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Methodology report

Methodology behind the CCC's carbon budget advice for the UK, Northern Ireland, Wales, and Scotland, published in 2025

Climate Change Committee

Methodology report – UK, Northern Ireland, Wales, and Scotland carbon budget advice

Climate Change Committee
21 May 2025

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Part 1: Cross-economy methodology

Chapter 1: Approach to the Committee's advice on the UK's Seventh Carbon Budget and carbon budgets for Northern Ireland, Wales, and Scotland

Introduction

The Committee is advising that:*

- The UK sets its Seventh Carbon Budget (which is the legal limit for UK net greenhouse gas emissions over the years from 2038 to 2042) at 535 $MtCO_2e$.
- Northern Ireland sets its Fourth Carbon Budget (also 2038 to 2042) as a 77% reduction in emissions compared to 1990 levels.
- Wales sets its Fourth Carbon Budget (covering 2031 to 2035) as a 73% reduction in emissions compared to 1990 levels.
- Scotland sets its First Carbon Budget (2026 to 2030) as a 57% reduction in emissions compared to 1990 levels, its Second Carbon Budget (2031 to 2035) as a 69% reduction in emissions compared to 1990 levels, its Third Carbon Budget (2036 to 2040) as an 80% reduction in emissions compared to 1990 levels, and its Fourth Carbon Budget (2041 to 2045) as a 94% reduction in emissions compared to 1990 levels.

The details of these recommendations and the key findings supporting them are set out in our UK Seventh Carbon Budget advice report, Northern Ireland Fourth Carbon Budget advice report, Wales Fourth Carbon Budget advice report, and Scotland Carbon Budgets advice report.

These carbon budget recommendations are based on the Balanced Pathway, which is an ambitious, deliverable pathway for the UK to reach Net Zero by 2050.† This pathway is based on detailed modelling of cost-effective, feasible decarbonisation options. This methodology report provides a summary of the Committee's analytical approach to developing this Balanced Pathway, describing the modelling approaches used and the supporting evidence base.

* Our recommended carbon budget levels for the UK, Wales, and Scotland all include the respective nations' shares of international aviation and shipping emissions. These are not included in our recommended level for Northern Ireland's Fourth Carbon Budget, although the Northern Ireland Executive should still work with the UK Government to reduce these emissions.

† Our advice on Northern Ireland's Fourth Carbon Budget is based on the Northern Ireland Net Zero Pathway, which is based on the Balanced Pathway but with additional allocation of direct air carbon capture and storage (DACCS), itself taken as a proportion of the UK-wide DACCS within the Balanced Pathway.

1.1 Methodology, data, and evidence behind our recommended carbon budgets

In this chapter, we set out our overarching approach to developing the Balanced Pathway, how this is structured, and the principles that we use in determining what measures to include in the pathway and the pace at which these are taken up:

- Section 1.2 summarises how we structure our modelling, including how our sectoral models fit together to form the Balanced Pathway.
- For completeness, Sections 1.3-1.6 repeat Chapter 2 from our Seventh Carbon Budget advice report, describing our overall analytical approach.
- Section 1.7 then provides further detail on our approach to developing and validating the assumptions that are included within this approach.
- Finally, Section 1.8 summarises the core outputs that are produced from our models and how these are aggregated together.

For each sector, specific details of the modelling assumptions used and how these are applied to determine the pathway are set out in the sectoral chapters of this document (Chapters 6-18). Details of how we estimate the cost of delivering our pathway and its impact on households and businesses can be found in Chapters 2-4. The uncertainties we have assessed are discussed in Chapter 5. Alongside this methodology report, we have published a set of accompanying data tables, which provide details of the key assumptions and data underpinning our analysis. These data tables may be updated in future to provide further information underpinning our analysis.

We have also published the following data and evidence behind our recommended carbon budgets:

- A dataset for the pathway, setting out more details and data on the pathway, including at sector and subsector level. A separate dataset has been published alongside each of the advice reports for the UK, Scotland, Wales, and Northern Ireland, covering what the pathway means in each nation.
- The data behind each of the charts in each of the advice reports.
- Supporting evidence, including a summary of responses to our public Call for Evidence and 17 new research projects that have fed into our analysis.

1.2 Our overall analytical process

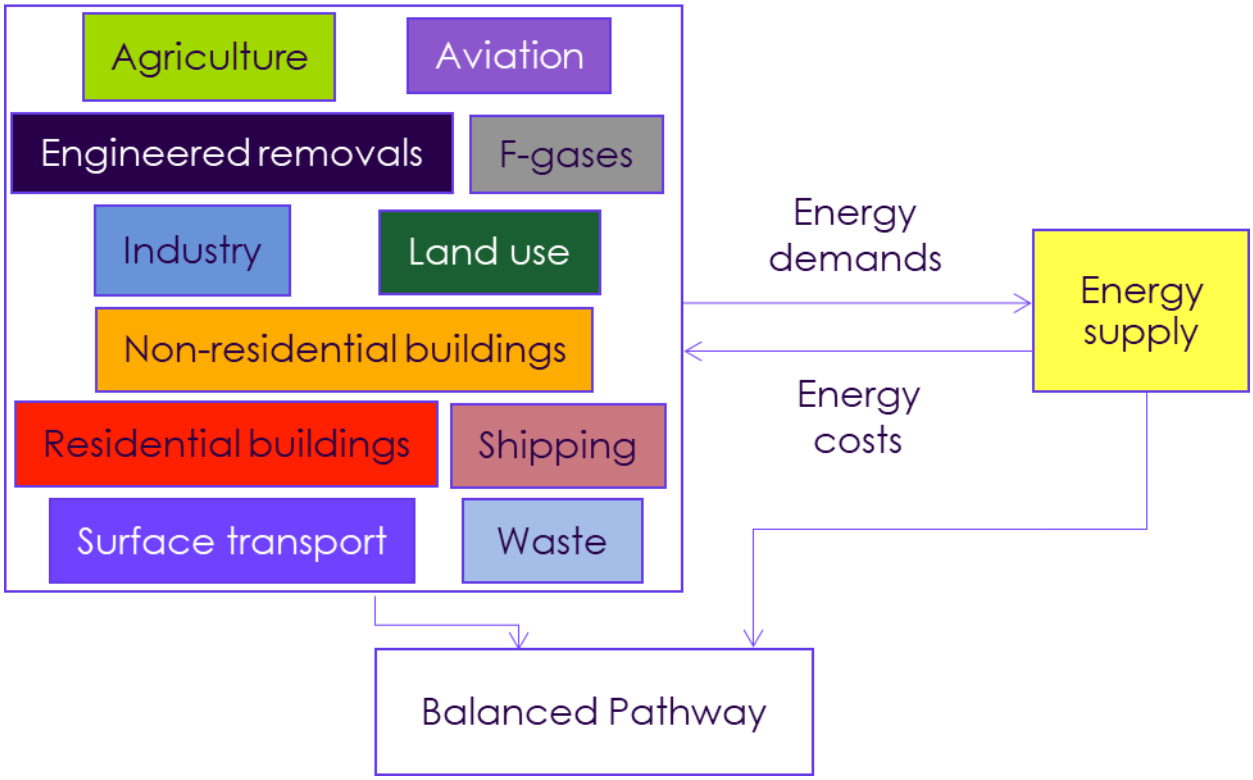
1.2.1 Our modelling approach

Our advice on the level of the UK's Seventh Carbon Budget, Northern Ireland's Fourth Carbon Budget, Wales' Fourth Carbon Budget, and Scotland's Carbon Budgets is informed by an updated Balanced Pathway. This is an ambitious, deliverable pathway that represents our assessment of the UK's best path to reach Net Zero by 2050, based on the latest evidence and data.

The pathway is developed by dividing the UK's emissions into sectors of the economy (see Section 1.2.2) and analysing these over the period from 2025 to 2050 (Figure 1.1).

- In each sector, we develop a baseline trajectory for how emissions would be expected to develop in the absence of further climate action, and a pathway which assesses the pace at which emissions could be reduced below this through credible decarbonisation actions.
- There is an iterative process between the energy supply sectors and the other sectors. The latter provide energy demands to the former, which impact the unit costs for each type of energy. The former provide energy costs to the latter, which determine the demands for each type of energy.
- Our approach to assessing uncertainties and options for going further or making up shortfalls in delivering this pathway is set out in Chapter 5.

Figure 1.1 Modelling process



Description: To develop our Balanced Pathway, we divide UK emissions into 11 energy-using sectors and the systems that supply the electricity and fuels that they require. Our analysis determines cost-effective and feasible rates of decarbonisation for each of these sectors.
Source: CCC analysis.
Notes: The energy supply block represents our electricity supply and fuel supply sectors.

Pathways for Scotland, Wales, and Northern Ireland

Emissions in Scotland, Wales, and Northern Ireland are modelled as part of the Balanced Pathway for our advice on the UK's Seventh Carbon Budget. This analysis has then been used as the basis for our advice on each nation's carbon budgets.

- As part of our analysis to develop the Balanced Pathway, we have assessed the emissions reductions that can be delivered in Scotland, Wales, and Northern Ireland. We have

accounted for differences in current and projected trends across the three nations as far as possible:

  - In all sectors, baseline starting points have been aligned to the latest available data on emissions and energy consumption for each nation (see Section 1.7).

  - In addition, we have included nation-specific assumptions where these are expected to drive significant differences in the level or pace of change compared to UK-wide averages. Our approach to developing these assumptions is set out in Chapters 6-18 of this methodology report.

  - As a result, the makeup of emissions reduction in each nation varies, with differing contributions according to the sectoral makeup of each nation's emissions and differing rates of decarbonisation across sectors. Details on the makeup and pace of emissions reductions are set out in the respective advice reports.

- For both Scotland and Wales, the level of ambition required to meet their individual Net Zero targets (2045 and 2050 respectively) and existing carbon budgets is consistent with that required to meet the UK's Net Zero target, in line with previous Committee advice.[1;2;3] Therefore, the Balanced Pathway provides both their contribution to the UK's pathway to Net Zero and ambitious, deliverable pathways to reach their Net Zero targets as well. We have used this pathway as the basis for our advice on Scotland's and Wales' carbon budgets.

  - The Balanced Pathway includes an allocation of engineered removals across nations. Our approach to this allocation is set out in Chapter 18.

- Northern Ireland's Net Zero target (2050) is more ambitious than the emissions reductions required in Northern Ireland to contribute to the UK's Net Zero target. Therefore, our advice on Northern Ireland's Fourth Carbon Budget is based on our Northern Ireland Net Zero Pathway, which goes beyond the Balanced Pathway in order to reach Net Zero for Northern Ireland by 2050.

  - The Northern Ireland Net Zero Pathway is identical to the Balanced Pathway except for the allocation of a proportion of the UK-wide DACCS deployment in the Balanced Pathway to Northern Ireland.

  - The considerations behind this allocation, as well as alternative approaches that could be followed to reduce this dependency on DACCS, are discussed in the Committee's advice on Northern Ireland's Fourth Carbon Budget.

1.2.2 Sector classifications

In the CCC's scenarios, UK emissions and energy demands are split into sectors and subsectors. The CCC's classification system was designed with the following considerations:

- **Policy relevance.** The sectors group emissions in a way that is consistent with the main policy levers involved. For instance, emissions from aviation are grouped as a sector, separately to surface transport, as the policy levers are largely mutually exclusive. This differs from other sector classifications, in which emissions from these different modes of transport are often grouped together.

- **Alignment to previous modelling projects.** The CCC has maintained the same sector classification as was used in previous carbon budget advice, meaning that our results have backwards compatibility. This is useful for quality assurance and change management.

There are a number of alternative sector classification systems that are used for presenting emissions data:

- **Net Zero Strategy (NZS) sectors.**[4] These were developed by the Department for Business, Energy and Industrial Strategy (BEIS) for the Government's 2021 Net Zero Strategy and were also used in the Government's 2023 Carbon Budget Delivery Plan. Box 1.1 compares the NZS sectors with the CCC's sectors.

- **Territorial Emissions Sectors (TES).**[5] These are the groupings used for the UK's emissions inventory. They are therefore designed with historical data in mind, so do not yet include engineered removals. The TES sectors, introduced in 2022, aim to present historical emissions data in more policy-relevant groupings, so are similar to the NZS sectors.

- **National Communication (NC) sectors**.[6] These were used for the UK's territorial emissions estimates until the 2024 release, when they were replaced by the TES sectors, which are more policy relevant. National Atmospheric Emissions Inventory (NAEI) datasets still provide the NC sectors for backwards comparability. Variations of the NC sectors have also been used for modelling projects by both the Scottish Government and the Northern Ireland Executive.

- **Sector classifications defined in devolved climate legislation.** In some cases, the Climate Change Acts or other relevant pieces of legislation define specific sectors which differ from the above definitions. While we have used our CCC sectors for our advice, our reports for the UK, Scotland, and Northern Ireland include a version of our emissions pathway regrouped into the sector definitions used in each nation's legislation or strategy. These are available in the datasets accompanying the advice reports.

The CCC is supportive of aligning methodologies for modelling projects, including those by the CCC, the UK Government, and in Scotland, Wales, and Northern Ireland. Presenting emissions scenarios in a common sector classification would greatly aid analysts in governments and academia to understand and compare the scenarios from different organisations. The TES sectors are a potential candidate for this, as they were developed most recently by the Department for Energy Security and Net Zero (DESNZ) with input from the devolved governments and the CCC – as well as an external consultation. For forward-looking scenarios, an additional sector for engineered removals could be added to the TES sectors.

Box 1.1
The CCC's sector definitions, compared to those used in the UK Government's Net Zero Strategy

The CCC's sector definitions are as follows:

- **Surface transport.** This includes emissions from all road vehicles and trains. The Government's sector classification groups transport sectors differently (see below).
- **Buildings.** Includes emissions from residential, public, and commercial buildings. We sometimes combine consider all buildings emissions together and sometimes consider residential and non-residential buildings separately.
- **Electricity supply.** Emissions from the generation, transmission, and distribution of electricity, which currently mostly come from gas power stations.
- **Industry.** This sector consists of cement & lime, iron & steel, chemicals, glass & other minerals, food & drink, paper, vehicles, non-ferrous metals, non-road mobile machinery, and other industry.
- **Agriculture and land use.** This includes emissions sources, from farming and peatlands, but also sinks, such as forestry and biomass (in the case of bioenergy crops, for example, only the carbon sequestered in the part of biomass that is not harvested is accounted within the land use sector; that sequestered in the harvested portion is accounted as offsetting the carbon released or sequestered when it is used in another sector). Land use includes all LULUCF (land use, land use change, and forestry). We sometimes consider agriculture and land use emissions together and sometimes consider them separately.
- **Fuel supply.** This covers the production of fuels including oil, gas, bioenergy, hydrogen, and synthetic fuels.
- **Waste.** Emissions in the waste sector are mostly from landfill and composting, wastewater, energy from waste (EfW), and incineration.
- **Aviation.** Emissions from domestic and military aviation and the UK's share of international aviation.
- **Shipping.** Emissions from domestic and naval shipping and the UK's share of international shipping.
- **F-gases.** Fluorinated gases are man-made greenhouse gases, and this sector covers their release across all areas of the economy. This includes release from aerosols such as medical inhalers as well as their use in refrigeration.
- **Engineered removals.** Removing carbon from the atmosphere by engineered means, as opposed to through land-based carbon sinks. This includes direct air capture with carbon capture and storage (DACCS), bioenergy with carbon capture and storage (BECCS), biochar, and enhanced weathering.

