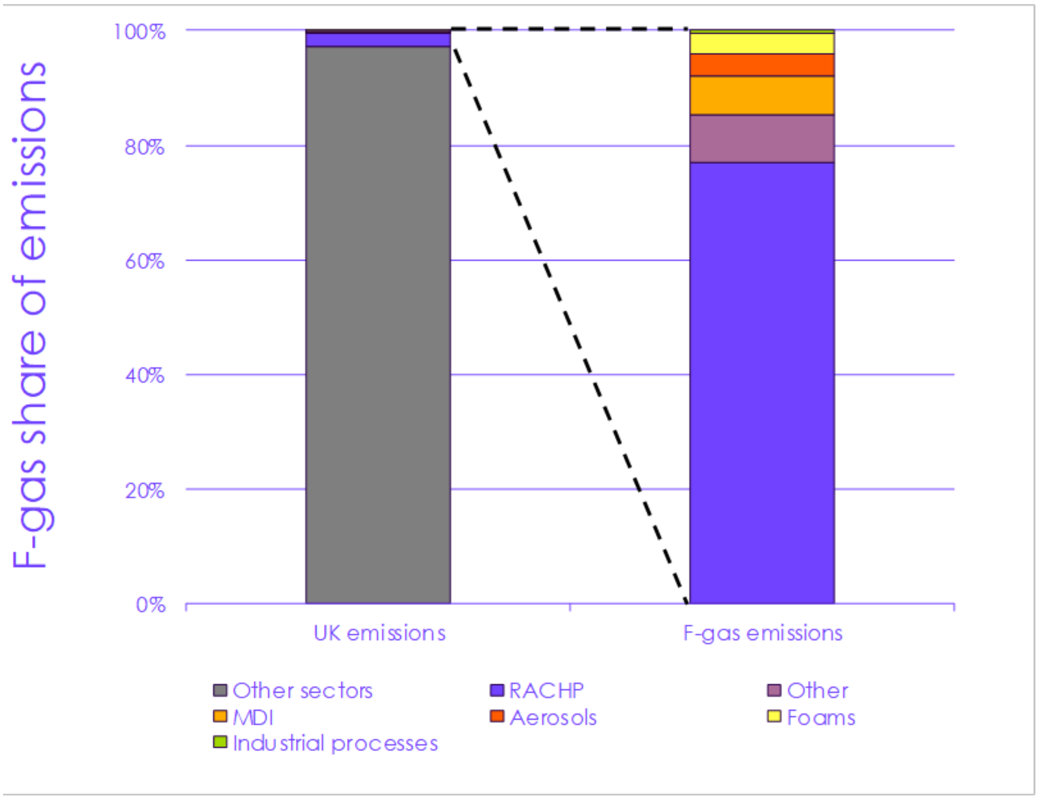
The four F-gases included in the UK emissions inventory are hydrofluorocarbons (HFCs), sulphur hexafluoride (SF_6), perfluorocarbons (PFCs), and nitrogen trifluoride (NF_3):

- **HFCs** (94% of total F-gas emissions in 2018) are used in refrigeration, air-conditioning appliances, aerosols and foams, metered-dose inhalers and fire equipment. They are emitted during the manufacture, lifetime and disposal of these products and can stay in the atmosphere for up to 270 years (although some have shorter lifetimes). HFCs have GWPs ranging from approximately 100 to around 15,000.
- **SF_6** (4%) is mainly used in insulation for electricity networks, magnesium casting and military applications. It stays in the atmosphere for around 3,000 years. SF_6 has a GWP of 26,087.
- **PFC** emissions (2%) result mainly from the manufacture of electronics and as a by-product of aluminium and halocarbon production. Their lifetime in the atmosphere ranges from 2,600 to 50,000 years. PFCs have GWPs of approximately 7,000 to approximately 19,000.
- **NF_3** emissions are currently very low (less than 0.001 $MtCO_2e$) and result from semi-conductor manufacturing. These emissions do not count towards the UK Net Zero target or carbon budgets. NF_3 stays in the atmosphere for around 700 years and has a GWP of 17,885.

The largest source of emissions in 2018 was leakage from refrigeration and air-conditioning systems (77%). These systems have mainly used HFCs since ozone-depleting chlorofluorocarbons (CFCs) were phased out. Other F-gas emissions came from technical aerosols (4%), metered-dose inhalers (7%), and foams (3%).

* Using AR5 Global Warming Potential values with carbon-cycle feedbacks. See Box 2.1 of the Sixth Carbon Budget Report

Figure 11.1 Breakdown of F-gases sector emissions (2018)



Source: BEIS (2020) *Provisional UK greenhouse gas emissions national statistics 2019.*
Notes: RACHP: Refrigeration, Air-Conditioning and Heat Pumps. MDI: Metered Dose Inhalers.

b) Trends and drivers

Total F-gas emissions peaked in 1997, reaching 24 $MtCO_2e$, around 80% of which was due to HFC and other halocarbon production (Figure 11.2). Between 1997 and 2000, F-gas emissions dropped significantly as a result of mitigation measures to reduce leakage in the industrial production of halocarbons. From 2001 to 2015, F-gas emissions rose slowly, mainly due increasing demand for the refrigerants used in air-conditioning and refrigeration. F-gas emissions fell by around 18% from 2015 to 2018 due to the introduction of new EU regulations.

The UK has signed up to a strong international legal framework for reducing F-gas emissions the Kigali Amendment to the UN Montreal Protocol, and was previously subject to the F-Gas Regulation (EU) 517/2014 and the Mobile Air Conditioning (MAC) Directive.

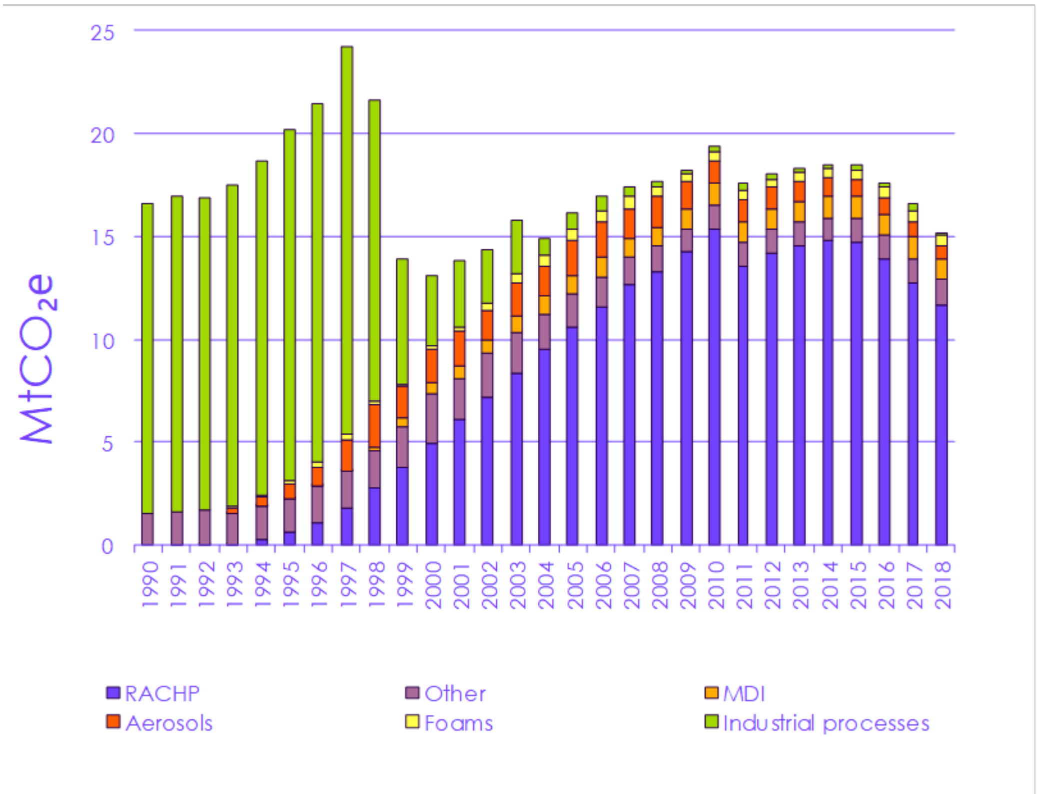
Legislation has been the key driver of a transition to low-GWP alternatives in recent years:

- The Kigali Amendment to the UN Montreal Protocol sets out pathways for developed and developing countries for controlling the production and consumption of HFCs. Under the amendment HFCs in developed countries will be reduced through incremental targets up to a cut of 86% by 2036. These plans are less stringent than the EU F-Gas Regulation up to 2034, after which the Kigali Amendment targets are more ambitious.