The sector definitions in the Government's Net Zero Strategy are broadly aligned with the CCC's, with some differences:

- **Energy from waste.** The CCC includes EfW under the waste sector, whereas the Government includes this in their power sector. We have chosen this classification because policy for EfW is typically developed together with other waste management policy.
- **Transport.** The Government uses 'domestic transport' and 'international aviation and shipping', where the domestic and military components of aviation and shipping are combined with surface transport. The CCC treats aviation, shipping, and surface transport as independent sectors. This is because policy levers for surface transport are largely independent of those for aviation and shipping.
- **Other differences** include the Government's grouping of waste and F-gases, which are separated in the CCC's classification. Similarly, emissions from refineries are counted within the CCC's fuel supply sector but are in the Government's industry sector. Finally, abatement from biomethane injection is included in the CCC's fuel supply sector, whereas the Government splits this across their buildings and industry sectors. This has a very small impact on the shape of the emissions pathways.

1.3 Baseline emissions with no further decarbonisation action*

1.3.1 The role of a baseline in our analysis

We compare our modelled pathway to Net Zero with a hypothetical baseline pathway that does not include further climate action, enabling us to calculate the required abatement, investment needs, costs, and savings associated with the future actions to reduce UK greenhouse gas (GHG) emissions.

In our baseline, low-carbon technologies generally remain at today's stock levels and today's efficiencies.†;‡ Projections for baseline emissions over time are based on projected changes to factors such as population, GDP, the warming climate, and fuel prices. Overall, this generally leads to a gradual increase in baseline emissions over time, although there are differences in each sector. There is also considerable uncertainty associated with the impact of many of these factors, which we address in Chapter 6. As our baseline reflects the latest evidence on the current stock share of low-carbon technologies and demand for high-carbon activities, it includes progress that has been made over recent years and therefore differs from that used in previous carbon budget advice.

Our approach to constructing a baseline allows us to demonstrate the full range of actions needed to reduce emissions, without taking a view as to whether they are driven by policy or markets. As a result, the full range of abatement actions that are required to move from today's world to Net Zero can be quantified and costed within our pathway. Our baseline is not intended as a projection of what may happen based on current trends or markets. This differs from other baseline definitions:

- The Government's Carbon Budget Delivery Plan uses a baseline derived from their Energy and Emissions Projections (EEP), which includes estimated emissions reductions from existing and some planned policies.[7]

- Some baseline definitions (including those used in government policy appraisal) include a projected uptake of low-carbon technologies in the absence of new policy.[8] For example, they would predict a rise in sales of electric vehicles (EVs).

1.3.2 Emissions in our baseline

In our baseline, emissions grow steadily to 16% above 2023 levels by 2050. This is driven mainly by the baselines for surface transport and aviation, which rise in line with population and GDP.

- In most sectors, our baseline assessment is based on either published government scenarios or government modelling. This provides a common basis for interpreting our advice.

* This section is equivalent to Section 2.1 in the Seventh Carbon Budget advice report.

† Where we refer to 'today', we typically mean the latest year for which data was available at the time of analysis. In most sectors this is 2023, but in some areas it will be 2022.

‡ In general, we assume that technologies remain at today's stock levels and efficiencies, but there are exceptions in some sectors due to modelling limitations. These include new aircraft efficiencies in aviation, productivity assumptions in agriculture, and tree planting and peatland restoration rates in land use. The assumptions that have been made in constructing the baseline in each sector are outlined in Chapters 6-18.

  - This includes the industry, agriculture, fuel supply, waste, and non-residential buildings sectors, for which we use EEP scenarios excluding emissions savings associated with any policies that go beyond those already being realised today.

  - In surface transport, we assume the vehicle fleet remains split among powertrains as it is today and use the core forecast from the Department for Transport's (DfT) National Road Traffic Projections - adjusted to match the latest actual data - to give the levels of traffic demand.[9]

  - Our aviation and shipping baselines are based on bespoke runs of DfT models, assuming no change in fleet makeups and demand primarily driven by GDP growth.*

  - For electricity supply, our baseline comes from modelling undertaken for us by AFRY, using their BID3 model which is also used by the Department for Energy Security and Net Zero (DESNZ).[10] It uses the level of electricity demand modelled in our baselines across sectors and assumes that new low-carbon generation is only deployed to replace existing low-carbon assets at end-of-life.

- In the other sectors, we developed our baseline using in-house or commissioned models.

  - In residential buildings, we commissioned Kamma to produce a baseline dataset representing today's building stock. The fabric of, and types of heating system used by, these existing buildings are assumed to remain the same over time, with demand for heating slightly declining as the climate warms. The housing stock grows in line with projected future housebuilding rates, with new builds using gas heating.

  - Our land use baseline is based on modelling by the UK Centre for Ecology and Hydrology. This is calibrated against the most recent inventory estimates of land use sources and sinks and projects forward recent trends in what land is being used for.

  - For F-gases, our baseline was produced by Ricardo, considering population changes and European legislation which is already affecting component design.

  - The baseline includes no engineered removals as these have not yet been deployed in the UK.

1.4 Developing our Balanced Pathway†

1.4.1 Approach to pathway analysis

Our advice on the level of the Seventh Carbon Budget is informed by an updated Balanced Pathway. This is an ambitious, deliverable pathway that represents our assessment of the UK's best path to reach Net Zero by 2050, based on the latest evidence and data.

- The pathway is developed by dividing the UK's emissions into sectors of the economy and determining credible emissions reductions for each from 2025 to 2050. In each sector, we start from the baseline and consider which emissions reduction options would be most suitable.

* In aviation, a small annual improvement to aircraft efficiencies is built into the DfT model and therefore into our baseline.

† This section is equivalent to Section 2.2 in the Seventh Carbon Budget advice report.

  - In many of the sectors that currently dominate the UK's emissions, including surface transport, buildings, industry, and electricity supply, cost-effective options are expected to be available to almost completely decarbonise the sector. The pathway therefore explores options to achieve this.

  - Some emissions are expected to remain in sectors with no credible way to completely decarbonise, including agriculture, aviation, waste, and land use sources. Our pathway explores the best balance between credible options to reduce emissions and balancing these with greenhouse gas removals, both in 'nature' (via carbon sequestration in land use sinks) and 'engineered removals' (such as approaches utilising carbon capture and storage (CCS)).

- Interactions between sectors are captured through modelling of the energy system required to supply the energy used in each sector. This includes consideration of the roll-out of low-carbon electricity generation, the role of flexibility in supply and end-use sectors, and other low-carbon energy carriers (for example, low-carbon hydrogen).

- In forming judgements on feasible actions for inclusion in our pathway, we consider a range of evidence, including the projected pace of technology development, possible shifts in societal attitudes, data on costs and choices, current and historical trends, and examples of progress in other countries. We have engaged with a broad range of stakeholders from across government, industry, and wider society to validate assumptions, and we convened a citizens' panel to explore the question of what an accessible and affordable vision of Net Zero would be for households.[*]

1.4.2 Key drivers and constraints in our modelling

We consider two broad types of emissions reduction action in our pathway:[†]

- **Roll-out of low-carbon technologies and land-based actions.** This includes the roll-out of electric and other low-carbon technologies and greenhouse gas removals, enabled by building a system that meets the required energy demand using a resilient mix of low-carbon sources. Credible roll-out rates depend on both the available supply of low-carbon technologies and the demand for them. Similar roll-out considerations also apply to actions within nature that can store carbon in land-based sinks or reduce emissions from land.

- **Reducing demand for high-carbon activities.** This depends on sustained household and business choices to reduce high-carbon activities. We include measures to improve the efficiency with which high-carbon technologies are used within this category.[‡]

When determining whether or when an option is suitable for inclusion in our pathway, we take an evidence-driven approach to assess an ambitious but deliverable level and pace of uptake. For both low-carbon technologies and reducing demand, we base our assessment on what has been achieved or evidenced to date. For low-carbon technologies, this involves relying on technologies that we can confidently assume will be ready to operate at scale before 2050 and assessing credible rates of uptake; for reducing demand, this involves considering successful case studies as well as current and historical trends and social research to assess what sustained shifts in choices

[*] The citizens' panel did not focus on appropriate levels of action (for example, the level of meat reduction or pace of heat pump deployment), but took these as given, and explored what would make these actions accessible and affordable.

[†] There are interdependencies between these actions (for example, technology can enable reductions in demand).

[‡] In our emissions modelling, we generally account for emissions reductions due to measures to reduce demand for high-carbon activities (including low-carbon choices and efficiencies) first, before the impact of low-carbon technologies. The abatement for these measures therefore shows what these measures would achieve with the baseline mix of technologies.

could feasibly be achieved by 2050. Our approaches in each area are outlined in Sections 1.5 and 1.6.

1.4.3 Factors that we consider in developing an emissions pathway

Under the Climate Change Act, carbon budgets must take account of a range of matters. We have considered all of these in our analysis:

- **Scientific knowledge about climate change.** The latest scientific understanding is summarised in Section 1.1 of the advice report. The 2050 Net Zero target, the UK's NDCs, and the Sixth Carbon Budget remain consistent with this - our analysis determines an ambitious, deliverable pathway to meet these in a cost-effective manner.

- **Technology relevant to climate change.** Our approach to modelling technology roll-out and the constraints that determine this is outlined in the following section (Section 1.5), as well as in the sectoral sections in Chapter 7 of the advice report.

- **Economic circumstances.** The costs and cost savings of the pathway are set out in Chapter 4 of the advice report, while the investment opportunities arising from these and the impact on the economy, businesses, and workers are assessed in Chapter 9 of the advice report.

- **Fiscal circumstances.** Fiscal impacts, including impacts on public spending, are assessed in Section 4.3 of the advice report. Some possible uses of taxation are discussed in Chapter 8 of the advice report.

- **Social circumstances.** Chapter 8 of the advice report explores the impacts of the pathway on households. This includes impacts on groups with protected characteristics and wider distributional impacts, while we consider impacts on fuel poverty in Section 7.2 of the advice report. Sections 1.5 and 1.6, and the sectoral sections in Chapter 7 of the advice report discuss the role household and business choices play in our modelling.

- **Energy policy.** Our analysis of the electricity and fuel supply sectors is set out in Sections 7.5 and 7.7 of the advice report, respectively. In addition, what the pathway means for overall demand for different energy carriers and its implications for energy security are explored in Section 10.2 of the advice report.

- **Differences in circumstances between England, Wales, Scotland, and Northern Ireland.** We summarise how the different circumstances in each nation are reflected in our analysis in Section 3.4 of the advice report. Emissions pathways for Scotland, Wales, and Northern Ireland are included in separate advice reports to each nation.

- **Circumstances at European and international level.** Section 1.1 of the advice report outlines the current international context, while Section 10.1 of the advice report assesses how our pathway fits within this context.

- **International aviation and shipping**. The contribution of international aviation and shipping emissions to the recommended budget level is discussed in Section 3.1 of the advice report, while our analytical approach to these sectors is set out in Sections 7.6 and 7.10 of the advice report.

There is clearly considerable uncertainty around how factors such as costs and feasibility will develop over a 25-year timeframe. We explore this in Chapter 6 of the advice report.

1.5 Roll-out of low-carbon technologies and land-based actions*

Our pathway depends on the rate of roll-out of a range of low-carbon technologies and land-based actions. It will be important to monitor indicators of technology development and uptake, as well as leading indicators (where available) of supply and demand. We discuss this in Chapter 5 of the advice report.

1.5.1 Low-carbon technologies

All of the technologies that we need already exist in some form: many are commercially viable and can be deployed at scale today; others are commercially viable but yet to be deployed at scale; and some novel technologies have been prototyped and demonstrated but require further support and refinement to commercialise. We also expect developments to result in improvements to existing technological solutions and to offer new options. We avoid relying heavily on speculative future technological advances lacking a firm evidence base.

There are two key components to our analysis of technology roll-out: cost effectiveness (both as a snapshot and from a dynamic perspective) and feasibility constraints on the pace of investment and delivery (both supply-side and demand-side). There have been substantial cost reductions in many low-carbon technologies over recent years. As a result, it is often feasibility constraints that are binding in determining the shape of the deployment pathways for many technologies.

Cost effectiveness

When constructing our sectoral pathways, consideration is given to the most cost-effective choice between alternative credible low- or zero-carbon technologies and emissions reduction measures, and to the timing of roll-out.

- **Snapshot cost effectiveness**: in general, we consider technologies for inclusion in the pathway only once they become cost effective compared to the UK Government's 'target-consistent' carbon values.[11]

  - We assess this by comparing the abatement cost of a new unit of technology (see Section 4.2.1) with the Government's carbon values, which represent the value that UK society places on avoiding emitting 1 tCO_2e. They were developed by the UK Government to be consistent with the 2050 Net Zero target and to take a least-cost approach to minimising cumulative emissions over the period to 2050.

  - A measure can be cost effective despite being more expensive than its high-carbon alternative if the cost difference is lower than the implied cost saving from reducing emissions. This will happen in the early stages of many technology roll-outs, and provides justification for incentives/regulations to enable uptake sooner than might occur if relying on financial costs alone. In many cases, this will help to drive costs down, resulting in low-carbon technologies eventually becoming cost saving. We do not directly calculate this spillover benefit in our cost effectiveness assessment, but we take it into account in our assessment of dynamic cost effectiveness (see below).

  - For many technologies (including solar, wind turbines, and batteries), consistent and rapid cost reductions have been seen over the past 20 years.[12;13;14] We project how

* This section is equivalent to Section 2.3 in the Seventh Carbon Budget advice report.

costs could develop in our pathway based on observed learning rates and expectations about how these may continue. Recent research found that the potential scale of cost reductions could be greater than considered in most energy-economy models.[15]

  - Many key measures (including EVs and heat pumps in new homes) have already reached snapshot cost effectiveness for at least some parts of the market. By the Seventh Carbon Budget period, this will be true in even more cases. At that point, feasibility constraints often play a more binding role in determining roll-out rates.

  - In cases where multiple competing low-carbon technologies are credible, we consider the costs and feasibility of each and generally select the most cost-effective feasible mix (for instance choosing electrification, hydrogen, or CCS across different industrial sites). Where one technology is already being deployed at scale and is clearly expected to dominate the market (as is the case with EVs), we focus on this in preference to more niche options, while in some cases where technologies are at an earlier stage of development (such as solid versus liquid direct air carbon capture and storage (DACCS)), we impose a split choice in our modelling to maintain optionality, reflecting current uncertainty.

- **Dynamic cost effectiveness:** while the carbon values provide a snapshot view of cost effectiveness, taking this approach alone can miss the benefits of early action in opening up additional opportunities for emissions reductions later on or cost reductions that could reduce the overall cost of reaching Net Zero. Therefore, where key early actions are not cost effective in a given year but result in lower costs in future years, they may be included.

  - Examples in our pathway include early action to decarbonise public buildings, which can help build supply chains to lower costs for commercial and domestic premises, and deployment of DACCS, which begins before snapshot cost effectiveness to enable operation at scale by the time it is cost effective.

There are a small number of cases where we include in our pathway things that do not individually achieve cost effectiveness or are less cost effective than other feasible options. These are justified either by considering beneficial co-impacts on the wider system or to maintain optionality in an uncertain aspect of the decarbonisation path (for example, sustainable aviation fuel (SAF)).

When considering the trade-offs between alternative technologies we are mindful that projected costs are uncertain, and the cost of currently expensive technologies may fall significantly in the future. However, if cost-effective alternatives are unlikely to be available in the near future, we develop our pathway on the basis of a more limited set of feasible technologies.

Feasible roll-out rates

The cost of abatement is taken together with a range of other considerations to determine a feasible, deliverable roll-out rate for each technology in our pathway. These include both supply- and demand-side factors. The importance of each factor varies depending on the sector and is based on the latest available evidence.

Supply of low-carbon technologies

Supply-side factors could constrain or enable the roll-out of low-carbon technologies. They include:

- **Maturity of technology**: this means how well-established a given technology is and how this is likely to change in the future. We only include technologies that are expected to become sufficiently established to reach large-scale operation or adoption in the UK before 2050.

  - We base this judgement on the internationally recognised system of technology readiness levels (TRLs).[16] We apply a guiding threshold of TRL 6 - generally only including technologies that we assess as being already at or above this level.* This represents those that have reached the stage of being demonstrated in a relevant environment.