This may not remain the case, as the EU plans to consider in 2022 an extension of the ambition of the F-Gas Regulation beyond 2030. The UK ratified the Kigali Amendment in November 2017 and the amendment took effect in January 2019.

- The 2014 EU F-Gas Regulation came into force in the UK in January 2015, and equivalent measures will be enforced into UK law in at the end of the transition period of leaving the EU. It introduced a number of new measures and strengthened the 2006 EU F-Gas Regulation:
  - The regulation sets a cap on the amount of HFCs that producers and importers are allowed to place on the market. The cap will be cut every three years until reaching a 79% cut by 2030 from 2015 levels.
  - Some uses of HFCs are exempt from the regulation, including medical use, military equipment and manufacturing of semiconductors. Emissions from SF_6 and PFCs are not included in the cap.
  - The regulation bans the use of F-gases in many new types of equipment where less harmful alternatives are widely available, such as fridges in homes or supermarkets, air-conditioning and foams and aerosols.
  - The regulation strengthens existing obligations in terms of mandatory 'management measures' including regular leak checks and repair, gas recovery at end-of-life, record keeping, training and certification of technicians and product labelling.
- The 2006 MAC Directive focuses on emissions from air-conditioning in new cars and vans. From 2017, all new cars and vans are required to use substances with a GWP less than 150.
- Emissions of PFCs from aluminium production are priced under the EU Emissions Trading System.

Figure 11.2 Breakdown of F-gases sector emissions (1990-2018)



Source: BEIS (2020) *Provisional UK greenhouse gas emissions national statistics 2019.*
Notes: RACHP: Refrigeration, Air-Conditioning and Heat Pumps. MDI: Metered Dose Inhalers. Emissions data is shown adjusted to AR5 Global Warming Potentials with carbon-cycle feedback and therefore does not match the total published UK Greenhouse Gas inventory.

Many applications that use F-gases can reduce their emissions, or be switched to lower-warming alternatives, with few costs and barriers. In 1990, manufacture of halocarbons was the largest source of F-gases emissions in the UK. Emissions fell substantially between 1997 and 2001, as a result of fitting abatement technologies at production sites. There is now little potential to further reduce emissions from this source.

However, there remain other source of F-gases and these will be more challenging to abate, typically due to long product lifetimes or a lack of viable alternative technologies to replace F-gases:

- **Refrigeration, air-conditioning and heat pump (RACHP) emissions where no low-GWP alternatives currently exist (approximately 5% of total 2018 emissions).** The EU F-Gas Regulation is already driving a shift from very high-GWP gases to lower-GWP options such as HFC-32, which is expected to be the dominant HFC refrigerant in 2040. There is, however, little current progress towards an even lower-GWP alternative. For small systems, hydrocarbon refrigerants such as propane are a good option, but high flammability limits the proportion of the market that can safely use hydrocarbon refrigerants. It is unlikely that more than 25% of the small sized air-conditioning market and 50% of the residential heat pump market could use hydrocarbons.[2]
- **Lifetime and disposal emissions from foams (approximately 2%).** It is extremely challenging to recover F-gas blowing agents from foams, typically used in building insulation, because of the difficulties in separating the foam from the associated building material.
- **Emissions from current gas-insulated high-voltage switchgear (GIS) (approximately 1%).** The long lifetime (up to 40 years) of high voltage switchgear equipment used in the electricity system, and the lack of mature non-SF_6 alternatives means that accelerating the replacement of existing GIS equipment would be difficult and very expensive. New equipment is more efficient and minimises leakage.
- **Other sources of F-gas emissions (approximately 5%).** Emissions from other small sources, including aluminium fugitives, semiconductors, solvents, military use, and laboratory use are difficult to reduce, reflecting a lack of alternatives. It is possible that there may be some scope to reduce emissions from halocarbon production and magnesium casting.
- **High uptake of low-carbon alternatives to Metered Dose Inhalers (MDIs) (approximately 8%).** Low-carbon alternatives to MDIs are abundant (e.g. Dry Powder Inhalers DPIs). Shifting to these alternatives will require behaviour change from practitioners and patients.

Despite these challenges, there is potential for further abatement that goes beyond the UK's existing regulation and international agreements.

a) Behaviour change measures

Metered dose inhalers (MDIs) use F-gases (HFA-134a and HFA-227ea) as propellants, and account for around 1 $MtCO_2e$ of annual emissions in the UK. There are two solutions to reducing emissions from MDIs:

- Viable alternatives to MDIs already exist in the form of dry-powder inhalers (DPIs), which do not use a propellant and therefore have zero F-gas emissions. Around 25% of all inhalers prescribed in the UK are currently DPIs, which is a much lower share than many European countries. In Denmark, more than 80% of all inhalers prescribed are DPIs. Increasing the uptake of DPIs in the UK has significant potential to reduce F-gas emissions, but will require changes to both patient and doctor behaviour.

- MDIs could switch to using a propellant with a lower warming potential. This new technology would have to be adopted by the National Health Service, but would require virtually no behaviour changes for patients. There is active research towards a low-GWP metered dose inhaler using the propellant HFA-152a, which could be in use by the end of 2025 and cut emissions from inhalers by around 90%.[3]

b) Technical measures

A range of low-GWP F-gases, or alternative technologies that do not cause climate change, are already available on the market, and new innovation will likely bring more forward (Box 11.1).

The deployment of lower-GWP or ultra-low-GWP alternatives to current F-gases in the refrigeration, air conditioning and heat pump (RACHP) sector has the potential to reduce emissions further than the existing baseline.

It is important to recognise that the RACHP market is highly complex, with many different market sectors and sub-sectors. This leads to the need for a range of different refrigerants that are designed to suit specific applications. Key variables that have informed our assessment of the potential for the RACHP sector to go further include:

- **System size**. RACHP systems vary in cooling capacity from under 1 kW (e.g. domestic refrigerators) to >10,000 kW for large industrial systems.

- **Temperature level.** Most refrigeration applications are either in the range 0°C to 5°C (e.g. for chilled food) or -15°C to -40°C (e.g. for frozen food). However, some refrigeration is required at much lower temperatures, between -60°C and -270°C. Air-conditioning typically provides cooling at temperatures in the range 10°C to 20°C. Heat pumps deliver heat at between 40°C and 120°C. This significant range of different temperatures requires various refrigerants to be available, with a range of thermodynamic properties that can be selected to suit the temperature level of the application.

- **Location / accessibility.** Some RACHP systems are located in areas with public occupancy e.g. shops, hotels, private residences. In such locations, safety issues might restrict the choice of available refrigerants or the size of refrigerant charge. For some RACHP applications, the equipment is located in a restricted area, with only trained personnel allowed access e.g. in factories or special machinery rooms. In these circumstances, a wider range of refrigerant options can be considered.

- **New equipment and retrofits.** Most refrigerant selections are made for new equipment, where the designer may have several options available. However, under an HFC phase-down it may also be appropriate to retrofit an existing plant with a lower-GWP refrigerant. In these circumstances there are many more design constraints and fewer refrigerants will be suitable.

Some areas of abatement measures highlighted in our Net Zero report were identified as technically feasible, but were not costed and market-ready solutions do not yet exist. These opportunities lie in military radar systems (AWACS), halocarbon and magnesium production, foams, semiconductors, and solvents. Abating emissions from these subsectors will require alternative low-GWP technologies to be designed and implemented. As these solutions are more less certain, they are included only in the Widespread Innovation and Tailwinds scenarios.

Box 11.1
New evidence on reducing F-gas emissions

The European commission has been a major driver of research into the prospect of using lower-GWP F-gases. Since our Net Zero report, they have published two further reports into the prospect of low-GWP refrigerants for new split air conditioning systems, and one into alternatives to F-gases used in switchgear and related equipment.

The major findings of these reports are that:

- There is growing potential for ultra-low-GWP alternatives to F-gases to be used in a greater range of cooling systems. Increasing knowledge, practices and know-how in how to manufacture, install, use and manage flammable refrigerants will allow even greater uptake, alongside countries revisiting their restrictions around F-gases alternatives.[4]
- There is an increasing pipeline of low-GWP F-gases that have the potential to reduce the average GWP of gases used in single split systems to less than 150.
- There are commercially available alternatives to SF_6 for many applications in electric switchgear and related equipment. These alternatives are marginally more expensive but have “almost identical” technical characteristics. Within the next two to five years, commercially viable alternatives to higher voltage systems using SF_6 could be available.[5] The deployment of SF_6-free equipment will be easier to do at the installation or replacement of a system rather than retrofitting systems mid-life.