  - Typical timescales for different technologies to progress from low readiness levels to deployment at scale mean we cannot reliably expect those currently below this threshold to play a significant role before 2050.[17] In practice, this is dependent on the specific type of technology and market conditions, so it is possible some early-stage technologies may progress more or less quickly than we have assumed in our modelling.

  - For emerging technologies in our pathway (those at TRL 6–7, including synthetic SAF and DACCS), we generally seek to minimise reliance on them as a sole solution and leave scope for optionality, for example, by including a mix of technologies and options to reduce demand for high-carbon activities in our pathway.

  - By contrast, in many cases where a technology has progressed to the highest TRLs and is being deployed at scale (for example, EVs and heat pumps), there is value in narrowing down the option space and ensuring that policy enables rapid roll-out of what is now becoming the clear best choice.

- **Construction timelines:** where the measure requires substantial new construction (of either the measure itself or facilities to produce it), we consider the lead-times associated with this construction. This is particularly relevant for more complex infrastructure projects.

- **Availability of energy and other resources:** we consider dependency on energy supply for energy-intensive processes, as well as whether the materials required to manufacture the technology are sufficiently available globally and whether supply chains for the UK will be able to scale up sufficiently quickly.

  - Efficient, low-carbon, electric technologies play a key role in our pathway. In our analysis, the electricity supply sector must decarbonise the existing system; increase supply of low-carbon electricity to meet new demands; and ensure resilience to the effects of climate change and extreme weather.[18]

  - We discuss overall demands for energy (including lower dependence on volatile global fuel markets) and for critical minerals in Section 10.2 of the advice report.

- **Availability of skilled workers and supply chains:** even when there is sufficient production capacity, trained workers need to be available to install or maintain new technologies. Depending on the technology, businesses may need to set up new supply chains, develop training materials, deliver new training to existing workforces, or build new capacity. The rate at which these can scale up is a key factor in determining the roll-out of heat pumps: these are a well-established technology for home heating, but their installation at scale will require the installer base to be retrained from primarily focussing on gas heating.[19] This is also an important factor in determining industrial decarbonisation rates.

- **Availability of supporting infrastructure:** in several areas, new technologies depend on wider supporting infrastructure to be able to deliver emissions reductions.

* We use IEA's framework and assessment as the basis for our TRLs, but we deviate from these in some areas based on our understanding of the latest evidence. For example, hydrogen aircraft were excluded from consideration because their development is not sufficiently well advanced to give confidence that they will be ready to play a significant role by 2050. We have also minimised the role of laboratory-grown meat, as this is likely at or below TRL 6.

  - This is true for all technologies that rely on low-carbon energy, as the energy system must be able to support this. It is particularly acute for renewables and industrial sites, for which grid connections and expanded transmission capacity will be needed.[20;21]

  - Technologies that rely on storing carbon are dependent on the pace at which geological stores and a network for transporting captured carbon to them can be established. Supply of low-carbon hydrogen, including to provide storable energy and as a feedstock for synthetic fuel, is similarly dependent on pipeline infrastructure.

- **Planning and regulatory timescales:** in some cases, the regulatory landscape will need to evolve to accommodate new technologies and enable markets to grow. In others, planning requirements can limit the pace of change. We generally try to ensure that planning and regulations do not constrain roll-out rates in the pathway if government could reasonably be expected to take timely actions to address these barriers.

  - Regulatory approval and clear business models are a prerequisite for some technologies that have not yet entered the market.

  - Delivering Net Zero will require rapid deployment of a range of new infrastructure and assets. How these interact with the communities in which they will be located is an important consideration, but it is also important that the planning system gives appropriate priority to the national importance of cutting emissions, adapting to climate change, and enhancing biodiversity.

Demand for low-carbon technologies

Feasible roll-out rates are also determined based on factors that could affect the pace at which consumers and businesses purchase and use low-carbon technologies effectively.* They include:

- **Household and business costs:** whether a technology will present a cost or a cost saving for a household or a business is important if take-up relies on private decisions between low- and high-carbon assets.

  - Many of the low-carbon technologies in our pathway incur an upfront purchase price premium but benefit from running cost savings. This is particularly significant for modelling EV uptake, where the running cost savings already outweigh the upfront price premium for some drivers.[22] Our analysis of EV uptake considers the role of both the upfront price and the total cost of ownership in determining purchase decisions.

  - Purchase prices of many technologies (including EVs) are falling quickly. While some do remain considerably more expensive today, a key determining factor is the point at which purchase price parity is reached. At this point, the low-carbon option will clearly be the cheaper option, given the running cost savings described above. As households tend to focus more on upfront costs, they may be reluctant to purchase the technology until this parity is reached.[23;24]

  - For technologies where this does not occur quickly (such as heat pumps), regulation and market mechanisms can accelerate cost reductions and purchase incentives from government can help close the gap (see Chapter 5 of the advice report on delivery). For some technologies, purchase price parity may not be reached before 2050. In that case, there may be an ongoing role for incentives, price-based levers (such as the UK Emissions Trading Scheme (UK ETS)), or mechanisms to distribute upfront costs across asset lifetimes (for instance, heat as a service). In such cases, we consider

* The interaction between the factors described in this section can be complex in driving consumer and business purchasing decisions. We follow a similar approach to that described for more sustained choices in Section 2.4 in developing our evidence base for which factors are expected to determine these one-off choices.

different options for government or households/businesses to pay, taking account of distributional and fiscal impacts (see Chapter 4 of the advice report on costs and Chapter 8 of the advice report on household impacts).

- **Social acceptability and consumer preferences:** in addition to purchase price and running costs, cultural and social norms and perceptions of technologies, as well as individual attitudes, play a role in determining the pace at which new technologies are adopted.
  - Most new technologies follow an 'S-curve' adoption profile, whereby roll-out begins with a slow ramp-up among innovators and early adopters, followed by a rapid acceleration as the technology hits mass market and then a slowdown as the final groups, more resistant or less able to adopt new technologies, are reached.[25;26] This typically reflects both changes in purchase price of new technologies as well as changing social norms and attitudes towards those technologies.
  - Consumers are also likely to consider wider benefits and impacts of low-carbon technologies. In many cases, these offer additional advantages (for example, a better driving experience in EVs or improved indoor air quality from heat pumps). However, some technologies (for example, low-carbon heating systems) may present additional barriers to consumers such as a more complex installation process.
  - To reach mass market adoption, consumers and businesses need to have familiarity with a low-carbon technology, and then confidence that low-carbon technologies can meet their needs.[27] Familiarity and confidence can take time to develop, and then accelerate through spillover effects and increased exposure.[28]
  - There is already strong public awareness of climate change and Net Zero in the UK.[29] It is possible that societal norms and consumer preferences will increasingly shift towards low-carbon choices, accelerating the roll-out of certain technologies (as with the increasing acceptance of LED light bulbs over the past decade or increasing consumer preference for EVs in Norway).[30;31] Effective consumer and business advice will be needed to enable this to happen consistently.
- **Natural stock turnover and early scrappage:** in many cases, low-carbon technologies are replacing existing high-carbon alternatives. In general, our modelling assumes this occurs only at the end of their physical lifetime.
  - This is the case for key consumer technologies such as cars and heat pumps - our pathway does not require people's current cars or boilers to be replaced earlier than their natural replacement cycles.
  - We include limited early scrappage in the non-residential buildings and industry sectors. Many of these premises are significant users of energy, so replacing high-carbon systems early can deliver large emissions savings. Mechanisms such as the UK ETS and low-carbon heating policies will be needed to ensure businesses are properly incentivised to do this when required. We also explore potential additional benefits of limited early scrappage in surface transport and residential buildings in our contingency options in Chapter 6.

In addition, existing or expected policy commitments (including government targets, regulations, and mandates) can set expectations for suppliers and consumers, affecting the pace at which roll-out occurs. Clear, consistent targets and messaging provide clarity to industry on timelines for scaling up supply and to consumers on expected technology availability. This builds confidence in the direction-of-travel and can help speed up roll-out.[32] Examples include existing targets on zero-emission vehicles and SAF and phase-out dates for new fossil fuel vehicles and boilers.

Key low-carbon technology roll-outs in the Balanced Pathway

The key constraints and enablers that determine the roll-out of some key technologies in our Balanced Pathway are set out in Table 1.1. Further discussion of the technologies assumed and the main factors determining roll-out rates can be found in the sectoral chapters of this report.

Table 1.1
Factors that determine roll-out rates of key technologies in the Balanced Pathway

	Supply-side						Demand-side					
	Maturity of technology	Construction timescales	Energy and other resources	Skilled workers and supply chains	Supporting infrastructure	Planning and regulatory timescales	Social cost effectiveness	Household/ business cost	Consumer preferences	Natural stock turnover	Early scrappage*	Existing policy commitments
Renewables and grid storage				Near-term pipeline	Grid and connections	Infrastructure planning						
EVs					Charging network			Until price parity reached	Observed preferences for EVs/ICEs			Phase-out date
Heat pumps - residential				Installer availability				International demand comparisons	Suitability for homes; level of demand			Phase-out date
Heat pumps - non-residential				Installer availability					Suitability for premises			Public sector emissions targets
Industrial heat				Installer availability	Hydrogen pipelines			Costs to industries				
SAF			Feedstock supply			Balance of SAF and DACCS						SAF mandate†
Low-carbon hydrogen supply			Surplus low-carbon power		Networks and storage							

CCS					Networks and storage	Infrastructure planning		Costs to industries				
Alternative proteins						Regulatory approval		Price parity	Taste; nutrition; reception			
DACCS			Electricity grid constraints		Networks and storage							Net Zero

Legend:

Factors included within our roll-out modelling.
Key factors that determine the pathway in our roll-out modelling.
Factors that are not explicitly constraints in our roll-out modelling, but we do assume that these develop at the rates required.

Notes: *In general, our modelling assumes that existing assets are replaced only at end-of-life. We include limited early scrappage in the non-residential buildings and industry sectors but constrain this to happen only when cost effective and feasible. †Our pathway does not meet the SAF mandate targets, but these are used to inform our assessment of the credible pace of scale-up of SAF production. In all cases shown, multiple factors play a key role in our modelling - the relative importance of these factors and how they combine to determine roll-out rates vary over the pathway and often between different settings in which the technology is being deployed.

1.5.2 Nature

Woodland creation, peatland restoration, and other land use changes can build the UK's land use sinks by enabling them to sequester more CO_2 and reducing emissions that come from land use. We follow a similar approach to that described for technology roll-outs above to determine feasible planting and restoration rates.

- Our analysis is based on an assessment of the existing and credible future availability of land for each purpose, which provides a starting point for assessing what changes can be achieved. As part of this, we consider differences in land type between the four nations of the UK. This allows for a more resilient mix of measures that are suitable for the land types available.

- Skilled workers and supply chains are key constraining factors in many cases. For example, for woodland creation, nursery and contractor capacity constrain the pace at which trees can be planted.[33]

- We also ensure that the actions included are consistent with wider environmental objectives, as land-based actions, if planned and delivered appropriately, can offer wider benefits to nature alongside delivering emissions reduction and carbon sequestration.

  – This includes following regulatory principles in assessing credible land-based actions, where these are available and considered robust (see Section 5.3 of the Seventh Carbon Budget advice report, Box 5.1).

  – We discuss the interaction of our pathway with wider nature objectives further in Section 7.4.3 of the advice report.

1.6 Reducing demand for high-carbon activities*

Our sectoral pathways include feasible reductions in demand for high-carbon activities, through both sustained low-carbon choices and increasing efficiencies. Just as with technology roll-out, it will be important to monitor delivery progress - this is considered in Chapter 5 of the advice report.

1.6.1 Sustained low-carbon choices

Our assessment of feasible sustained shifts away from high-carbon activities is based on relevant comparable evidence, considering observed shifts and necessary enabling conditions.

- Reducing demand for high-carbon activities can constitute a switch to a low-carbon alternative (for example, from car to public transport), a reduction in a high-carbon activity (for example, reducing flying), or a combination of the two. When considering a switch, we consider what conditions would need to be in place for the low-carbon choice to be easy, attractive, and affordable to enable people to shift and sustain habits.

- These sustained low-carbon choices can be enabled by technological and market-driven shifts in consumer preferences, changing societal norms, public information, regulation, and price incentivisation.† We consider sustained low-carbon choices as an option to reduce emissions where there is a technological solution, but more efficient alternative approaches help reduce emissions along the path to Net Zero (for example, reducing waste or switching from car to public transport) or where there is no technological solution in our pathway to completely eliminate emissions (as in aviation and meat and dairy production).

For many demand-side measures, costs and cost savings accrue less directly, can be spread across the system (as with network benefits from public transport), and are difficult to quantify.[34;35] We typically do not attempt to quantify cost effectiveness of these measures directly. Instead, we draw on a range of evidence such as trends, case studies, behavioural science, and wider evidence.

Observed shifts and wider impacts

To inform our assessment, we consider relevant comparable evidence that shows what shifts can be delivered and their impacts. These include:

- **International and domestic case studies:** we consider case studies where strong performance is already being seen as well as comparable shifts that have been observed historically. In each case, we consider how comparable these are to the present UK context and the actions that would be needed to enable similar outcomes to be achieved.

- **Current trends and consumer preferences:** as for technology choice, societal norms and public attitudes towards low- and high-carbon options play a role in how choices develop.

  - Where consumer attitudes are already moving towards lower-carbon alternatives, there are opportunities to build on these. This is the case, for example, with recent trends around increased focus on sustainability in consumer food choices.[36]

* This section is equivalent to Section 2.4 in the Seventh Carbon Budget advice report.

† This section covers our approach to shifts that involve repeatedly choosing lower-carbon alternatives or a repeated overall reduction in high-carbon activities. It does not include the role of choices in one-off purchases of low-carbon technology (for example, purchase of a heat pump or an EV), which fall within the considerations for technology roll-out in Section 2.3.

  - In some cases, there is latent potential for people wanting to adopt low-carbon choices, but other barriers (such as affordability or availability) currently hinder this.[37]

- **Geographical variation:** we also consider how factors driving demand reduction might vary by devolved administration and region. This includes considering, for example, how potential for modal shift varies in rural and urban areas.[38]

- **Co-impacts and distributional impacts:** we consider how shifts away from high-carbon activities and the levers used to achieve them impact household options and costs. Often, low-carbon choices also offer positive wider impacts, for example on public health and wellbeing.[39;40] Co-impacts and household impacts are discussed in Chapter 8.

Impact of policy levers

We consider the factors that influence people's decision-making and the potential effectiveness of actions to enable low-carbon choices. In doing this, we focus mainly on behavioural science evidence on people's actual behaviour and choices, with less emphasis on studies that assess people's intentions and attitudes towards these choices. Our citizens' panel explored how policies could make some of the low-carbon choices considered in our pathway accessible and affordable for all households. Relevant levers include:

- **Public information and awareness:** increased information about the emissions impact of different goods and services can be an important prerequisite and support a shift, but is unlikely to lead to substantial changes on its own.[41]

- **Choice environment:** ensuring that low-carbon options are readily and widely available or that the barriers to choosing these are lower than for their high-carbon alternatives will allow more people access to the opportunity to make these choices.

  - Provision of, for example, improvements to active travel infrastructure can encourage a shift away from private cars, while increased availability of plant-based products has been shown to increase sustained choices of plant-based foods.[42;43]

  - Nudges, such as changing where and how products are displayed, have also been shown to increase low-carbon choices.[44;45]

  - We focus primarily on options that enable more people to make low-carbon choices through increasing the availability of attractive options for consumers, but measures to discourage high-carbon options can also help deliver shifts.

- **Relative price signals:** we consider the effect that reducing the price of low-carbon alternatives or, where required, increasing the price of high-carbon activities can have on consumers' willingness to select and sustain a low-carbon choice.

  - Shifts are more likely to be successful if the incentives to consumers are aligned to the required shift. For example, reducing the costs of plant-based alternatives to meat that are comparable in taste, texture, and preparation method could enable more people to choose these options for some of their meals.

  - There is potential for innovation to make some low-carbon alternatives (for example, alternative proteins) more substitutable for high-carbon choices and to bring down prices.

Key sustained low-carbon choices in the Balanced Pathway

The key factors that determine the assumed level of key demand shifts in our pathway are set out in Table 1.2. Further discussion of the low-carbon choices assumed and the main factors determining the level of the resulting shifts can be found in the sectoral chapters of this report.

Table 1.2
Evidence and factors that inform the level of key sustained low-carbon choices in the Balanced Pathway

	Evidence on observed shifts and wider impacts				Evidence on impact of policy levers		
	International and domestic case studies	Current trends and preferences	Geographical variation	Distributional and co-impacts	Information and awareness	Choice environment	Relative price signals
Meat and dairy consumption							
	• Assume continuing trends in falling red meat and rising white meat consumption. • Estimate an additional shift from meat and dairy to lower-carbon foods from behavioural science and price elasticity studies of information provision and changes in availability/price of alternatives. • Check nutrition and distributional impacts and evidence of behavioural differences across regions.						
Aviation demand							
	• Model reduction in flying if the cost of decarbonising, including consideration of non-CO_2 effects, were added to the cost of flying. • Review of literature and price elasticities, plus in-house analysis to assess if policy levers to achieve this would be feasible and distributionally acceptable. • Factor regional flight needs into demand splits between devolved administrations.						
Recycling							
	• Consider current and historical trends in England, Scotland, Wales, Northern Ireland, and internationally. • Review of current recycling targets and associated models that estimate the impact of different policy levers on UK recycling rates.						
Modal shift							
	• Review of evidence on interventions in UK towns and cities and on progress in leading countries, such as Germany, Switzerland, and the Netherlands. • Consider the potential for modal shift in differing geographical types in the UK (for example, built-up urban areas compared to rural areas) and potential for changes to the choice environment (for example, bus service improvements).						

Industrial resource efficiency							

- Review of DESNZ analysis on current and maximum levels of resource efficiency achievable by 2035 for the highest impact measures (including clinker substitution in cement production and refurbishing of existing buildings instead of new builds).[46]
- Supplement with additional evidence on current trends in the UK and internationally and case studies, to inform the assumed uptake of resource efficiency.
- Consider evidence on the effectiveness of policy levers (primarily regulatory and price-based) within UK jurisdiction.

Legend:
Factors that were reviewed but did not inform the final level.
Key factors that informed the final level of demand shift assumed.
Factors that were not explicitly considered in our evidence review.

Notes: In all cases shown, multiple factors informed the level of sustained low-carbon choices deemed appropriate for inclusion in our pathway.

1.6.2 Efficiency improvements

Measures to improve the efficiency with which high-carbon activities are undertaken can include a mix of physical and process changes (for example, energy efficiency measures in homes) and sustained low-carbon choices (for example, more efficient driving styles). These are particularly important in sectors where low-carbon technologies do not become available until later (or not at all). In such cases, the increased length of time for which the high-carbon assets are in operation increases the amount of emissions reduction that efficiency improvements can deliver.

- Uptake rates of physical and process changes that improve efficiency are, in many cases, determined by similar factors to those described for low-carbon technologies in Section 1.5, balancing cost effectiveness and feasibility.
  - In many cases (including improvements to aircraft performance, industrial processes, and HGV fuel consumption), the efficiency improvements in our pathway build upon trends that already make financial sense for businesses operating these assets.[47]
  - Many efficiency measures are mature and well-established, which means that supply-side constraints on deployment are typically less binding.[48] This includes both improvements in the performance of high-carbon technologies (for instance, through growing hybridisation and light-weighting in vehicles) and measures that reduce end-use energy consumption (for example, insulation in homes, businesses, and industrial processes).
- Improvements to operating efficiencies through sustained choices are assessed through similar considerations to those described above for other sustained low-carbon choices.

1.7 Developing and validating assumptions

1.7.1 Engagement, evidence, and scrutiny

To develop and validate the assumptions and evidence that form the basis of our Balanced Pathway, we have undertaken detailed research and modelling and have engaged with a range of experts (Figure 1.2). This included:

- A public call for evidence, which was published in November 2023 and ran until January 2024. We received 88 responses, which we have considered as part of the evidence base informing our analysis. We have published a summary of these responses alongside this report.[49]

- Substantial in-house and commissioned modelling and analysis, along with 17 new research projects exploring topics including the composition of the UK building stock, power system decarbonisation and resilience, and abatement potential in the agriculture sector.[50;51;52]

- Roundtables and advisory groups to gather input from experts, business groups, and policy officials. In addition, we have undertaken regular engagement with a broad range of stakeholders to ensure that our advice is based on up-to-date evidence.

- A citizens' panel to explore the question of what an accessible and affordable vision of Net Zero would be for households.[53]

Figure 1.2 Engagement, evidence, and scrutiny to inform our recommended UK Seventh Carbon Budget and carbon budgets for Northern Ireland, Wales, and Scotland

1 Public engagement
Open call for evidence, receiving 88 responses covering all sectors.

2 Broader engagement
Roundtables across different sectors.

3 One-on-one meetings
Meetings with individual stakeholders covering all sectors and statutory requirements.

4 Committee expertise and scrutiny
24 Committee meetings (including three with Adaptation Committee) to scrutinise analysis.

5 New research
17 independent research projects commissioned to feed into our analysis.

6 New modelling
Bespoke runs of 35 sector- and subsector-specific models.

7 Citizens' panel
Panel of 26 citizens to explore an accessible and affordable vision of Net Zero for households.

Description: Our recommended Seventh Carbon Budget and our carbon budget advice to the devolved administrations are based on an extensive range of evidence, including detailed sectoral modelling, new independent research, substantial stakeholder engagement, and a citizens' panel.
Source: CCC analysis.

1.7.2 Cross-sectoral assumptions

Many of the assumptions that we make are bespoke to a particular sector, based on the evidence set out in Section 1.7.1. These are described in detail in the sectoral chapters of this document. But there are some assumptions that are common across our sectoral models. We describe these here.

Historical emissions and energy data

Our modelled scenarios are calibrated against historical data for emissions and energy, using the following sources. We chose energy and emissions data sources that are consistent with each other.

Historical emissions

The UK's inventory of emissions is the National Atmospheric Emissions Inventory (NAEI), developed by a consortium under contract to DESNZ. This is a comprehensive database that estimates the emissions of a range of reportable GHGs across the list of source categories that are in scope of the United Nations Framework Convention on Climate Change (UNFCCC) process. This inventory forms the basis of the UK's GHG emissions national statistics and emissions submissions to the UNFCCC.[54]

- **Territorial UK emissions.** All emissions data in our analysis are based on the latest update to the inventory available at the time our modelling was undertaken – this is the final 1990-2022 inventory of emissions as published by DESNZ in the final 2022 emissions statistics.[55] For most sectors, we also use the 2023 provisional estimates of emissions (which estimate CO_2 emissions – without any change to the assumed inventory basis – based on energy consumption data) as the latest data on which to base our modelling.[*];[56]

- **Territorial emissions from Scotland, Wales, and Northern Ireland.** For modelling emissions from Scotland, Wales, and Northern Ireland, we base the starting points for our pathways on the inventory emissions data published by the NAEI.[57] Note that provisional 2023 data are only published at a UK level, so for these we used the final 2022 inventory as the most recent available estimate of historical emissions across all sectors.

- **Imported emissions**. The UK's Seventh Carbon Budget, carbon budgets for Scotland, Wales, and Northern Ireland, and the Balanced Pathway are all produced on a territorial basis, which is the accounting framework under which the UK's targets are assessed. However, we also present historical data on the UK's imported emissions (see Chapter 10 of the Seventh Carbon Budget advice report). For this analysis, we use published statistics from the Department for Environment, Food and Rural Affairs (Defra), as well as unpublished data from Leeds University which provide a more detailed breakdown of imported emissions than the published statistics.[58]

Historical energy demands

The datasets published alongside our carbon budget advice reports categorise energy consumption into the following fuel groups: coal, oil, gas, bioenergy, non-bio waste, hydrogen, and electricity. We calibrate our models to historical data from the following sources (with the most recent data being for 2022 in all cases):

- **Fuel demands.** For all energy sources apart from electricity, historical data were sourced from NAEI Energy Background Data.[59]

[*] Provisional 2023 estimates are not made for non-CO_2 greenhouse gases, so 2022 data are used for the agriculture, land use, waste, and F-gases sectors, in which these gases are dominant.

- The NAEI Energy Background Data is largely based on the Digest of UK Energy Statistics (DUKES). However, there are instances where the activity data used are not based directly on DUKES, instead utilising alternative data sources, such as UK Emissions Trading Scheme (UK ETS) data or operator-reported data.[60]

- This dataset, unlike DUKES, is published in a format consistent with the emissions inventory, meaning that it can be re-aggregated more easily into the CCC's sector classification (see Section 1.2.2).

- Fuel demands for Scotland, Wales, and Northern Ireland were sourced from unpublished NAEI data. Energy demand data at this level were provided to the CCC in an aggregated format so as to not disclose commercially sensitive information. Using NAEI energy data ensures internal consistency between the modelled scenarios for the UK and for each nation.

- **Electricity demand.** Electricity consumption data are not part of the NAEI Background Data, so we use data from the DUKES electricity commodity balance.[61] This was supplemented by the Subnational Electricity Consumption data, which were used to estimate electricity demands by sector for each nation.[62] Where available, nation-specific datasets and publications also inform our electricity demand modelling.

  - There is no published Government dataset on electricity demand by nation at the level of granularity required to be able to aggregate it into the CCC sector classification; electricity demand is not within the scope of the NAEI dataset. For our electricity demand starting points, we therefore calibrate against estimates using the following process. This applies to sector-level electricity demands for Scotland, Wales, and Northern Ireland.

    - Electricity demands for Scotland, Wales, and Northern Ireland were obtained from the Government's Subnational Electricity Consumption data.[63] This dataset is not broken down by sector level, so historical electricity demands by sector for Scotland, Wales, and Northern Ireland were estimated by applying the sectoral breakdown at UK level to the total electricity demand of each nation in turn. For example, if a sector makes up 30% of total UK electricity demand, it is assumed that this percentage is the same for each nation. We cross-checked these estimates against separate publications from each country where these were available.[64]

    - Our sectoral energy demand pathways for Scotland, Wales, and Northern Ireland are then calibrated to these sectoral estimates, with the exception of sectors where electricity demand is calculated from the bottom up by the model (for example, buildings). Where the bottom-up estimate differs from the approach outlined above, other sectors are adjusted to ensure that total electricity demand for each nation matches the reported value in the Subnational Electricity Consumption statistics.

Carbon values

As described in Section 1.4, we consider cost effectiveness against the UK Government's 'target-consistent' carbon values in constructing our sectoral pathways (Figure 1.3).[65]

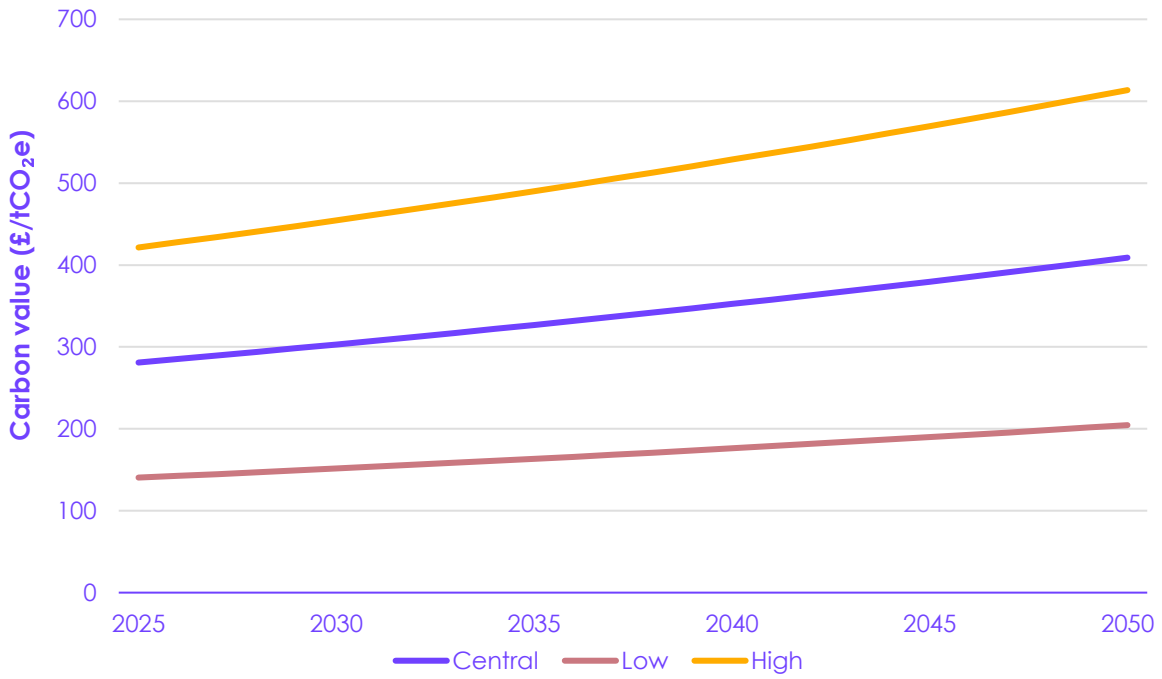
- We generally use the Government's central carbon values, which have been set consistent with the Government's Net Zero Strategy and are anchored to the median carbon price in

the Intergovernmental Panel on Climate Change's (IPCC's) analysis of global scenarios consistent with global warming of 1.5°C.[*;66]

- The carbon values increase over time, reflecting the increasing value that society places on avoiding one tonne of emissions as we get closer to the Net Zero target.

- In many cases, the measures considered in our pathway are already cost effective against the carbon value. However, some are not currently cost effective, but are projected to become so as their costs fall below the increasing carbon value.

Figure 1.3 Carbon values



Descriptions: The carbon values have been developed by the UK Government to be consistent with the UK reaching Net Zero by 2050. They grow over time.
Source: DESNZ (2023) *Green Book supplementary guidance: valuation of energy use and greenhouse gas emissions for appraisal*.

Energy costs

A key component of calculating abatement costs (see Chapter 2) is the cost of energy used for both low-carbon and high-carbon processes. In line with supplementary guidance to the Green Book, we use long-run variable costs (LRVCs) to value changes in energy consumption.[†;67] In using LRVCs, the aim is to reflect the costs of adding an additional unit of energy demand, to help inform decisions over which decarbonisation options best support a socially cost-optimal outcome.

- LRVCs are used instead of retail energy prices to reflect the social costs of changes in energy consumption, because retail prices include:

[*] We use the Government's high carbon value in the aviation sector, as a proxy for currently high and uncertain technology costs and non-CO_2 effects, and in decarbonisation of public sector buildings, to recognise the added value in going faster in this area to show government leadership and help build supply chains to lower costs for commercial and domestic premises.

[†] Long-run variable costs are the parts of the retail price that represent actual costs to society that vary according to the level of consumption.

  - Fixed costs that will not change in the long run with changes in energy consumption, such as fixed policy costs and fixed operating costs of energy retailers.

  - Carbon costs, as these are valued separately.

  - Transfers between groups in society, such as taxes and margins.

For oil, coal, and road transport fuels, we use the LRVCs provided alongside the Green Book supplementary guidance. We also use these as the basis for our gas LRVCs.

- The Green Book supplementary guidance does not include LRVCs for shipping fuels, aviation fuels, and different forms of bioenergy and wastes. We therefore developed LRVCs for these fuels, aligning with Government data and assumptions where possible.

- Our electricity LRVCs differ from those provided in the Green Book supplementary guidance as we exclude estimates of the Renewables Obligation, Feed-in-Tariffs, and existing Contracts for Difference support costs as these are fixed costs and should therefore be captured in the retail price instead of the LRVC.