3. Approach to analysis for the Sixth Carbon Budget advice

This section details how the options for abatement outlined in Section 2 are utilised in our different scenarios.

a) Analytical methodology

Our baseline assumes that the UK remains in an equivalent regulatory environment to that of the EU. Our projections of F-gas emissions under this regulatory framework indicate this will deliver significant abatement across several sectors:

- **Refrigeration, air conditioning and heat pumps (RACHP)** emissions fall by 75%, from 12 MCO_2e in 2018 to around 3 $MtCO_2e$ in 2030, allowing for a substantial increase in the number of heat pumps in the UK (Box 11.2).
- **Technical aerosols** emissions fall by 94% between 2017 and 2022 to less than 0.05 $MtCO_2e$ following the ban of high-GWP F-gases.
- **Fire Protection Systems (FPS)** emissions to fall by around two-thirds by 2030 and to zero emissions by 2038.
- **Manufacture of new foams** emissions fall to zero in 2023, following a ban on the use of high-GWP F-gases as blowing agents in 2022.
- **Gas Insulated Switchgear (GIS)** emissions from GIS in electricity networks are expected to fall slowly (35% from 2017 to 2030), as older SF_6 equipment is replaced with modern equipment with much smaller SF_6 charges and lower levels of leakage.

This baseline regulation results in F-gas emissions reaching 3.4 $MtCO_2e$ by 2050, a reduction of 85% on 1990 levels and 84% on 2018. The scenarios in this report show that an additional 1-2 $MtCO_2e$ can be achieved on top of these baseline reductions.

Box 11.2

Methodology for F-gas emissions associated with refrigerant leakage in heat pumps

Emissions in each scenario are influenced by the total number of heat pumps assumed to be deployed in that scenario in buildings (see Chapter 2 of this report).

Net GHG benefits of heat pumps. The greenhouse gas benefits of switching from fossil fuel heating to heat pumps far outweigh the potential increase in HFC emissions from refrigerant leakage:

- Analysis for the Government in 2014 showed that for every additional 1 tCO_2e of additional HFC emissions from refrigerant leakage in heat pumps, there are 161 tCO_2e of CO_2 savings due to avoided emissions from gas boilers and efficiency improvements.
- This analysis assumed a power sector that was decarbonised to be consistent with the UK's old 80% target for 2050, at 32 gCO_2/kWh_e. In our Balanced Net Zero pathway, the UK would reach that level of electricity carbon intensity before 2035 (see Chapter 5), and the net greenhouse gas savings of heat pumps with a Net Zero power sector in 2050 will therefore be even greater.

In all our scenarios, millions of heat pumps are deployed by 2050. This will cause F-gas emissions to rise, but this increase will be orders of magnitude lower than the carbon savings.

If these heat pumps use lower-GWP F-gases or alternatives (as explored in our scenarios), this rise can be even smaller, and the net benefit even greater.

Market-ready solutions. The existing UK F-gas regulation applies to heat pumps, meaning that producers for the UK (and EU) market are mandated to shift to lower-GWP gases.

This regulation is already driving a shift from high-GWP gases to lower-GWP options such as HFC-32, which is expected to be the dominant HFC refrigerant in our analysis during the Sixth Carbon Budget period.

Switching to low-GWP technology may also lead to efficiency improvements in heat pumps. However, as our analysis of the residential buildings sector already includes efficiency improvements for heat pumps (Chapter 2), we do not include any additional carbon savings in this chapter, to avoid 'double counting' efficiency improvements.

Potential for further abatement. There is little current progress towards an even lower-GWP alternative to HFC-32. For small systems, hydrocarbon refrigerants such as propane are a good option, but high flammability limits the proportion of the market that can safely use hydrocarbon refrigerants. It is unlikely that more 50% of the residential heat pump market could use hydrocarbons.

There is little likelihood of an ultra-low-GWP refrigerant with similar properties to HFC-32 becoming available, so the industry would need to look for a 'not-in-kind' design. One possibility would be to use the type of air-conditioning technology adopted in car air-conditioning – based on HFO-1234yf. This has a GWP of just four, which could reduce F-gas emissions further by around 1 $MtCO_2e$. This more speculative technological solution is not included in our Balanced Net Zero Pathway.

Alternative technological solutions are being developed and our analysis should not be interpreted as a recommendation on which particular low-GWP or ultra-low-GWP solution for heat pumps is most suitable.

Source: Eunomia Research for DECC (2014) *Impacts of leakage from refrigerants in heat pumps*; Ricardo and Gluckman Consulting (2018) *Assessment of the potential to reduce UK F-gas emissions beyond the ambition of the F-gas Regulation and Kigali Amendment*.

b) Emissions in the Balanced Net Zero Pathway and exploratory scenarios

Due to the strong regulatory environment in the UK, our scenarios all show similar emissions reductions over time compared to current levels.

We use exploratory scenarios to explore different pathways to 2050:

- **Abatement beyond the baseline in all scenarios.** This results in 2050 emissions being 2.5 $MtCO_2e$ in 2050. All scenarios include:
  - **Lower leakage rates of refrigerants** due to improved equipment design, technical training and more controls on end-of-life disposal.
  - **Lower-GWP alternatives in small retail condensing units, small industrial sites and in marine industries**, replacing R-448A and R-449A units.
  - **Retrofits to lower-GWP alternatives** for large industrial R-404A refrigeration systems and R-134A air conditioning units in cars.
  - **Metered dose inhaler (MDI) improvements and substitutes.** Existing beclomethasone dipropionate and compound drug MDI inhalers are replaced with dry powder inhalers. Salbutamol MDIs are reformulated to use lower-GWP aerosols from the mid-2020s.
- **Balanced Net Zero Pathway.** Our Balanced Pathway results in 2050 emissions of 2.5 $MtCO_2e$. The pathway includes the measures in the Widespread Engagement scenario, but has slightly higher emissions overall due to further heat pump rollout in the buildings sector.
- **Headwinds scenario.** Our headwinds scenario contains the measures included in all scenarios (see bullets above) and nothing else. This achieves emissions on 2.5 $MtCO_2e$ by 2050.
- **Widespread Engagement scenario.** This scenario assumes that increased willingness to change behaviour results in increased uptake of dry powder inhalers (DPIs), specifically the replacement of salbutamol MDIs with DPIs. The emissions difference between a low-GWP MDI and a zero-emission DPI is extremely marginal, so this behavioural change makes little difference to emissions compared to the Balanced Net Zero Pathway, reaching 2.5 $MtCO_2e$ in 2050.
- **Widespread Innovation scenario.** Our Widespread Innovation and Tailwinds scenarios go further than the other scenarios, modelling HFC-32 replaced by a lower-GWP alternative. There is preliminary research being done into the technical capacity for hydrocarbons to replace HFC-32. Measures from our 2019 Net Zero report described as technically feasible but un-costed are included in this scenario. They are assumed to cost the UK-wide carbon price in the year of abatement (Chapter 1). Including these additional measures results in 2050 emissions of 1.6 $MtCO_2e$.
- **Tailwinds scenario.** This scenario includes all measures from the widespread engagement and innovation scenarios, resulting in 2050 emissions of 1.4 $MtCO_2e$.