For electricity and low-carbon hydrogen, we followed an iterative process to develop our own LRVCs, given that these costs are themselves a function of overall energy demand. As a starting point, we based our electricity LRVCs primarily on the costs in our 2023 report on Delivering a reliable decarbonised power system and network costs from DESNZ analysis. Our hydrogen LRVCs were based on our power system report, BEIS hydrogen production costs, and Arup's Future of Great Britain's gas network report (commissioned by the NIC and Ofgem – this also contributes a very small component to our gas LRVCs).[68] These provided an initial estimate of the cost of using energy in a decarbonised system.

- We applied these costs in our sectoral modelling to determine cost-effective and feasible uptake levels for the decarbonisation measures included in our end-use sector pathways. This then produced a new set of energy demands for each energy carrier over the period from 2025 to 2050, which we were then able to feed into our energy supply models (modelling the electricity system and the production of other low-carbon fuels – see Chapters 10 and 12).

- We then undertook a second iteration of sector modelling, to determine our final sectoral decarbonisation pathways. In turn, the energy demands from these pathways were then fed back into a final iteration of the energy supply modelling to produce our final decarbonisation and supply pathway for these sectors.

- This final iteration also produced an updated set of LRVCs. We made a final adjustment to the sectoral costs at the whole-economy level to account for any differences from the initial LRVCs, but did not undertake another run of sectoral decarbonisation models. The final LRVCs were generally within 10% of the initial set used in our sectoral modelling. We undertook a range of sensitivity tests to validate that such differences would not lead to significant changes in the resulting emissions pathway (see Chapters 6-18).

- Our LRVCs across the period from 2025 to 2050 are set out, across 46 different fuels and end-use variants, in the accompanying data tables.

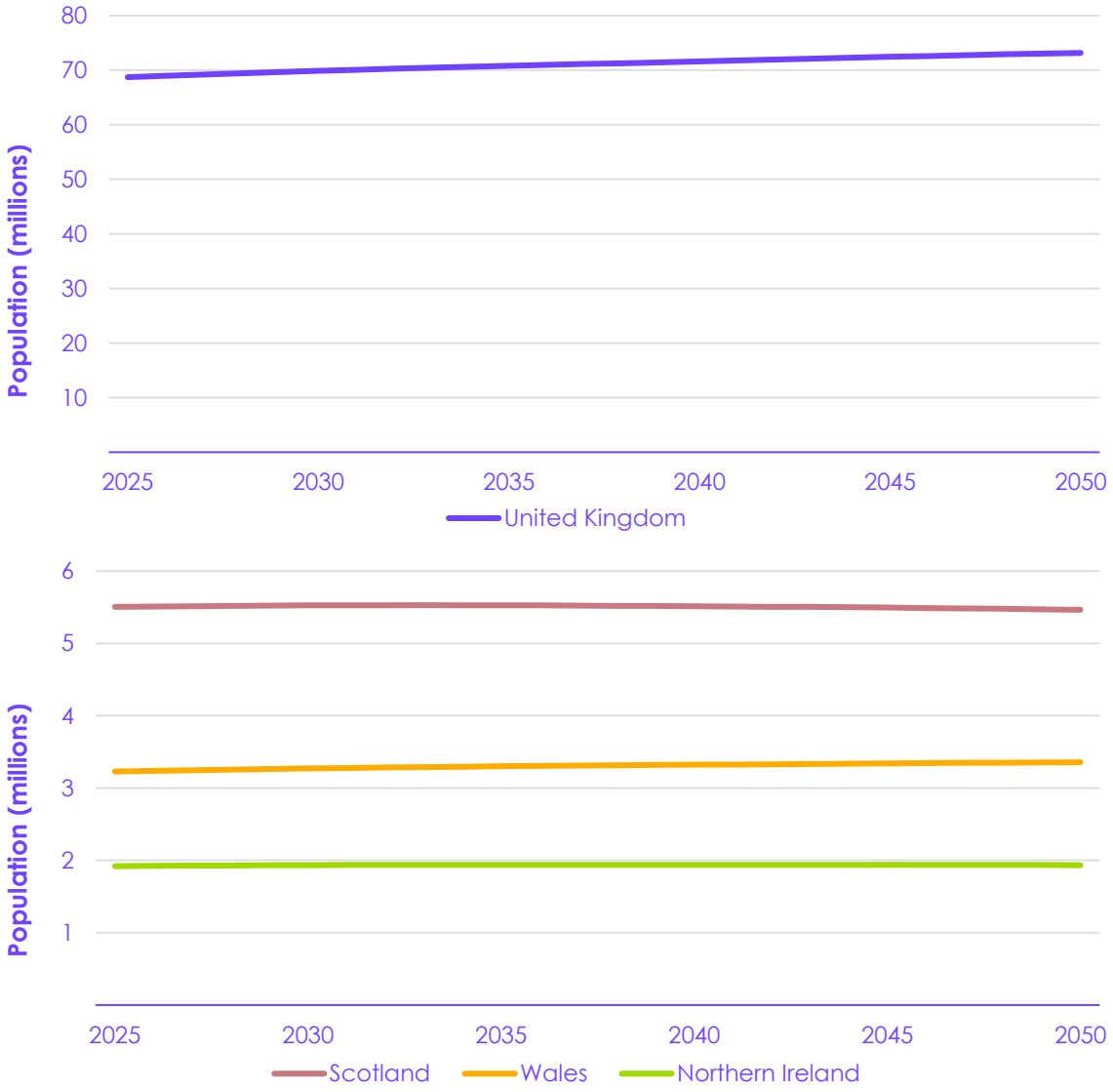
Population and the economy

Our forecasts for population and economic growth are aligned with those used in the Government's Energy and Emissions Projections (EEP), to help give a common basis for interpreting the pathway.

- For population, we use the Office for National Statistics (ONS) 2020-based interim national population projections. In line with the assumptions used in the reference case of the October 2023 EEP publication, we use the year ending June 2022 international migration variant population scenario published in January 2023.[69;70] This provides population projections for the whole UK as well as for Scotland, Wales, and Northern Ireland (Figure 1.4).

- For GDP growth, we use the Office for Budget Responsibility (OBR) projections on real UK GDP growth rate for 2023-2027 and long-term economic determinants for 2028 onwards.[71] To align with the October 2023 EEP publication, we use the growth assumptions as published in March 2023 (Figure 1.5). The OBR does not produce separate GDP projections for Scotland, Wales, and Northern Ireland. Therefore, we assume that their GDPs grow in line with these assumptions on UK-wide GDP growth, starting from the latest 2022 actual data on Scottish, Welsh, and Northern Irish GDP.*

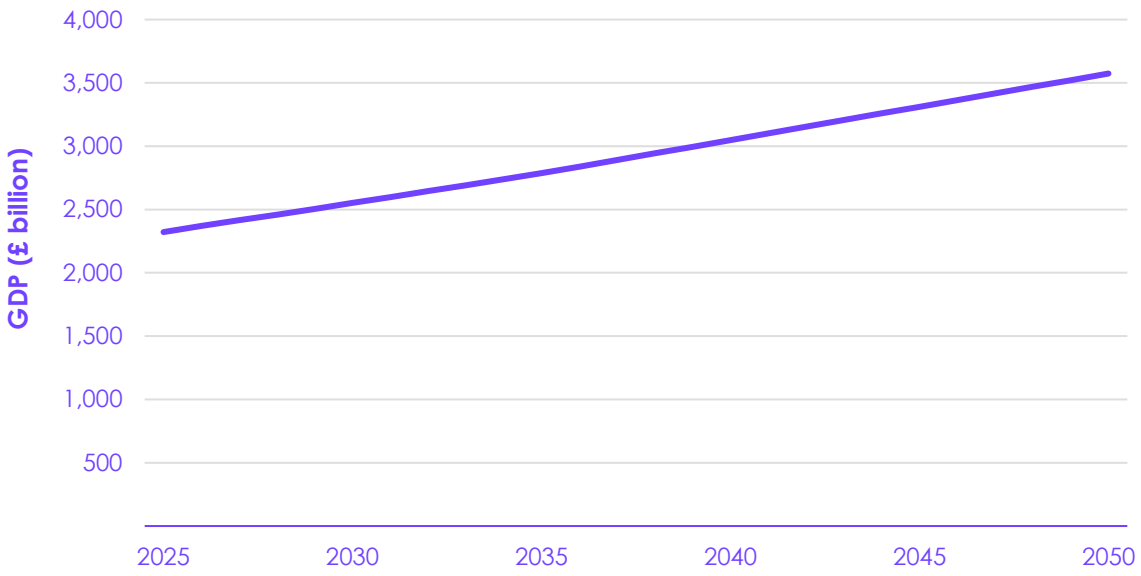
Figure 1.4 Population assumptions



Description: Our population assumptions for the UK and Wales grow steadily over time. For Scotland and Northern Ireland, these are more level out to 2050.
Source: ONS (2023) *2020-based interim national population projections: year-end June 2022 estimated international migration variant*.

* In our advice reports, we assess the overall cost of the transition as a percentage of annual GDP for each nation. For these calculations, we have used the OBR projections referenced here in our UK advice, the Scottish Fiscal Commission's projection of Scottish GDP in our Scotland advice, and assumed constant GDP in our Wales and Northern Ireland advice.

Figure 1.5 UK GDP assumption



Description: Our assumed level of UK GDP grows out to 2050.
Source: OBR (2023) *Long-term economic determinants – March 2023 Economic and fiscal outlook*.

Carbon capture and storage

Carbon capture and storage (CCS) is an option for decarbonising some parts of the industry and waste sectors, as well as enabling engineered removals, hydrogen production, and long-term storable, dispatchable power generation. Cross-sectoral assumptions provide consistency across these areas (although recognising that performance and characteristics will vary across different applications).

Cluster start dates

Table 1.3 shows our assumed earliest feasible CCS start dates in each cluster or area of emitters considered in our modelling. This is based on a combination of information published by the UK Government and the cluster projects, and the judgement of the Committee.

Table 1.3
Earliest feasible CCS cluster start dates

Cluster/area of emitters	Start date	Cluster/area of emitters	Start date
Humberside	2028	**Peterhead**	2030
Humberside (inland)	2028	**South Wales**	2033
Merseyside	2028	**Derry/Londonderry**	2035
Teesside	2028	**Medway**	2035
Grangemouth	2030	**Southampton**	2035
Peak District	2030		

Notes: The CCC assumed start dates for Humberside, Merseyside and Teesside are one year later than the Government's published start dates of 2027 due to delays in deploying CCS in these clusters.

Available capture technologies

In our modelling, we assume that the following CCS capture technologies will be available for emitters to use:

- First generation amines.
- Advanced amines.
- Calcium looping.

Capture rates

Table 1.4 shows the capture rates we assume for the different sectors and subsectors. These vary by application, due to factors such as the concentration of CO_2 within different gas streams.

Table 1.4
CCS capture rates assumed in the Balanced Pathway

Sector/subsector	Capture rate	Assumption source
Industry	90% up to 2040 and 95% from 2041 to 2050	Sixth Carbon Budget & Deep-Decarbonisation Pathways for UK Industry (Element Energy)
Waste	90% up to 2040 and 95% from 2041 to 2050	Sixth Carbon Budget & Deep-Decarbonisation Pathways for UK Industry (Element Energy)
Electricity supply	90% up to 2030 rising to 92% in 2040 and then 95% in 2050	Sixth Carbon Budget & Net Zero – Technical Report
Fossil fuel supply	90% up to 2040 and 95% from 2041 to 2050	Sixth Carbon Budget – Methodology & Element Energy NZIP model - documentation
Hydrogen supply with methane reformation	95%	BEIS Hydrogen production costs (2021)
Hydrogen supply with Bioenergy with Carbon Capture and Storage (BECCS)	90%	BEIS Hydrogen production costs (2021); DESNZ 2023 Generation costs
Biofuel supply with BECCS	75% in 2030 rising to 84% in 2040 and then 90% in 2050	Sixth Carbon Budget
Biomethane supply with BECCS	75% in 2030 rising to 84% in 2040 and then 90% in 2050	Sixth Carbon Budget

CO_2 transport and storage

We assume that most captured and stored CO_2 will be transported to permanent geological stores (likely located in the North Sea or the East Irish Sea – see Chapter 18) by pipeline. Pipelines are modelled as being available to each cluster within Great Britain in line with the availability dates discussed above.

- We assume that the average cost of CCS transport and storage through piped infrastructure is £39.36 per tCO_2 for industry, waste, and most BECCS, and £41.72 per tCO_2

for electricity supply, fuel supply, electricity supply BECCS, and DACCS. This is based on the cost given in a 2018 report by Uniper for BEIS and a 2021 BEIS report respectively, inflated into 2023 prices and with 66% optimism bias applied to the capex part of this cost.[72;73] We expect that this cost would be the same across sectors in practice; the use of two different values here was due to modelling constraints.

- Based on a 2020 report by Element Energy and BEIS, we assume that only emitters that produce less than 0.1 $MtCO_2$ may use trucks to transport their CO_2 to storage.[74] This is because the report's results suggest that trucking is likely to be cheaper than pipeline transport only for CO_2 volumes below this amount.

- Pipeline transport may not be available for CCS (including the additional DACCS included in the Northern Ireland Net Zero Pathway) located in the Derry/Londonderry cluster or elsewhere in Northern Ireland. We assume that CO_2 captured in these locations is shipped to the UK's HyNet cluster, incurring additional cost of around £10 per tCO_2. In our advice on Northern Ireland's Fourth Carbon Budget, we discuss the other options that could be available for transporting and storing this CO_2.

1.7.3 Roll-out of low-carbon technologies

In developing our assumptions on credible roll-out rates for low-carbon technologies, we have considered details of the specific technology choices available as well as wider evidence around technology transitions that are happening or have happened in the UK or overseas, today and historically.

For many of the technologies considered, there is developing empirical evidence on actual roll-out rates and costs, as take-up is growing either in the UK or overseas. This includes key technologies such as electric cars (for which sales are growing towards mass market levels in the UK and many other countries) and heat pumps (which are a well-established technology in many other countries). In addition, there are numerous examples of rapid roll-out of energy infrastructure and consumer technologies throughout history that can be drawn upon to provide comparable evidence on the feasible pace of technology transitions.

Technology cost assumptions

Assumptions around the rate at which costs reduce play an important role in determining both the point at which low-carbon technologies become cost effective and therefore eligible to be taken up in the Balanced Pathway (for those that are not already cost effective), and the rate at which consumers and businesses choose to adopt them (see Section 1.5).

We base our cost projections on past evidence on the rate at which costs have changed as deployment has scaled up, both for the specific technology in question and similar comparable technologies, as well as projections of future costs from the relevant industries and independent sources. Full details of the assumptions used to determine rates of cost reduction can be found in the discussions of methodology in each sector in Chapters 6-18.

- The rates of cost reduction for key technologies in our pathway fall within the range of reduction rates that have been seen to date for key low-carbon technologies worldwide (Table 1.5).

- The costs of new technologies are typically expected to fall as deployment scales up. This is a result of the benefits of learning by doing and economies of scale, with the exact rate at which costs reduce varying between different technologies (Box 1.2).

- In several areas, there may be potential for costs to fall more quickly than we have assumed, driven by ongoing innovation and learning effects as markets scale up.

Table 1.5
Comparison of cost learning rates for key low-carbon technologies in the Balanced Pathway with those seen historically

Key low-carbon technology	Learning rate implied by the cost reduction assumptions in the Balanced Pathway (latest historical data to 2050)	Example estimates of learning rates seen in cost reductions to date
Offshore wind*	12%	12%[75], 14%[76], 15%[77], 8–18%[78]
Solar PV	20%	19%[79], 20%[80], 20–22%[81], 24%[82]
EV batteries	16%	16%[83], 16–18%[84], 19%[85], 25%[86]
Heat pumps	11%	10%[87], -2–35% (median 18%)[88], 20%[89]
Direct air capture†	12%	10-12%[90], 10–15%[91], 11–13%[92]

Source: See endnotes; CCC analysis.
Notes: (1) The table shows technology cost learning rates, which represent the percentage reduction in technology costs for every doubling in deployment. (2) For offshore wind and solar PV, the learning rates shown represent those assumed within our sectoral modelling (see Chapter 10). For the other technologies included in this table, we have used the cost reduction assumptions underpinning our sectoral models together with the global deployment projections published in the International Energy Agency's Net Zero Emissions scenario (using total global deployment on the basis that these technologies are likely to be supplied through global markets) to calculate the learning rates implied by our cost reduction assumption in the Balanced Pathway. (3) The estimated learning rates seen to date are based on a review of a range of literature for either the technology referenced or similar comparable technologies. *Some of the values quoted are for all wind power, rather than offshore wind specifically. †For direct air capture, these examples are based on forecasts rather than actual data, due to the minimal deployment to date.

Box 1.2
Technology costs – why they fall

The costs of key technologies and how they are assumed to change over time in our pathway are set out in Table 1.5 above and Table 4.1 of our Seventh Carbon Budget advice report. We expect most low-carbon technologies to have falling costs over time as their deployment in the UK ramps up, based on a technology-specific learning curve or build rate.

The learning rate is the rate of cost reduction per doubling of deployment. This can be used to estimate the potential for cost reduction of different technologies based on empirical evidence.[93] The potential for costs to fall can vary depending on particular technology characteristics, namely:

- **Technology type:** certain technologies have greater potential for cost reduction due to learning by doing.[94]
  - More modular and standardised technologies, such as batteries, EVs, heat pumps, and solar panels, can be reproduced at scale, therefore benefitting more from economies of scale.
  - More complex or 'bespoke' technologies or infrastructure, such as a nuclear reactor or home retrofit, typically have less potential for cost reduction.
- **Market potential:** the residual market for a given technology, which is determined by total deployment potential/market size and stage of deployment, determines the scope for further cost reduction.
  - More emerging technologies, such as electrolysers, or those with the largest market potential, for example EVs, have the greatest scope for cost reduction as they become more widespread.
  - More widespread technologies, such as steam turbines, or those with a limited market potential, for example products that are likely to be used only in very specific applications, have more limited scope for cost reduction.
  - In many cases, low-carbon technologies are produced and supplied through global markets. Therefore, the potential for cost reductions is dependent on the pace at which global deployment doubles. For this reason, we have used projections of global market size, where relevant, to estimate the pace at which costs will fall.

We have used learning rates based on historical data to guide and validate many of our cost assumptions for low-carbon technologies, selecting comparable case studies based on the above characteristics.

Technology adoption rates

As set out in Section 1.5, constraints on feasible roll-out rates also play a key role. Where possible, in developing our assumptions on feasible uptake rates of low-carbon technologies in each sector, we have drawn on emerging evidence on take-up or relevant comparable historical case studies to guide our assumptions about how quickly these technologies could be built or adopted in the UK.

- Low-carbon technology uptake is typically expected to follow familiar 'S-curve' dynamics, whereby roll-out accelerates quickly as production scales up and prices fall.

- These S-curves have been seen in a range of past technology transitions and infrastructure roll-outs in the UK (Figure 1.6). The pace at which these adoption rates have grown demonstrates that it is possible to develop significant new infrastructure and achieve mass-market deployment of new technologies within the 25-year time window available between now and 2050.

In our sectoral modelling, we consider the pace at which these S-curves can be expected to develop for a range of low-carbon technologies, considering the characteristics of each technology, evidence on current and emerging supply and demand for each technology, and evidence on the pace at which relevant comparable technologies have been taken up both in the UK and overseas.

- In some instances, empirical data on technology adoption rates are used in conjunction with wider evidence (for example, industry engagement) to inform feasible roll-out rate assumptions in our pathways, while for others we use case studies of roll-outs of similar technologies either elsewhere or in the past to validate our assumptions.

  - Using a combination of empirical data and wider evidence allows us to incorporate all relevant constraints that could influence the pace at which technologies can be deployed as far as possible, based on both observations of past transitions and current expectations.

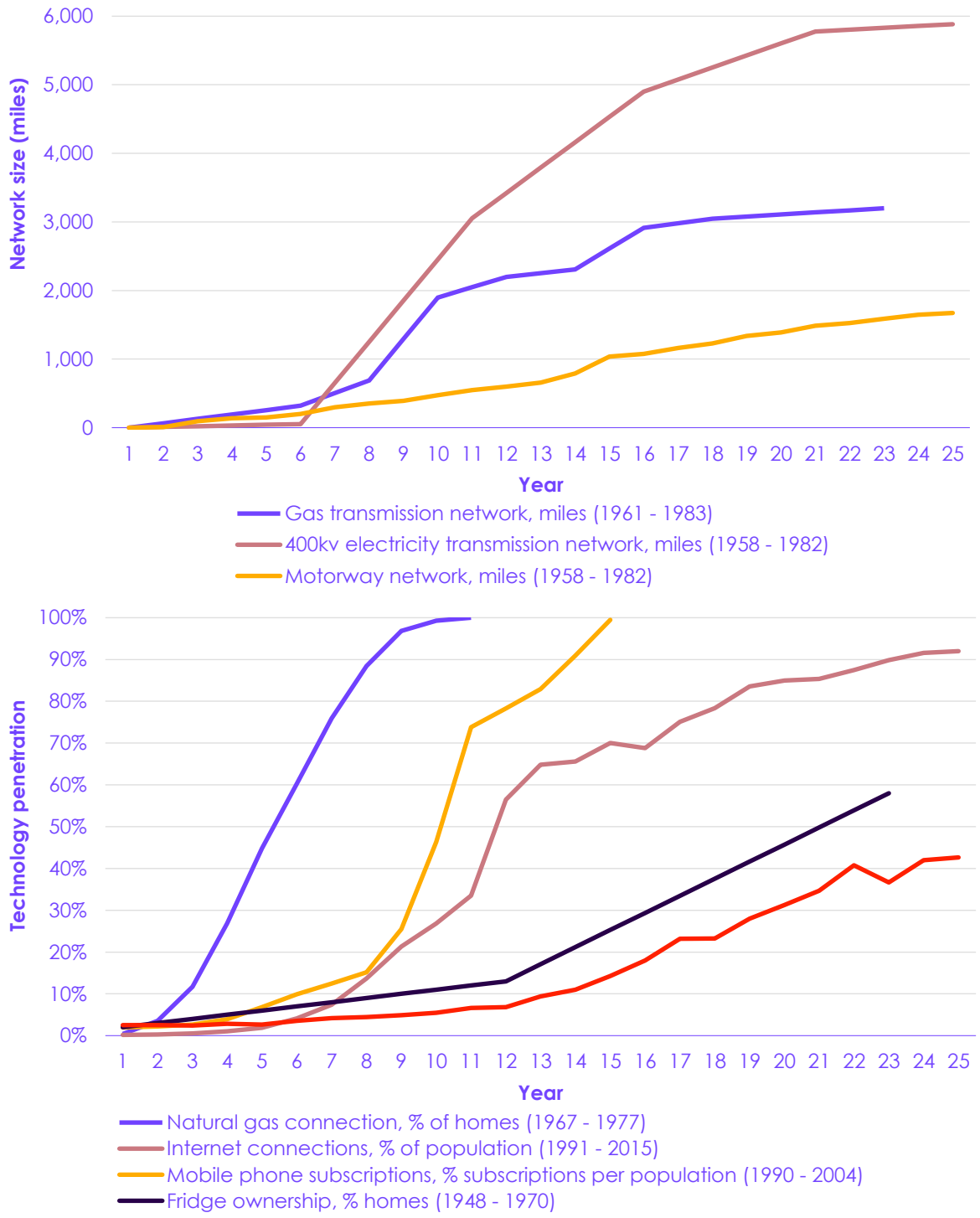
  - We give particular focus in our assessment of supply chain constraints to areas in which the required workforce growth is large relative to the current workforce. This is particularly the case in residential and non-residential buildings, industry, and land use (see Chapters 7, 14, 8, and 17 respectively).

- Where examples of adoption rates either in other countries or historically are used to inform our pathways, we typically calculate compound annual growth rates (CAGR) of deployment based on at least 5 years' worth of empirical data.

- To help validate the deliverability of the technology roll-outs within our pathway, we sought to identify case studies which are broadly comparable to the UK's Net Zero transition in terms of the type of technology and the market in which the transition occurs. Some relevant examples are shown in Figure 1.7.

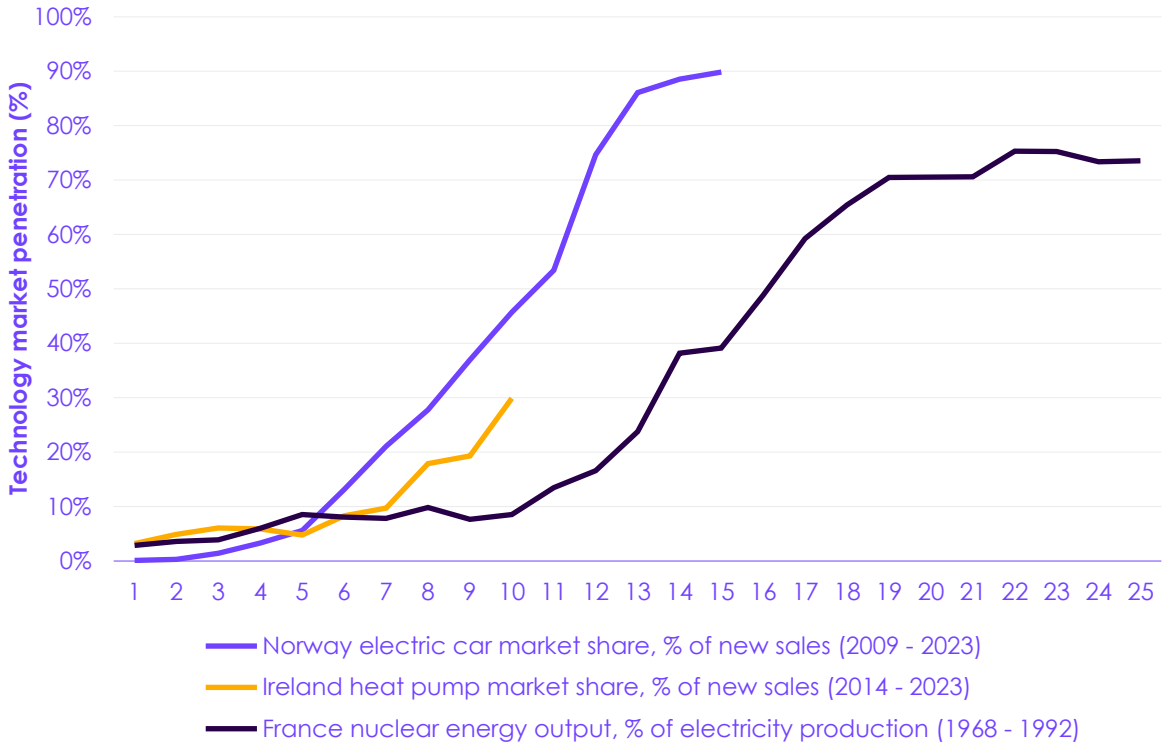
Full details of the evidence that has been used to develop and validate assumptions underpinning the assumed roll-out rates for each of the key technologies in our pathway can be found in the discussions of the methodology in each sector in Chapters 6-18.

Figure 1.6 Historical examples of the build rate and adoption of selected infrastructure and technologies in the UK



Description: The first chart shows the rapid expansion of new infrastructure networks including the gas transmission and electricity transmission networks across the UK during the past half-century. The second chart shows the rapid adoption of new technologies such as natural gas, fridges, the internet, and mobile phones during the same time period.
Sources: Our World in Data; Statista; World Bank; US Energy Information Administration; Institute for Refrigeration; Sheail, J. (1991) *Power in Trust: The Environmental History of the Central Electricity Generating Board*; Williams, T.I. (1981) *UK Gas NTS - A history of the British gas industry*; Arapostathis, S., Laczay, S., and Pearson, P.J.G. (2019) *Steering the 'C-Day': Insights from the rapid, planned transition of the UK's natural gas conversion programme*.
Notes: (1) Not all of these examples were used to inform or validate our pathways. They are intended to illustrate observed rates of technological and infrastructure change. Data have been re-based to a 25-year timeframe. (2) In the second chart, the 'Natural gas connection' line represents the cumulative share of gas network customer homes that were converted from town gas to natural gas by the given year (excluding new customers who were connected to natural gas from the outset). (3) The 'Internet connections' line represents the share of the population using the internet in the given year. (4) The 'Mobile phone subscriptions' line shows the ratio between the number of subscriptions and the population (so it can exceed 100%). (5) The 'Fridge ownership' line is based on three datapoints (1948, 1959, and 1970), with the chart showing a linear interpolation between these points.

Figure 1.7 Historical examples of the roll-out of selected low-carbon technologies overseas



Description: The chart presents selected examples of rapid adoption of low carbon technologies in European countries, including heat pumps in Ireland, electric cars in Norway, and nuclear power in France.
Sources: European Heat Pump Association, DfT, DESNZ.
Notes: Not all of these examples were used to inform or validate our pathways. They are intended to illustrate observed rates of technological and infrastructure change. Data have been re-based to a 25-year timeframe.

1.7.4 Reducing demand for high-carbon activities

In determining the level of reduction in demand for high-carbon activities that can be achieved through sustained low-carbon choices in our pathway, we focus on evidence of achievable shifts. To do this, we follow a hierarchy of evidence, focusing on actual observed evidence of the sorts of factors set out in Section 1.6 where possible (Table 1.6).

- We reviewed a range of evidence across all levels of the hierarchy, but in determining credible shifts for inclusion in the Balanced Pathway, we give preference to those types of evidence near the top of this hierarchy where possible. This allows us to focus on shifts that have been proven to be deliverable within our pathway.

- In many cases, consumer or business choices also play a role in determining the uptake of low-carbon technologies (as discussed in Section 1.7.3 above). Therefore, in some areas we used similar evidence considerations to inform or validate our assumptions around choices between high- and low-carbon technologies.

- Full details of the evidence that has been used to develop and validate assumptions on the level of shifts from high- to low-carbon activities in our pathway can be found in the discussions of the methodology in each sector in Chapters 6-18.

Table 1.6
Hierarchy of evidence used to determine shifts away from high-carbon activities in the Balanced Pathway

Type of evidence	Description
Current observed trends	Current observed UK trends in household behaviours.
Comparable shifts in leading countries	The extent to which choices have successfully been shifted away from high-carbon activities in other countries, together with evidence on the comparability of the country in question and consideration of the factors that played a role in achieving these shifts.
Comparable shifts in the past	The extent to which comparable shifts in choices have been achieved in the past, including consideration of the factors that played a role in achieving these shifts.
Behavioural trials	Behavioural trials looking at actual low-carbon choices, often as a result of a particular intervention.
Preference studies	Surveys, interviews, deliberative processes, and willingness to pay studies.
Knowledge and awareness studies	Studies exploring people's knowledge or awareness of particular low-carbon options.
Go faster scenarios	Hypothetical scenarios proposed that could achieve greater shifts away from high-carbon activities.

1.7.5 Our approach to developing assumptions for Scotland, Wales, and Northern Ireland

In developing the Balanced Pathway, we have accounted for differences in current and projected trends across Scotland, Wales, and Northern Ireland as far as possible. We do this in two ways:

- In all sectors, baseline starting points have been aligned to the latest available data on emissions and energy consumption for each nation (as described in Section 1.7.2).
- In addition, we have included nation-specific assumptions where these are expected to drive significant differences in the level or pace of change compared to UK-wide averages.
  - In these areas, we follow the same approach as outlined above to develop nation-specific assumptions for the roll-out of low-carbon technologies and for reducing demand for high-carbon activities.
  - The key differences in assumptions are set out in the sectoral chapters of this methodology report.
- Emissions reductions in Scotland, Wales, and Northern Ireland contribute around one-fifth of the total UK-wide emissions reduction in the Balanced Pathway by 2040.
  - The total contributions to emissions reduction in each nation are similar to their shares of current emissions.
  - Without decarbonisation in Scotland, Wales, and Northern Ireland, emissions reductions across the UK would fall short of reaching Net Zero by around 100 $MtCO_2e$.