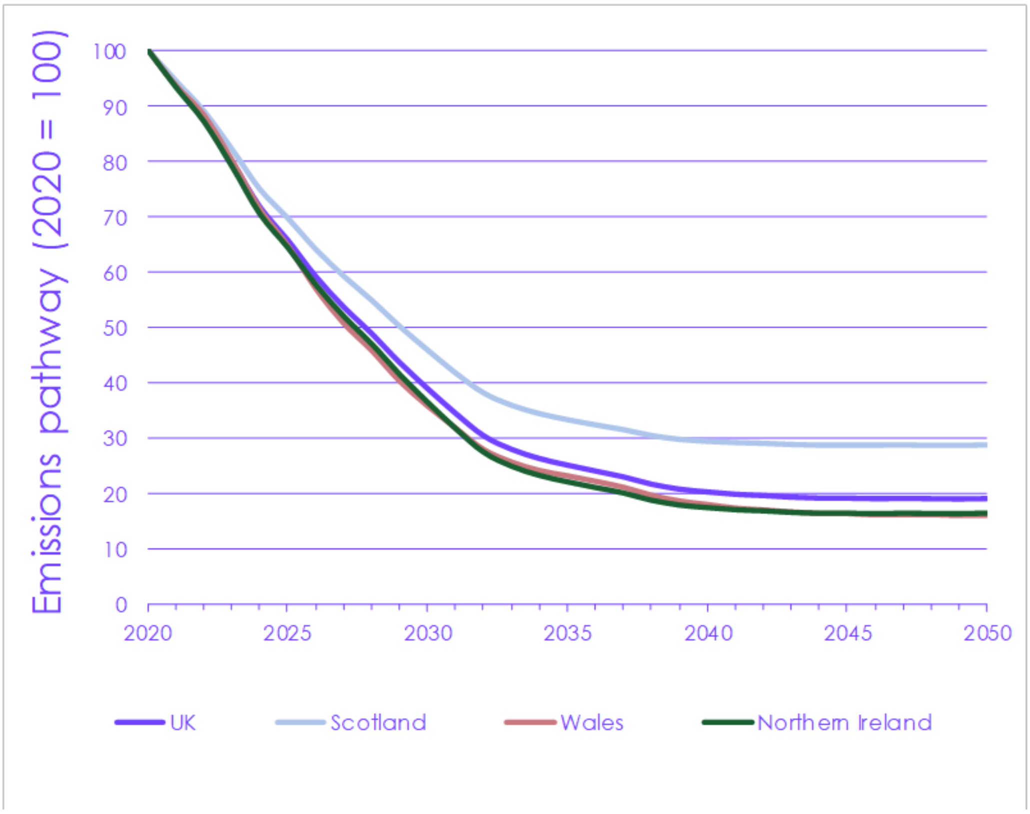
c) Deriving scenarios for emissions in Scotland, Wales and Northern Ireland

To determine the pathways for Scotland, Wales and Northern Ireland, we apply the same measures from the UK to current emissions sources of F-gases. Different existing shares of F-gases sources results in different speeds and depths of decarbonisation for the different parts of the UK:

- F-gases emissions from aluminium production and semiconductor production are higher in Scotland than the rest of the UK.
- There are no emissions from magnesium production in Scotland and Northern Ireland.

Due to the different shares of existing emissions, Northern Ireland and Wales can reduce emissions marginally faster and deeper than Scotland, which more closely mirrors the path that the UK takes (Figure 11.3).

Figure 11.3 Comparison of the Balanced Net Zero Pathway for the UK, Scotland, Wales, Northern Ireland



Source: CCC (2020) Sixth Carbon Budget analysis.

d) Approach to uncertainty and potential impacts of COVID-19 on sector emissions over time

Given the strong regulatory framework to drive down baseline emissions, the principal risk of not reducing F-gas is that policy is not maintained or enforced. This can be minimised through:

- **Maintaining a regulatory framework at least as strong as EU F-Gas Regulation.** Legislation has been passed that enables the UK to set a quota system that is independent from the EU quota. Defra has committed to maintaining the same percentage reductions as the EU F-Gas Regulation. The UK should match any strengthening of the EU system in the near future.

- **Minimising non-compliance, especially in the RACHP sector.** The Environment Audit Committee has reported evidence of suspected non-compliance, especially as EU F-Gas Regulation increase demand for lower-GWP refrigerants, and a lack of resources for the Environment Agency to carry out adequate inspections.

- **Increasing training and certification for F-gas users.** The current regulatory framework does not require retrospective training for workers trained under previous regulations and allows untrained members of the public to top-up their own car air-conditioning units with high-GWP refrigerants. The Government should consult with industry and bring forward proposals to ensure that all those who handle refrigerants have up-to-date training.

A further risk to the pathway is public knowledge of the warming impacts of metered dose inhalers (MDIs) and acceptance of dry powdered inhalers (DPIs):

- **Lack of awareness.** Previous analysis for the Committee has found a lack of awareness of the high global warming impact of metered dose inhalers (MDIs). The UK prescribes fewer DPIs than most other EU countries, despite evidence that DPIs can be more effective in clinical use for a large proportion of patients. This lack of knowledge is a behavioural barrier to a transition away from high-GWP MDIs. The Environmental Audit Committee corroborated this finding, reporting that low take-up of DPIs in the UK is, in part, due to low awareness of DPIs as an alternative among patients and GPs.[6]

- **Behavioural barriers** may also exist as patients and medical practitioners are reluctant to switch to new devices.

- **Promoting the use of DPIs** is likely to require engagement across organisations such as the Royal College of GPs, the British Thoracic Society and the National Institute for Health and Care Excellence (NICE) and the NHS Sustainable Development Unit. Clinicians and patients must be informed of the equivalent (or better) performance of DPIs and low-GWP MDIs as well as the environmental benefits.

- **Low-GWP MDIs** are another option that are currently in development and would require less behaviour change from patients while still cutting emissions by around 90%.

The COVID-19 pandemic does not present a material risk to the F-gases emission pathway.

Endnotes

[1] CCC (2020) *2020 Progress Report to Parliament*

[2] Ricardo and Gluckman Consulting (2018) *Assessment of the potential to reduce UK F-gas emissions beyond the ambition of the F-gas Regulation and Kigali Amendment.*

[3] European Pharmaceutical Review (2020) *Environmentally friendly pressurised Metered Dose Inhaler to be developed*.

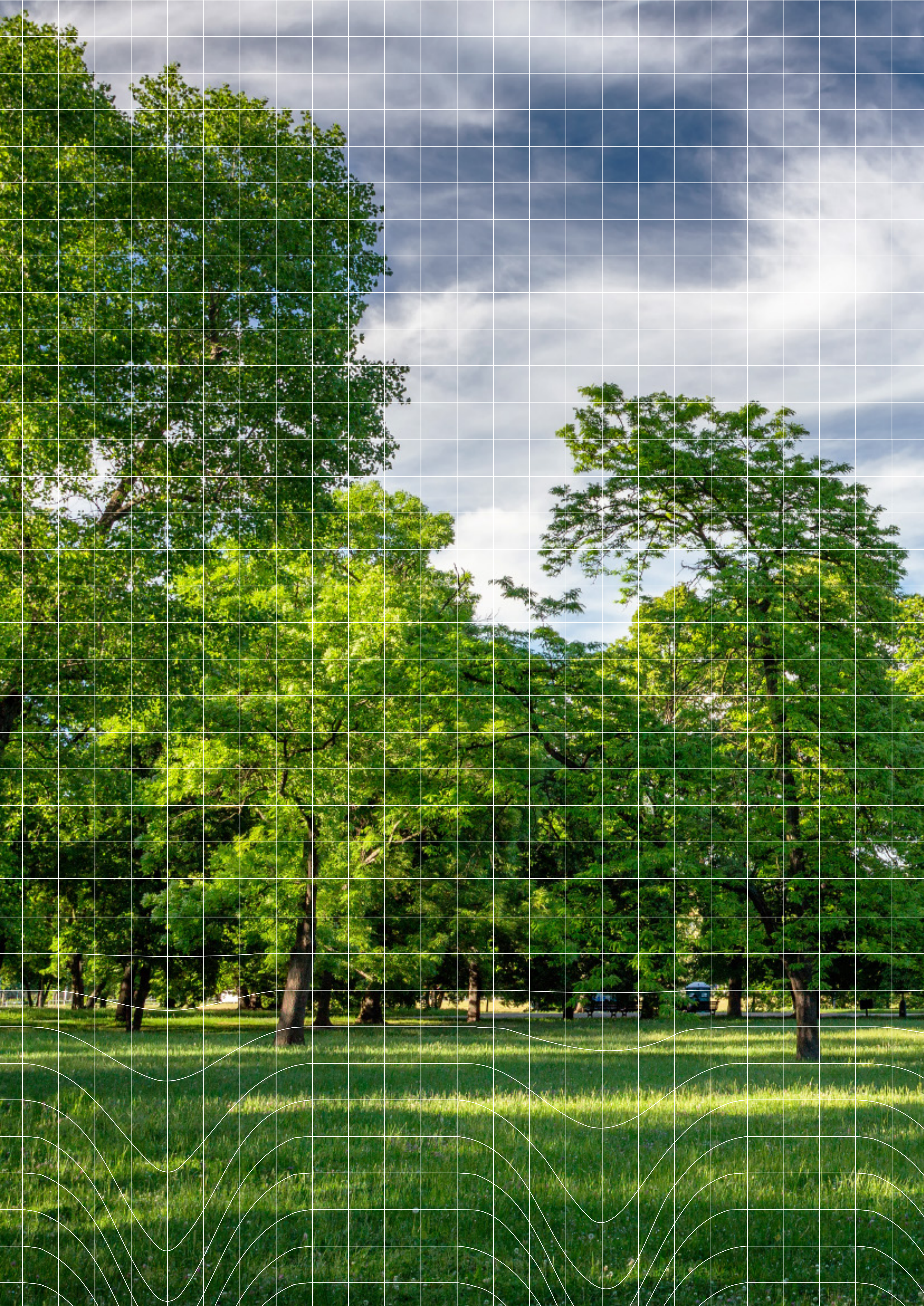
[4] European Commission (2020) *The availability of refrigerants for new split air conditioning systems that can replace fluorinated greenhouse gases or result in lower climate impact*

[5] European commission (2020) *Assessing the availability of alternatives to fluorinated greenhouse gases in switchgear and related equipment, including medium-voltage secondary switchgear*

[6] House of Commons Environmental Audit Committee (2018) *UK Progress on reducing F-gas emissions.*

Chapter 12

Greenhouse gas removals



Introduction and key messages

This chapter sets out the method for the greenhouse gas (GHG) removals sector's Sixth Carbon Budget pathways.

The scenario results of our costed pathways are set out in the accompanying *Advice report*. Policy implications are set out in the accompanying *Policy report*.

For ease, these sections covering pathways, method and policy advice for the GHG removals sector are collated in *The Sixth Carbon Budget – GHG removals*. A full dataset including key charts is also available alongside this document.

The key messages from this chapter are:

- **Background**. There have been no GHG removals recorded to date in the UK via the engineered GHG removal technologies within scope of this chapter. Wood in construction abatement has to date been partially counted within the Land Use, Land Use Change & Forestry (LULUCF) sector.
- **Options for reducing emissions**. Options for GHG removals include bioenergy with carbon capture and storage (BECCS), Direct Air Capture of CO_2 with storage (DACCS) and wood in construction. BECCS and DACCS involve long-term geological storage of captured CO_2, whereas wood in construction involves a decades/centuries-long temporary store of biogenic CO_2 in the buildings stock.
- **Analytical approach**. Based on the results of an updated analysis on the best use of bioenergy, we have allocated bioenergy and waste resources to conversion routes and sectors to maximise GHG savings and fit within the scenario framings of other end-use sector choices. CO_2 capture rates have then been applied to calculate BECCS removals in a bottom-up analysis. DACCS deployment has been calculated based on remaining aviation gross emissions. Wood in construction savings are based on increased use in new-build houses, less the harvested wood product removals already accounted for in the Land Use sector.
- **Uncertainty**. We have used the scenario framework to test the impacts of uncertainties, to inform our Balanced Net Zero Pathway. The key areas of uncertainty we test relate to domestic and imported biomass availabilities, different allocations of bioenergy between sectors and hence different counterfactuals being displaced by BECCS. We also test different capital, operating and fuel costs for DACCS (given its relative immaturity).

We set out our analysis in the following sections:

1. Sector emissions
2. Options for reducing emissions
3. Approach to analysis for the Sixth Carbon Budget

a) Breakdown of current emissions

Engineered GHG removals are currently not a sector in the UK GHG inventory (land-based removals are covered in Chapter 7). There are therefore no emissions or savings from engineered GHG removals in 2018, or in previous years.* They are only expected to be deployed from the 2020s onwards.

b) Emissions trends and drivers

In a Net Zero 2050 context, engineered GHG removals will be driven by remaining gross emissions across the economy that need to be offset (after LULUCF sinks accounted for), and the willingness of these gross emitting sectors, consumers or Government to pay for these GHG removals. Before 2050, the level of GHG removals will depend on any sector-specific targets, and market or policy design incentivising a ramp-up in GHG removals over time. Other key drivers will be availability of CCS infrastructure, supplies of sustainable, low cost biomass feedstocks for BECCS, supplies of low-carbon hydrogen for DACCS, and the rate of new house building for wood in construction.

* Wood use in construction is a carbon store that is currently used in the UK. To date there has been no explicit tracking of this as a dedicated pool of carbon but some of the changes to this pool have been captured (and will be captured going forward) within the Land Use, Land Use Change and Forestry (LULUCF) parts of the GHG inventory.

There are a wide variety of technology options proposed for removal of greenhouse gases from the atmosphere. The vast majority of these focus on CO_2 removal (as opposed to other GHGs), and our analysis also focuses only on CO_2.

Only a few CO_2 removal options have been fully or partially commercialised, and our analysis focuses on commercial options or those with the most development activity that are most likely to be commercialised globally in the coming decade.

Three emissions reduction options have therefore been explored within the GHG removals sector. These are:

- **Bioenergy with carbon capture and storage (BECCS)**. These technologies convert biomass, biogas and biogenic wastes into another energy vector (power, heat, hydrogen, fuels or methane), while at the same time capturing 90%+ of the biogenic CO_2 produced and sending it for geological sequestration. We have modelled six main BECCS categories:
  - **BECCS power**. Use of domestic or imported biomass to generate electricity, including retrofitting CCS to existing biomass power plants and new-build plants with CCS.
  - **BECCS energy from waste**. Use of UK residual mixed wastes to generate electricity. Involves retrofitting CCS to energy from waste power plants, with the biogenic fraction of the CO_2 captured counted as BECCS.
  - **BECCS in industry**. Use of domestic biomass, biogas and biogenic wastes to generate process heat via combustion, for up to 20 different industrial processes in the Manufacturing & Construction sector.
  - **BECCS hydrogen**. Gasification of domestic or imported biomass to syngas, then catalysis to hydrogen.
  - **BECCS biofuels**. Gasification of domestic biomass and UK biogenic wastes to syngas, then catalysis to Fischer-Tropsch (FT) biojet, biodiesel, and liquid heating fuels including liquid petroleum gas (bioLPG). In this BECCS category, some of the biogenic carbon remains in the resulting fuel, displacing fossil fuels, with less CO_2 sent to CCS.
  - **BECCS biomethane**. Upgrading of biogas to biomethane for UK gas grid injection (by separating out CO_2), or gasification of domestic biomass to syngas then catalysis to synthetic natural gas (bioSNG). In this BECCS category, some of the biogenic carbon remains in the resulting fuel, displacing fossil fuels, with less CO_2 sent to CCS.

  In the BECCS hydrogen, biofuels & bioSNG options above, gasification + catalysis is only one indicative technology option, and although other thermo-chemical & biological routes to these products are possible and being developed, we have not modelled these alternatives.

Similarly, for BECCS power, BECCS energy from waste and BECCS in industry, post-combustion capture has been modelled, but this is only one indicative option amongst several alternative conversion and capture technologies that are also under development.

- **Direct Air Capture with carbon capture and storage (DACCS)**. CO_2 is extracted directly from the air, with the use of a liquid solvent or solid sorbent, that is then re-heated to produce a CO_2 stream for sequestration. Significant amounts of electricity and heating fuel (assumed to be low-carbon hydrogen) are used in the process.
- **Wood in Construction**. Timber and wood panel products used in the construction of new buildings. This involves a temporary store of biogenic carbon out of the atmosphere, for the lifetime of each building (typically 50-100 years). The current UK GHG inventory does not explicitly track the size of the carbon pool in buildings, but changes in the store of wood within buildings will be partially included within the Land Use, Land Use Change and Forestry (LULUCF) harvested wood product inventories.* In this chapter we only report the additional carbon sink from increasing wood use in construction that is not already tracked with the current LULUCF inventory in order to avoid double counting. We consider scenarios that increase the use of wood in construction above current levels, increasing the total amount of biogenic carbon stored within the built environment.

Other engineered GHG removals options, such as enhanced weathering, biochar, biomass burial and carbon-negative cements, have not been modelled in our scenarios. As set out in our 2019 *Net Zero Technical Report*,[1] these options are more uncertain, need further development and may not in some cases achieve the same GHG savings as those options we have modelled. We have not modelled ocean-based sequestration options, due to legal frameworks and limited or uncertain potentials. Geoengineering options such as solar radiation management[2] are also ruled out of scope, as these do not directly influence the GHG emissions reported under the scope of the Climate Change Act.