1.8 Outputs from our modelling

1.8.1 Core outputs from our modelling

Our modelling in each sector produces outputs describing the emissions and energy demand within the sector, each year across the period from 2025 to 2050.

- In some models, both of these variables are modelled directly, while in others the modelling focusses primarily on either emissions or energy demand, with the other calculated from this using emissions factors.
- The details of how these outputs are determined from the assumptions described in Sections 1.3-1.7 can be found in Chapters 6-18. In this section, we summarise how these variables are aggregated and what they mean in general.
- Our sectoral models also produce detailed analysis of the costs associated with each decarbonisation measure. How these are calculated, what they mean, and how they are aggregated into an overall costing estimate are detailed in Chapter 2.

1.8.2 Emissions outputs

Our analysis covers emissions of all targeted GHGs in the Climate Change Act – these are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and a variety of fluorinated gases (F-gases). Our sectoral models produce time series of emissions of each of these gases, and these time series are reported within our dataset and aggregated into total emissions using global warming potentials.*

Global warming potentials

Global warming potential (GWP) values are used to convert emissions of non-CO_2 GHGs into their carbon dioxide equivalent. In line with current UNFCCC reporting and as applied in the UK's emissions inventory, we use GWP100, which compares the warming effects of gases over a 100-year time horizon.[95;96] Also in line with current international practice, we use the GWP values reported in the IPCC's Fifth Assessment Report without climate-carbon feedbacks (Table 1.7).[97]

Table 1.7
Global warming potentials used in the Balanced Pathway

Greenhouse gas	Global warming potential (AR5 without climate-carbon feedbacks)
CO_2	1
CH_4	28
N_2O	265
F-gases	Varies by gas – up to 23,500

* Each of our sectoral models produces estimates of CO_2, methane, and nitrous oxide emissions. Emissions of F-gases are modelled separately as their own sector in our analysis. See Chapter 16 for further details.

The use of these GWP values allows us to aggregate our sectoral modelling outputs up into our overall Balanced Pathway. This is our cross-economy pathway described in Section 1.2.1.

Emissions factors

Where our models convert between energy and emissions data, this is done using emissions factors, which represent the quantity of each GHG released from the use of a unit of each energy carrier.

- For electricity and hydrogen, these emissions factors are zero, as the use of these fuels does not directly produce GHG emissions. The emissions factors we use represent the direct emissions associated with energy used. Indirect emissions, such as the emissions produced in generating electricity, are considered separately (see below).

- For other fuels, we use emissions factors based on the conversion factors published by DESNZ.[98] These report the amount of each GHG (in GWP100 terms as described above) produced from the combustion of 1 kWh of each fuel.[*]

Performance against existing emissions targets

A key step in validating and shaping our modelling results is testing the pathway's performance against existing UK, Scottish, Welsh, and Northern Irish emissions targets. As the purpose of setting targets in advance is to provide a consistent commitment to the pace of decarbonisation, our approach ensures that the pathway meets these targets wherever this is feasible to achieve.

- The Balanced Pathway therefore meets the targets to which the UK is already committed: the Fourth (2023-2027), Fifth (2028-2032), and Sixth (2033-2037) Carbon Budgets, the UK's 2030 and 2035 Nationally Determined Contributions (NDCs), and Net Zero by 2050.

- The pathway also meets the 2045 Net Zero target in Scotland and the 2050 Net Zero target in Wales, as well as Wales' Third Carbon Budget (2026-2030) and 2030 and 2040 decadal targets.

- Northern Ireland's 2050 Net Zero target requires emissions reductions beyond those realised for Northern Ireland in the Balanced Pathway. Therefore, we define our Northern Ireland Net Zero Pathway to include the additional DACCS required to bridge this gap. This pathway also meets Northern Ireland's First (2023 to 2027), Second (2028 to 2032), and Third (2033 to 2037) Carbon Budgets, as well as its 2030 and 2040 decadal targets.

Sectoral attribution of emissions reductions

The emissions reported in our sectoral pathway represent the direct emissions produced in each sector (that is, those emissions produced directly by sources within the sector). Indirect emissions (for example, the emissions embedded in producing the fuel or electricity used in end-use sectors) are captured through our modelling of that upstream process (in particular, our fuel and electricity supply modelling) where these occur in the UK.

- Therefore, emissions embedded in the construction of new buildings are captured in our assessment of the emissions associated with cement and steel production (for example). These are included within our industry sector, where they occur in the UK.

- As discussed in Section 1.7.2, our Balanced Pathway covers territorial UK emissions, as required under the Climate Change Act. This means that if some of the steel used in constructing a new building is made overseas, then the emissions associated with its

[*] One exception is our shipping modelling, which uses slightly different tank-to-wheel emissions factors that are built into the design of the external model that we have used.

production will not be included in the pathway. In Chapter 10 of the Seventh Carbon Budget advice report, we recommend that the Government should monitor imported emissions and identify priority sources and policy levers that can be used to reduce these emissions alongside delivering territorial emissions reductions to meet carbon budgets.

Reductions in emissions (termed 'abatement') are attributed to the specific measures that deliver them in our model outputs, to enable us to identify the actions that contribute to emissions reductions. Our published dataset provides a detailed breakdown of the abatement delivered by each of the measures that we have modelled.

Determining the recommended carbon budget levels

Our modelled emissions pathway provides the basis for the Committee's recommended levels for the UK's Seventh Carbon Budget, Northern Ireland's Fourth Carbon Budget, Wales' Fourth Carbon Budget, and Scotland's carbon budgets.* These recommended levels are set in line with the total emissions (for the UK's Seventh Carbon Budget) and the average reduction compared to 1990 emissions levels (for Northern Ireland's, Wales', and Scotland's carbon budgets) over the relevant five-year carbon budget periods, rounded to avoid excess precision.

- The UK's recommended Seventh Carbon Budget has been rounded up to the nearest 5 $MtCO_2e$.
- The recommended levels of Northern Ireland's Fourth Carbon Budget, Wales' Fourth Carbon Budget, and Scotland's carbon budgets have all been rounded down to the nearest percentage point.
- We have rounded the budget recommendations in these directions (up in emissions terms for the UK and down in percentage reduction terms for the devolved administrations) to ensure that the recommended levels represent emissions reduction activity equal to or lower than that in our pathway. In this way, we ensure that these targets are set at the most ambitious rounded levels that our pathway demonstrates to be achievable.

1.8.3 Energy demand outputs

Our sectoral models calculate the level of demand in each sector across the following energy carriers:

- Electricity.
- Gas (split by gas that is used with CCS (abated) and without (unabated)).
- Oil (including all fuel uses of oil).
- Solid fuel (mostly coal/coke).
- Bioenergy.
- Non-bio waste.
- Hydrogen.

* Our advice on the UK's Seventh Carbon Budget, Wales' Fourth Carbon Budget, and Scotland's carbon budgets are based on our Balanced Pathway. Our advice on Northern Ireland's Fourth Carbon Budget is based on the Northern Ireland Net Zero Pathway, which is based on the Balanced Pathway but with additional allocation of direct air carbon capture and storage (DACCS), itself taken as a proportion of the UK-wide DACCS within the Balanced Pathway.

- Sustainable aviation fuel.
- Shipping fuels (ammonia, methanol, and synmethanol).

Measures of energy demand

The sector outputs are calculated in terms of the gross demand for each energy carrier for that sector. We add these up to produce time series of the total demand for each energy carrier in our pathway, as shown for instance in Figure 10.5 in the Seventh Carbon Budget advice report.

- In some cases, these gross demands can double count energy use across the whole system.
- For instance, where electricity is used to produce green hydrogen, this will appear as a gross demand for electricity in the fuel supply sector and a gross demand for hydrogen in the end-use sector where this is used.
- Our final dataset therefore shows both these gross energy demands for each sector and the final energy demand data, which captures just the final energy carrier used, to remove this double counting.
- In addition, we report primary energy data, which attempts to quantify the underlying energy sources that feed into the system (for example, the energy produced by wind power). There are various approaches to measuring this to ensure that the outputs are comparable between fuels (Box 1.3).

Box 1.3
Measuring energy demand

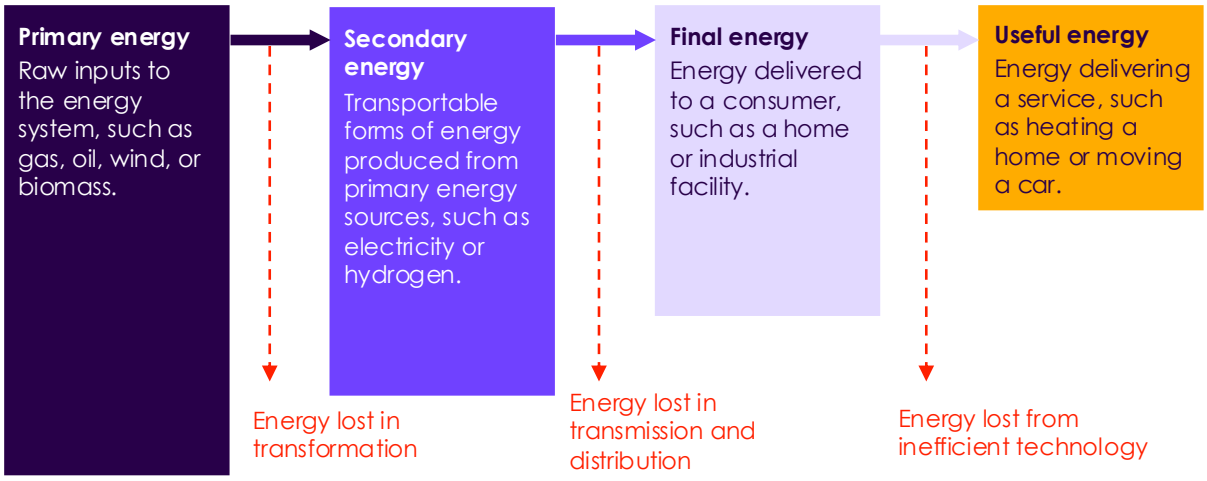
Energy demand can be measured at each stage of the system, and is expressed as primary, secondary, final, or useful demand (Figure 1.8). Between each stage, energy losses are incurred, for example, in transmission and distribution or through waste heat due to inefficiencies in end-use appliances. An efficient energy system is one with similar levels of primary and useful demand.

When comparing relative contributions of fossil fuels and renewables to the energy mix, the primary energy metric overstates the role of fossil fuels, as it does not account for the thermal losses in converting energy to other forms.[99] This misconception is sometimes referred to as the primary energy fallacy.[100] Similarly, the final energy metric does not consider losses between final and useful energy, such as the energy wasted in cars and boilers.

The substitution method for calculating primary energy demand aims to overcome the primary energy fallacy, by putting combustible fuels (for example, gas) and non-combustible inputs (for example, wind) on a level footing.[101] The non-fossil generation is scaled up to the level it would be if it had the same efficiency as a typical gas power plant. Using this method, the contribution of fossil fuels to primary energy supply in the Balanced Pathway decreases from 73% in 2025 to 14% in 2050.

However, despite their simplicity, percentage-based energy mix metrics are limited, and can only describe a single stage of the system. Energy system flow diagrams with quantified losses (such as Figure 10.4 in our Seventh Carbon Budget advice report) are a more accurate way to describe the composition of the energy system.

Figure 1.8 Energy demand metrics



Description: Energy flows through the system from primary inputs and is converted into secondary energy sources, before being delivered to a consumer as final energy. Useful energy then represents the energy services required by the consumer.
Source: Adapted from Ritchie, H. (2022) *Primary, secondary, final, and useful energy*.

The energy system

Our end-use sector models determine the energy demand for each energy carrier, and our energy supply models determine how these demands can be met in a low-carbon way. As described in Sections 1.2.1 and 1.7.2, there is an iterative process between the energy supply sectors and the other sectors. The flow of energy through the system as a whole is illustrated in our Sankey diagrams, shown in Figure 10.4 in the Seventh Carbon Budget advice report. These diagrams visualise the energy system in 2025 and 2050, showing the gross energy demands for each energy carrier together with the primary sources that supply these demands.

The Sankey diagrams also include an estimate of the amount of final energy that is converted into useful energy to meet demand for energy services (that is, things like mobility in a car or warmth in a heating system). These estimates are rounded to the nearest 100 TWh.

- These useful energy demands are not calculated in our models, but instead are estimated based on the typical energy efficiencies of the predominant technologies used in each sector (for example, an electric car for transport in the 2050 system, compared to a petrol car in the 2025 system). Experimental statistics from the Government also informed our estimate of useful energy, particularly for the industry sector, which is composed of processes with a large range of efficiencies (see Table 1.8 below).

- This enables us to estimate the amount of final energy that becomes useful energy, as well as the amount of energy wasted as part of these end-use processes.

- This wasted energy is added to our modelled estimates of losses earlier in the process (for example, inefficiencies in using primary sources of energy and transmission losses) to form our overall estimate of the amount of energy wasted across the whole system.

Table 1.8
Representative efficiencies for end-use technologies used in analysis of useful energy demand

Technology or process	Representative efficiency	Notes
Car (ICE)	20%	The average efficiency for a petrol car.[102]
Car (EV)	90%	The average efficiency for an EV car, including energy recovered from regenerative braking.[103;104]
Heating (gas)	80%	The efficiency of a typical gas boiler.[105]
Heating (low carbon)	220%	The efficiency of a typical air source heat pump.[106]
Other home energy use	70%	The representative efficiency for non-heat energy use in homes, including lighting, cooking, and appliances.[107]
Aircraft	30%	The efficiency of a jet engine at cruise.[108]
Industrial processes	50%	The average efficiency of the range of industrial processes included in the Government's experimental statistics.[109]

Source: CCC analysis.
Notes: All values are rounded to the nearest 10%. Some of the values shown are averages across a range of products, whereas others are the efficiencies of specific models which are considered representative of the existing stock. These are the values that we use to estimate useful energy in Figure 10.4 in the advice report; in most cases, different, generally more granular, assumptions are used in our sectoral models (see the relevant sectoral chapters).

1.8.4 Warming effect from GHG emissions

Figure 3.11 in the Seventh Carbon Budget advice report shows how the UK's contribution to global temperature change would develop in the Balanced Pathway. To produce this assessment, we estimate the warming effect from the GHG emissions produced in the UK historically and in the Balanced Pathway.

- For historical emissions, we use the GHG inventory for 1990 onwards, supplemented with data from the PRIMAP-hist national historical emissions time series for years before 1990.[110]
- We then apply a conversion formula to the CH_4 emissions to convert them from GWP100 into GWP*, as this provides a measure of the warming effect relative to CO_2.[111]
- We then multiply the total emissions in GWP* by the transient climate response to cumulative emissions, which was estimated in the IPCC's Sixth Assessment Report to be 0.45 degrees per 1,000 $GtCO_2e$. This estimates the impact of UK emissions on global temperature change.
- To present this in Figure 3.11, we then divide this by the latest observed level of GHG-induced global warming (1.57°C in 2023) to show this relative to the UK's contribution to this current total.[112]

1.8.5 The Balanced Pathway in an international context

The Climate Change Act prescribes 'circumstances at…international level' as matters to be taken into account in the Committee's advice on, and the Government's setting of, carbon budgets. Chapter 10 of our Seventh Carbon Budget advice report sets out our assessment of how the Balanced Pathway sits in an international context, viewed primarily through the lens of the principles of the UNFCCC and the Paris Agreement.