Carbon capture and utilisation (e.g. in aviation synthetic fuels) is not a permanent store of CO_2, and so is not a form of GHG removal, even if the CO_2 is from Direct Air Capture. Where these occur in our scenarios, we have included them as reductions in sector (e.g. aviation) emissions as appropriate, rather than as CO_2 removal.

Bio-based plastics and bio-based chemicals are similarly a temporary store of biogenic carbon, unless these products are disposed of with CCS, in which case they would fall under BECCS energy from waste.

* It is only partially included as the longest lifetimes for wood products within the inventory (35 years) can be a significant underestimate of the lifetime of buildings. Our scenarios therefore have total removals from wood in construction of 1.4 $MtCO_2$/year in 2050, with 1.0 $MtCO_2$/year recorded in the LULUCF sector, and 0.4 $MtCO_2$/year recorded in this GHG removals sector.

a) Summary of scenario choices

As a reminder from Chapter 3, section 11 of the *Advice Report*, Table 12.1 below gives the results of the scenarios for each type of GHG removal considered.

The Baseline scenario has no deployment of BECCS and DACCS. For the use of wood in construction we do not use a formalised baseline approach, but instead track the additional removal of CO_2 that would appear in the UK GHG inventory under a more comprehensive tracking of the carbon in buildings in possible future inventory methodologies.

Table 12.1
Engineered GHG removals scenarios for the UK ($MtCO_2$/year in 2050)

	BECCS power	BECCS energy-from-waste	BECCS in industry	BECCS hydrogen	BECCS biofuels	BECCS bio-methane	DACCS	Wood in construction
Headwinds	39	10	4	23	10	0.6	0	0.4 (+1.0 in LULUCF)
Widespread Engagement	30	1	3	0	9	0.5	0	0.4 (+1.0 in LULUCF)
Widespread Innovation	16	5	3	12	11	0.5	15	0.4 (+1.0 in LULUCF)
Balanced Net Zero Pathway	19	7	3	14	8	0.6	5	0.4 (+1.0 in LULUCF)
Tailwinds	39	7	3	36	11	0.5	15	0.4 (+1.0 in LULUCF)
Baseline	0	0	0	0	0	0	0	NA

The following discussion goes through each of the GHG removals options and scenarios in turn.

Bioenergy with CCS (BECCS)

The GHG removals from BECCS are determined by the biomass, biogas & bio-waste resource allocations in the Fuel Supply sector (e.g. the amount of biomass allocated to making jet fuel) or assumptions in the Waste sector (e.g. recycling rates impacting residual waste arisings), combined with the bioenergy process efficiencies and CO_2 capture rates set by each of the other sectors. The BECCS results are therefore determined by factors outside of this sector, with the key trends explained below:

- There are only small variations between the scenarios in 2050 for BECCS in industry, BECCS biofuels and BECCS bio-methane, due to similar demands and supply availabilities for these routes. Earlier years show greater variation, due to differing start years and ramp-up rates being applied, or some routes being deployed then transitioning (e.g. bioSNG plants being retrofitted to biohydrogen in Widespread Innovation and Tailwinds).
- Other BECCS options have greater variation in 2050.

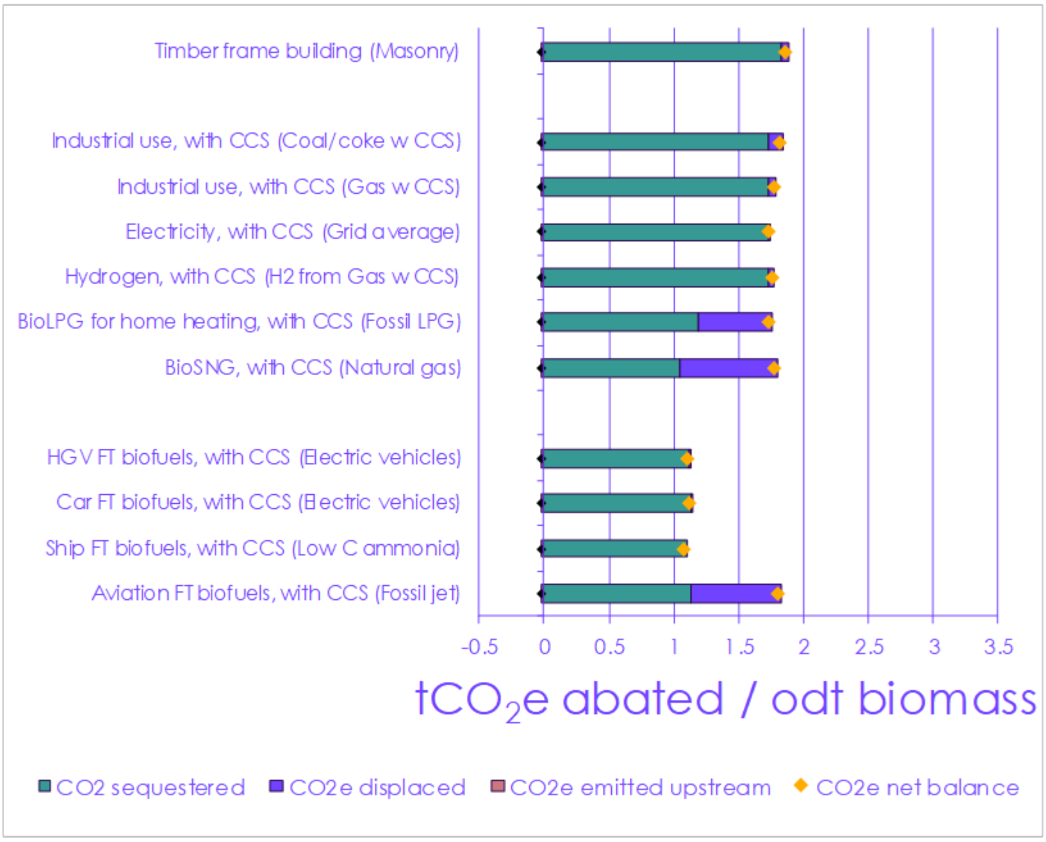
  - In Headwinds and Tailwinds, BECCS power and BECCS hydrogen deployment is high, due to the highest availability of biomass imports. Whereas in Widespread Innovation, BECCS power is more limited, due to phasing out of biomass imports over time.
  - In Widespread Engagement, less technology development is assumed, so there is no reliance on BECCS hydrogen, and biomass imports are allocated to BECCS power instead. In this scenario, the majority of residual waste is also allocated away from Energy from waste plants by 2050 and sent to waste-to-jet routes instead, explaining the low BECCS energy-from-waste values.
  - In Headwinds, residual waste arisings are large, due to less action on waste prevention and recycling than in other scenarios, and so the BECCS energy-from-waste values are also higher compared to other scenarios.
- The Balanced Pathway has a blended approach across the BECCS options, due to modest levels of biomass imports and residual waste, and some technology development with the use of BECCS hydrogen and BECCS biofuels.

The exact splits of the different BECCS options are not designed to be prescriptive, rather illustrative, given that all these BECCS options achieve very similar and high GHG savings per tonne of feedstock (Figure 12.1). Further analysis of best uses of bioenergy and waste is given in the Fuel Supply methodology (Chapter 6).

If significantly less of one BECCS option is carried out, it is likely that more of another BECCS option will be required, unless progress on gross emissions reductions elsewhere in the economy is faster than expected.

There will be considerable variation in BECCS costs depending on location, size, feedstock costs, cost of capital and the ability to retrofit to existing facilities. These variations may lead to some BECCS routes being preferred over others. Some options are also at a higher technology readiness level than others and seen as lower risk to investors. The UK policy incentives made available for negative emissions and future market dynamics of power, hydrogen, fuels and heat prices will also play a critical role in determining the potential profitability of the different options, and so their future deployment – we have not attempted to estimate profitability, only indicative resource costs.

Figure 12.1 Best use of biomass in 2050



Source: Ofgem (2018) *Biomass Sustainability Dataset 2016-17*; CCC analysis.
Notes: Counterfactuals given in brackets. Upstream emissions include cultivation, processing, transportation and direct land-use change, but indirect land-use change and changes in land carbon stocks when no land-use change occurs are excluded. Upstream min-max range from Ofgem feedstock data (sawmill co-products, Miscanthus, SRC, wood pellets, forest residues and brash bales).

Direct Air Capture of CO_2 with storage (DACCS)

There is no deployment of DACCS in the Headwinds and Widespread Engagement scenarios, due to less ambitious technology development assumptions being taken, combined with higher energy costs than in other scenarios, making DACCS more expensive and unlikely to be deployed by 2050.

- In the Widespread Innovation scenario, the deployment of DACCS starts in 2035 and ramps up to fully offset the 2050 residual gross emissions from the Aviation sector (15 $MtCO_2$/year). The start date of 2035 is when DACCS, under the optimistic hydrogen, power and capital cost assumptions of the Widespread Innovation scenario, first becomes cost-effective (at £169/tCO_2e) when compared against BEIS high carbon value projections. By 2050, in this scenario DACCS costs are assumed to reach £120/tCO_2.

- In the Tailwinds scenario, the deployment of DACCS and its cost profile is replicated from the Widespread Innovation scenario.

- In the Balanced Pathway, due to less ambitious hydrogen, power and capital cost assumptions being taken, DACCS only becomes cost-effective at £210/tCO_2e in 2040, so starts being deployed at this date. The ramp-up to the 2050 deployment of 5 MtCO_2/year is also less ambitious, with an assumption made that DACCS would reach around one third of the Widespread Innovation level. By 2050, in this scenario DACCS costs in this scenario are assumed to reach £180/tCO_2.

Wood in Construction

Given that each scenario produces a significant amount of UK timber and wood-based products in the UK, well in excess of housebuilding demands, we assume the same scenario for increased use of wood in construction across all our pathways.

The proportion of timber-framed new build houses rises rapidly from around 28% today to over 40% by 2050. Engineered wood systems remain a minor contributor, reaching 5% by 2050. Our scenarios are based on the number of housing starts rising to over 320,000 each year by 2050, consistent with the Government's house building ambition. This scenario is based on an independent report from the Bangor Biocomposites Centre that we commissioned as part of our 2018 *Biomass in a low-carbon economy report.*[3]

b) Sector classifications

With our current sector classifications, emissions reductions in the end use sectors from the displacement of high-carbon fuels with negative-carbon fuels have been split – with the gross emission reductions (from high to zero) counted outside of the GHG removals sector, and only the negative emissions part of the abatement (from zero to negative) counted within the GHG removals sector. This does not constitute a recommendation on emissions accounting, merely what we have assumed for this analysis.

Similarly, when mixed residual waste (which has a biogenic fraction and a fossil fraction) is used in a conversion process (e.g. energy-from-waste, or waste to jet fuel), only the biogenic CO_2 captured and sequestered is counted within GHG removals. The fossil CO_2 captured and sequestered, or the fossil CO_2 not captured, is accounted for as an emissions reduction or emissions within the relevant sector (e.g. within Waste for energy-from-waste, or within Fuel Supply for waste to jet).

End use sectors investing in negative emission options, e.g. as part of achieving an individual sector net zero goal, is not classified in our analysis as being counted within that sector. For example:

- Airlines paying for DACCS in the UK, in order to offset their gross emissions, would have this DACCS counted in our analysis within GHG removals.

- Ship operators paying for tree planting in the UK, in order to offset their gross emissions, would have this land-based sink counted within the LULUCF sinks sector.

However, we recognise that sector policy or targets could be set up that allow removals to be allocated to that sector to reduce their gross emissions. Provided double-counting of the same removals is avoided (via excluding them from the GHG removals or LULUCF sinks sector), this would be an acceptable alternative accounting methodology.

And for example in the Aviation sector, our sector classification also means that while e.g. some sustainable aviation fuels could be carbon negative on a lifecycle basis at the point of use (if there is upstream biogenic CCS involved in their production), our analysis of the Aviation sector only considers the direct accounting CO_2 emissions from the use of low-carbon fuels, i.e. zero and not negative.

If an alternative accounting methodology were followed, the negative emissions from upstream biogenic CCS could be counted within the Aviation sector, but then these upstream negative emissions would have to be excluded from the GHG removals sector to avoid double-counting.

c) Analytical steps

The analysis for greenhouse gas removals in the Sixth Carbon Budget only covers CO_2, and covers the removals over the UK as a whole.

Constant properties over time are assumed for biomass, waste, biogas, biofuels and biomethane densities, calorific values and combustion CO_2 emission values (with only waste varying in biogenic vs. fossil fractions over time from the Waste sector analysis). Values are taken from Defra conversion factors.[4] For a discussion of feedstock and product costs, see the Fuel Supply methodology (Chapter 6).

GHG removals are split into three sub-sectors (and abatement methods): BECCS, DACCS and Wood in Construction. Each sub-sector uses a different analysis methodology, as described below.

BECCS

- We have ensured that overall consumption of biomass and waste feedstocks was within available sustainable resource limits. These resource estimates and their changes over time are discussed in more detail in the Fuel Supply methodology (Chapter 6).
- BECCS deployment follows the sectors in which BECCS technologies are used: BECCS power in the Power sector, BECCS energy-from-waste in the Waste sector, BECCS in industry from the Manufacturing & Construction sector, and BECCS hydrogen, biofuels & bio-methane in the Fuel Supply sector. Similarly, input feedstock and energy flows (and their DA splits) are recorded in each of these sectors. For further details on deployments and energy flows, see each sector's chapter of this Methodology Report (for BECCS energy-from-waste, see Chapter 4 on Element Energy modelling).
- It is assumed that CO_2 capture technology improves to 2050, so that BECCS processes that produce power, heat or hydrogen are able to capture 95% of the emitted CO_2 for sequestration by 2050 (e.g. through improved plant design, improved solvents). BECCS biofuels and BECCS bio-methane processes are assumed to start from a lower base (based on early plants focusing initially on higher concentration CO_2 streams, and perhaps not capturing more dilute flue gases or smaller less viable streams), but over time these plants also are assumed to improve to an aggregate 90% capture rate, where CO_2 streams across the conversion plant are being captured (including flue gases and smaller streams). BECCS capture rate assumptions over time for each option are given in Table 12.2.

- These capture %s for BECCS biofuels and BECCS bio-methane only consider the amount captured out of the carbon that is lost between the input feedstock and the output fuel product – the %s do not consider the carbon within the product fuel. In the case of BECCS power, energy-from-waste, industry and hydrogen, no carbon ends up in a product, so these %s are the same as the captured % of input feedstock carbon.

Table 12.2
BECCS CO_2 capture rates (% of CO_2 released in conversion)

	BECCS power	BECCS Energy from Waste	BECCS in industry	BECCS hydrogen	BECCS biofuels	BECCS bio-methane
2030	90%	90%	90%	87%	75%	75%
2040	92%	95%	95%	92%	83%	83%
2050	95%	95%	95%	95%	90%	90%

- BECCS capital and operating costs are determined in each of the sectors in which BECCS technologies are used, with differences modelled for the application, retrofit vs. new build and use of domestic vs. imported biomass feedstocks. For further details on capital and operating costs, efficiencies, lifetimes and interest rates, see each sector's methodology chapter. Where a choice of feedstocks is not given, it has been assumed that domestic biomass or waste feedstocks are used, not imported biomass. A fixed downstream CO_2 transmission and storage cost of £15/tCO_2 is also applied to all BECCS options.

- BECCS £/tCO_2 abatement costs are calculated as:

  $(£/MWh_{BECCS} - £/MWh_{counterfactual})/(tCO_2e/MWh_{counterfactual} - tCO_2e/MWh_{BECCS})$

  The counterfactual varies by sector:

  - BECCS power: wholesale grid electricity without BECCS (which by 2050 is a scenario blend of mostly zero-carbon emission sources)
  - BECCS energy-from-waste: energy-from-waste plants without CCS (see Chapter 4)
  - BECCS in industry: process heating without CCS (Manufacturing & Construction sector baseline of no further climate policy action, see Chapter 4)
  - BECCS hydrogen: natural gas reforming with CCS*
  - BECCS aviation biojet: fossil jet fuel
  - BECCS biodiesel: fossil diesel
  - BECCS bioLPG: fossil LPG
  - BECCS bioSNG and BECCS biomethane: fossil natural gas

* In some scenarios, a combination of natural gas reforming with CCS and hydrogen imports (from renewable electrolysis abroad) is displaced by BECCS hydrogen. However, hydrogen imports have a very similar cost and emissions factor to domestic gas CCS sources, so the counterfactual calculation is almost identical.

DACCS

- Deployment profiles for $MtCO_2$/year follow the trajectories discussed above, with an assumed 0.3 $MtCO_2$/year in the first year of commercial deployment (2035 or 2040, depending on the scenario).
- Electricity and heating fuel (hydrogen) use factors are derived from academic literature, industry and IEA sources, with conservative values improving over time to 2050.[5] Energy and hydrogen costs for each scenario are taken from our Power and Fuel Supply analyses. Electricity and hydrogen inflows to the sector are split into DAs (see below).
- Capital and non-energy operating costs for DAC, plus a 25-year lifetime and 6% discount rate, are taken from Royal Society (2019),[6] to be consistent with DAC synthetic jet fuel production costs. This downwards DAC cost trajectory is applied to the Widespread Innovation and Tailwinds scenarios, whereas capital and non-energy operating costs are assumed to be doubled for the Balanced Net Zero Pathway (still within the Royal Society range, but nearer the top of the range instead of nearer the bottom).
- Total £/tCO_2 DAC costs are calculated, with a fixed downstream CO_2 transmission and storage cost of £15/tCO_2 then applied to convert DAC costs into DACCS costs. These DAC costs are also used in the Fuel Supply sector for producing synthetic jet fuel for aviation – see the Fuel Supply methodology (Chapter 6).

Wood in construction

- Our scenarios see the total gross storage of carbon in UK buildings rise from around 1.2 $MtCO_2e$/year currently to 2.3 $MtCO_2$/year by 2050 (1.9 $MtCO_2$/year in 2035).
- However, GHG inventory methodologies mean that only removals from wood sourced from the UK will count to the UK GHG inventory. We assume that two-thirds of sawn wood, all cross-laminated timber and one-third of wood-based panels are imported from outside the UK consistent with current (2012) patterns. For UK GHG accounting purposes this means that the total accounted sequestration from wood in construction would rise from 0.8 $MtCO_2$/year in 2019 to 1.4 $MtCO_2$/year in 2050 (1.2 $MtCO_2$/year in 2035) in all scenarios.
- We allow for how wood products are currently incorporated in the LULUCF sector of the GHG inventory to ensure that overlap is accounted for and double counting avoided. We estimate around 0.4 $MtCO_2$/year in 2050 of this sink is not captured within the LULUCF sector under current accounting methodologies (0.2 $MtCO_2$/year in 2035). Abatement from the avoided use of high-carbon construction materials is accounted for within our manufacturing and construction sector (Chapter 4).
- No additional costs are assumed for achieving GHG removals via wood in construction, beyond those costs already included in the Land Use and manufacturing & construction sectors.

d) Devolved administrations

There are no engineered removal emissions in 2018 in the UK or devolved administrations (DAs), beyond any wood in construction already accounted for in the LULUCF sector. Going forwards, there are different choices about how the negative emissions from each GHG removal option might be located between the different parts of the UK. The following methodology points are known:

- BECCS: As per IPCC guidance[7], BECCS removal is based on the location of biogenic CO_2 capture, not the location of biomass production or geological CO_2 sequestration. The allocation of BECCS between the DAs will therefore depend where BECCS plants are constructed or retrofitted.
- DACCS: IPCC guidance is not yet given, but following the same approach as for BECCS would allocate the DACCS removals based on the location of the capture of CO_2 from the atmosphere, i.e. where the DAC plants are physically located.
- Wood in Construction: splits to devolved administrations follow harvested wood production in the Land Use sector, as per the IPCC methodology. There are some modest differences between scenarios over time, based on the different tree planting rates assumed.

It is therefore clear where Wood in Construction removals are allocated for each scenario. However, where BECCS and DACCS plants will be constructed across the UK is highly uncertain. Key considerations are likely to be:

- High density of local feedstocks or else access to biomass import facilities, noting that different scenarios have varying mixes of domestic and imported biomass (e.g. Headwinds has high biomass imports, whereas biomass imports phase out in Widespread Innovation). DACCS will instead require hydrogen to be available locally for process heating. The Fuel Supply methodology (Chapter 6) sets out the expected locational splits of biomass and waste feedstocks.
- Distance to CCS sequestration hubs and CO_2 pipeline infrastructure. The Manufacturing & Construction and Fuel Supply methodologies (Chapters 4 and 6) provide further details of CCS locations.
- Nearby industrial users or markets for the products, particularly those products that are more expensive to transport (e.g. BECCS hydrogen plants near users of hydrogen, or BECCS bio-methane near the gas grid, or BECCS power plants on the power grid). This consideration is not applicable to DACCS.
- Power use, water use, chemical use, waste disposal aspects.
- Planning and local community support.
- Available local labour force and transport links.
- Any additional local supportive policies targeting GHG removals (e.g. business loans, planning zoning).

BECCS and DACCS plants will likely be sited based on a combination of the above factors. Delivering the total amount of engineered removals within a given scenario could lead to very widely varying allocations of removals to devolved administrations, depending on these location decisions.

Our scenarios are not intended to be prescriptive, only illustrative. We have therefore presented our analysis for the DAs without any GHG removals, and then indicated what share of the total UK GHG removals would have to be allocated to/achieved within each DA to achieve Net Zero in each DA. We have not specified how much BECCS and DACCS are likely to be built in each DA – this is potential work for the future, requiring sophisticated spatial optimisation, building on the work of e.g. the Energy Technologies Institute and others.[8]

e) Uncertainties

Uncertainties in the scenario analysis fall into the following main categories:

- **COVID-19**. Given there are no GHG removals yet in the UK, these have not been impacted by COVID-19. We have not attempted to calculate a long-term reduction in energy demand due to structural changes in GDP due to COVID-19; nor have we considered any potential reductions in supply via failures of feedstock suppliers, supply chain actors or potential plant operators. There remain some uncertainties as to the size of the energy industry that will emerge post-COVID, and the role each sector will play in developing GHG removals.
- **CCS availability**. The BECCS and DACCS deployments are predicated on UK CCS infrastructure beginning at commercial scale in the mid-2020s and being widely available across the UK from 2030. No locational constraints have been placed on BECCS and DACCS roll outs. If CCS were delayed, this would also delay BECCS deployment, and potentially DACCS if delays extended well past 2030.
- **Technology characterisation**:
  - Our modelling assumes increasing efficiencies and capture rates, and declining capital and operating costs over time. Given the complexities of 24 different routes across 15 sectors, it was only possible to implement a fleet/sales approach for capital costs (i.e. plants built earlier cost more) and the added capital costs of transitioning one plant type to another (e.g. FT biodiesel to FT biojet in a particular year).
  - It was not possible to implement this approach for other metrics – this means that in each year, the efficiency, operating costs and capture rate of a route is the same across all the plants in that route, regardless of when each plant was built.
  - Our assumptions about efficiency improvements are therefore modest to account for this fleet impact (only an increase of 1-5 percentage points from 2020 to 2050, depending on the route).
  - Capture rates could also feasibly be improved after installation, with further process optimisation, new equipment or improved materials (e.g. new solvents).
  - Operating costs are expected to fall with experience and greater automation, sharing overheads across a fleet of plants, and as plants scale up in size with commercialisation.
- **Application of costs**. Our costs for BECCS and DACCS plants are indicative. There is likely to be a broad range of costs around our estimates, given differences in site size, location, existing equipment, cost of capital and lifetimes. Smaller projects or projects further from CCS hubs or feedstock/energy sources might cost significantly more than modelled.

Endnotes

[1] CCC (2019) *Net Zero Technical Report*

[2] BEIS (2020) *The UK Government's View on Greenhouse Gas Removal Technologies and Solar Radiation Management*

[3] Bangor Bio-Composites Centre (2019) *Wood in Construction in the UK: An Analysis of Carbon Abatement Potential, Extended Summary*, published as supporting evidence for CCC (2018) *Biomass in a low-carbon economy*.

[4] Defra (2020) *Greenhouse gas reporting: conversion factors 2020*

[5] Marcucci et al (2017) *The road to achieving the long-term Paris targets: energy transition and the role of direct air capture;* Creutzig et al (2019) *The mutual dependence of negative emissions technologies and energy systems;* Keith et al. (2018) *A process for capturing CO2 from the atmosphere;* IEA (2020) *Energy needs for DAC technologies for CO2 use and storage.*

[6] Royal Society (2019) *Sustainable synthetic carbon based fuels for transport*

[7] IPCC (2020) *2019 Refinement to the 2006 IPCC Guidelines*, page 5 of Chapter 8, Volume 1

[8] ETI (2015) *Insights into the future UK Bioenergy sector, gained using the ETI's Bioenergy Value Chain Model (BVCM)*

December 2020

The Sixth Carbon Budget
Methodology Report

Climate Change Committee
151 Buckingham Palace Road London
SW1W 9SW

www.theccc.org.uk
@theCCCuk