We conclude that the Balanced Pathway represents a fair and ambitious contribution to global efforts to tackle climate change, and is a credible contribution towards limiting long-term global warming to the 1.5°C benchmark referenced in the Paris Agreement. The remainder of this section sets out the methodology behind the components of our analysis which together lead to that conclusion.

The Balanced Pathway compared to planned emissions reductions in G7 economies

In Figure 10.1 of our Seventh Carbon Budget advice report, we compare the emissions reductions implied by the Balanced Pathway with targets set or being considered by other G7 economies. The targets we consider are set out in Table 1.9.

Table 1.9
G7 targets considered in our comparison

Economy	2030	2040	2050	Notes
UK Balanced Pathway	-65% on 1990 level	-87% on 1990 levels	-100% on 1990 levels	These reductions include emissions from international aviation and shipping and are therefore not directly comparable to the UK's NDCs.
Canada	-40% to -45% on 2005 levels		-100% on 2005 levels	Does not include emissions from international aviation and shipping.
European Union	-55% on 1990 levels	-90% on 1990 levels	-100% on 1990 levels	The European Commission has recommended that the European Union (EU) reduces its emissions by 90% by 2040 on 1990 levels including emissions from international shipping and aviation; this is not yet formalised as the EU's target.
Japan	-46% on 2013 levels		-100% on 2013 levels	Since our Seventh Carbon Budget advice went to print, Japan has submitted a new NDC with targets for 2035 (-60% on 2013 levels) and 2040 (-73% on 2013 levels). These were not included in our analysis.[113] Does not include emissions from international aviation and shipping.
United States	-50% to -52% on 2005 levels		-100% on 2005 levels	Since our Seventh Carbon Budget advice went to print, the United States has announced its intention to withdraw from the Paris Agreement, effectively nullifying its emissions targets.[114] Does not include emissions from international aviation and shipping.

Source: CCC analysis; UNFCCC (2022) *Nationally Determined Contributions Registry*; European Commission (no date) *2040 climate target*; The White House (2025) *Putting America First In International Environmental Agreements*.

The steps taken to compare planned emissions reductions are as follows:

- We compile historical GHG data. For Canada, Japan, and the United States, this is sourced from National Inventory submissions to the UNFCCC.[115;116;117] For the European Union (EU), this is sourced from the European Environment Agency.[118]

- We source 2030 targets from official submissions to the UNFCCC, 2040 targets from the European Commission's website (being the only other G7 economy with a 2040 target under consideration), and 2050 targets from government websites and policy statements.[119;120;121;122;123;124]

- With the targets and historical data, we derive implied percentage reductions on two base years: 1990 and 2022. These are chosen to provide a broad range of historical bases for comparison.

- Where targets are presented as ranges, we apply the mid-point in our comparison.

In making the comparisons, we note that different economies may use different accounting methods and have different scopes for their targets, such as the inclusion or exclusion of emissions from international aviation and shipping (IAS), and the treatment of sources and sinks in the land use sector. For example, the EU's NDC scope includes emissions from IAS. We compare all targets at face value – when converting between base years we apply nominal percentage targets to total net GHG emissions in the base year excluding emissions from IAS (except for the UK) – to avoid the need for judgements on accounting approaches which may be open to interpretation.*

Comparison of UK ambition with IPCC global emissions scenarios consistent with the Paris Agreement

In Figure 10.2 and Table 10.1 of our Seventh Carbon Budget advice report, we compare the emissions reductions implied by the Balanced Pathway with global scenarios consistent with achieving the temperature goal of the Paris Agreement.

The steps taken are as follows:

- We take global scenarios underpinning the IPCC's Sixth Assessment Report (AR6) from the AR6 Scenarios Database hosted by the International Institute for Applied Systems Analysis (IIASA).[125]

- We extract scenarios aligned with the two benchmarks within the Paris Agreement temperature goal.

  - We use the IPCC's C1 '1.5°C with no or limited overshoot' category for scenarios consistent with limiting warming to 1.5°C above pre-industrial levels. Scenarios in this category reach or exceed 1.5°C during the 21st century with a likelihood of ≤67%, and limit warming to 1.5°C in 2100 with a likelihood >50%. Limited overshoot refers to exceeding 1.5°C by up to about 0.1°C and for up to several decades.[126]

  - We use the IPCC's C3a category for scenarios consistent with limiting warming to well below 2°C above pre-industrial levels. Scenarios in this category limit peak warming to 2°C throughout the 21st century with a likelihood of >67%.[127] C3a is chosen over the broader C3 scenario set to isolate least-cost global scenarios and omit those constrained to deliver global NDCs in 2030.

* We make no further adjustment to account for the EU NDC's inclusion of emissions from IAS when converting to the 2022 baseline.

- From each of these scenario sets, we extract GHG emissions and population pathways. We take the 'AR6 climate diagnostics | Infilled | Emissions | Kyoto Gases (AR5-GWP100)' metric for GHG emissions. We combine the two to derive GHG emissions per capita pathways.

- UK emissions per capita under the Balanced Pathway are derived using the 2021-based interim edition of population projections by the Office for National Statistics (published in 2024).[128]

- From the scenario sets, we extract the median and 5th and 95th percentile ranges. These are chosen to align with presentation in IPCC AR6.

The IPCC's least-cost global scenarios in these categories generally assume cost-effective global action beginning in 2020. Given that global emissions have not fallen in line with these scenarios since 2020, the challenges of aligning with these global scenarios in future are growing. In contrast, the UK has delivered on its targets to date, albeit that these were aligned with an 80% reduction by 2050 rather than Net Zero, and faster progress is needed to deliver on future targets.

Ambition implied by the Seventh Carbon Budget compared to an illustrative set of equity metrics

In Figure 10.3 of our Seventh Carbon Budget advice report, we compare the emissions reductions implied by the Balanced Pathway in 2040 with an illustrative set of equity metrics. These metrics offer a range of interpretations of a country's equitable contribution to global mitigation efforts.

Our approach is as follows:

- We take equity metrics for the UK from the Paris Equity Check.[129] While several other equity analyses exist, we judge the Paris Equity Check to be the most relevant and useable. Given the broad range of potential approaches to selecting, interpreting, and operationalising these metrics applied in the literature, they are most useful in providing a ballpark range.

- We omit the constant emissions ratio metric (also referred to in the literature as 'grandfathering'), as this is generally recognised as not adhering to principles of equity.[130]

- As these equity metrics are presented excluding emissions from IAS, we compare them to the Balanced Pathway excluding emissions from IAS for consistency.

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Chapter 2: Costs, investment, and fiscal impacts

Introduction

This chapter sets out the methodology behind our assessment of the cost of delivering the Balanced Pathway, as well as how we estimated the fiscal impact.

- All our whole-economy costs are relative to the baseline: they are additional, compared to a hypothetical scenario where the UK does not take further decarbonisation actions.
- We calculate the additional capital and operating expenditure of delivering the Balanced Pathway for each sector. These values are then aggregated to give our overall cost assessment. This chapter describes what is considered within these estimates and the calculations that are performed to generate the various cost measures that we present in our advice reports.
- Most of the investment required in the Balanced Pathway is expected to come from the private sector, provided the right incentives are in place. We have estimated a range of possible outcomes for public expenditure, based on illustrative, high-level policy options. This range is based on assumptions of areas in which public investment is expected to be required.

2.1 Whole-economy costs

This section sets out the costing methodology used to estimate the whole-economy costs of the Balanced Pathway, set out in Chapter 4 of the UK Seventh Carbon Budget advice report and Section 2.5 of the Northern Ireland Fourth Carbon Budget advice report, Wales Fourth Carbon Budget advice report, and Scotland Carbon Budgets advice report.

2.1.1 General approach to whole-economy costs

Our whole-economy costs intend to capture the costs and cost savings of meeting the Balanced Pathway, at an economy-wide level. All our whole-economy costs are relative to the baseline: they are additional, compared to a hypothetical scenario where the UK does not take further decarbonisation actions.

Costs in the baseline

The baseline reflects a scenario in which there is no further decarbonisation in the UK, which is used as a reference point to measure the cost of building a Net Zero economy, compared to what would otherwise be spent. More detail on how the baseline is defined can be found in Section 1.3.

- The baseline does not capture the cost of loss and damage that would result from failing to address climate change. This is because climate is driven by global, not just UK, emissions.
- We do not comprehensively model baseline costs and are therefore unable to provide full estimates of the gross cost (baseline plus additional) of the Balanced Pathway. However, we recognise the value to some stakeholders of understanding gross capital expenditure

for low-carbon technologies in the Balanced Pathway and are therefore looking to publish our best estimates, where possible, in due course.

Additional costs in the Balanced Pathway

Our whole-economy cost analysis uses Green Book-aligned social costs.[1] Details on the scope of capital and operating costs is included in Boxes 2.1 and 2.2.

- Social costs are the cost of materials, labour, machinery, energy, and other factors of production that are required to deliver the measures in our pathway. Aligning with the Green Book, we only include costs which are net additional to the economy. Costs such as taxes and subsidies are considered transfers and not included in our whole-economy costs, since they net out across the economy as a whole.

- In our whole-economy cost analysis, we only use monetary costs and savings. There are some non-monetary costs and benefits associated with the Balanced Pathway, such as changes to health and biodiversity. They are addressed separately (both quantitatively and qualitatively) in Chapter 8 of the Seventh Carbon Budget advice report.

- All costs are presented in real 2023 prices.[*,2] Changes in costs over time represent changes in deployment or real changes in cost (for example, the falling cost of technology). See Chapter 1 and the sectoral chapters for further details of the factors that we consider in determining our assumptions that drive these changes.

The approach to costing is largely based on the methodology adopted for the UK Sixth Carbon Budget advice report, with some adjustments:

- **Cost of capital.** In the Sixth Carbon Budget, we used cost of capital as a proxy for the risk of a project. In our updated methodology, we include optimism bias instead (an adjustment based on the tendency to reliably underestimate costs), which is more in line with the Green Book.

- **Treatment of low-carbon technology in the baseline.** In the Sixth Carbon Budget, we assumed that low-carbon technologies already in the baseline would be replaced with high-carbon alternatives when they reach the end of their lifetimes. In our updated methodology, we generally keep the stock of low-carbon technologies constant in the baseline. This means that the cost of replacing existing low-carbon technologies at the end of their asset lifespans is included in both the baseline and Balanced Pathway. For power generation and surface transport equipment, which account for the majority of deployed low-carbon technologies, replacements are expected to be cost competitive or cost effective with respect to fossil-fuel technologies.

Uncertainty

Projected future costs are generally uncertain and are estimated using a range of assumptions across different sectors. Significant sources of uncertainty include costs of fossil fuels (especially in the baseline) and the costs of some technologies that are at an early stage of development, such as sustainable aviation fuel (SAF) or engineered removals. These can have knock-on effects for deployment and uptake of low-carbon technologies. Sensitivity in costing assumptions is discussed in Section 5.2.4 and in Chapters 6-18.

[*] Our inflation assumptions are consistent with the reference scenario presented in Annex M of Energy and Emissions Projections (EEP) published by the Department for Energy Security and Net Zero (DESNZ).

2.1.2 Calculating costing variables

Additional capital expenditure

Additional capital expenditure is the additional investment cost or cost saving required to meet the Balanced Pathway, relative to a baseline of no further decarbonisation. If the low-carbon asset is more expensive than the high-carbon asset, the additional capital cost will be positive. If it is cheaper, the additional capital cost will be negative, representing a net saving.

- We estimate the additional capital expenditure in the Balanced Pathway, to capture the extra cost of new or upgraded assets. This is carried out at measure level within each sector and aggregated upwards, to calculate additional capital expenditure estimates at the measure, subsector, and sector level. This is followed by further aggregation and analysis to form whole-economy costs.

- Capital expenditure includes the creation or upgrade to an asset with a lifetime of greater than one year. See Box 2.1 below for more detail on the scope.

- Capital expenditure is captured in the year that it is spent, for example, the year of construction or deployment. We do not include financing costs. This approach to the timing of capital expenditure is consistent with the Green Book. This can result in a 'lumpy' capital expenditure profile. Where there is a large project (for example, a nuclear power plant), capital expenditure is spread over a number of years, reflecting time to build.

- Historical data suggest that certain types of large projects reliably underestimate their costs. To account for this, we multiply our cost estimates by a project-specific optimism bias, to give a more accurate assessment of the likely actual cost. We apply optimism bias in accordance with Green Book supplementary guidance.[3]

  - We include optimism bias based on various factors including technology type, project type, ability to mitigate risk, and historical cost data.

  - For example, in the electricity supply sector, we assume an optimism bias of only 11% for solar PV projects, which are mature, standardised, and modular in nature. Gas carbon capture and storage (CCS) projects, in comparison, are more complicated and yet to be deployed at scale, so we apply a higher optimism bias of 29%.

Box 2.1
Scope of capital expenditure in the baseline and the Balanced Pathway

The broad scope of capital expenditure is:

- **New or replacement technology**. Vehicles, equipment, infrastructure, machinery, and natural capital (trees, hedgerows) that are new or are replacing high-carbon assets. Electric vehicles (EVs), heat pumps, wind turbines, electric arc furnaces, and new energy generating facilities are all new capital expenditure.
- **Upgrades.** Upgrades to existing assets will also typically involve capital expenditure if new lasting assets are being added. For example, replacing the engine on a ship to make it compatible with low-carbon fuel, which counts towards low-carbon expenditure, but also extends the asset's lifetime. This includes significant upgrades or additions to existing assets (for example, buildings, industrial facilities, adding CCS to existing industry or waste facilities, significant efficiency measures in industry, land, and infrastructure – such as in energy, transport, and waste).
- **Enabling infrastructure**. We include enabling infrastructure, such as EV chargers or CCS pipes and storage, that are specific to low-carbon assets. We do not include roads but do include upgrades to rail infrastructure to support electrified rail.
- **Direct staffing cost**. Labour required to install capital is included in capital expenditure (for example, for carrying out building upgrades to prepare for heat pump installation where required).

We do not include:

- **Policy and other intangible costs.** We do not include costs such as public engagement or research and development (R&D) costs in whole-economy cost estimates.
- **Negligible costs.** Not all measures will have expenditure requirements or costs associated with them and for others the costs might be negligible and so not be worth including.

Additional operating expenditure

Additional operating expenditure is the additional operating cost or cost saving required to meet the Balanced Pathway, relative to a baseline of no further decarbonisation. This is carried out at the measure level within each sector and aggregated upwards, to calculate additional operating expenditure estimates at the measure, subsector, and sector level. This is then aggregated to form whole-economy costs.

- Operating expenditure is the ongoing expenditure required to deploy and operate assets or measures, such as fuel, routine maintenance, and staffing costs associated with operations (for example, nuclear plant operatives). See Box 2.2 for more detail.

- As with capital expenditure, this variable reflects the difference between the in-year operating cost of high-carbon assets in the baseline and the in-year operating cost of low-carbon assets in the Balanced Pathway. Low-carbon electrified technologies are usually cheaper to run than fossil-fuel technologies, as they tend to be more efficient and are powered by low-cost renewable electricity. In these cases, additional operating expenditure is negative.

- For some measures, the additional operating costs are negligible (for example, if maintenance costs of a low-carbon technology are expected to be similar to maintenance costs in the baseline for the high-carbon technology). Where this is the case, we assume no additional cost. For some measures, such as for CCS or SAF, operating costs in the pathway are higher than in the baseline.

- We calculate energy costs using long-run variable costs (LRVCs) of energy supply (see Section 1.7.2).[4] The LRVC is defined as the parts of the retail energy price that represent actual costs to society that vary according to the level of energy consumption. Therefore, they exclude:

- Fixed costs that will not change in the long run with changes in energy consumption, such as fixed policy costs and fixed operating costs of energy retailers.

- Carbon costs, as these are valued separately.

- Transfers between groups in society, such as taxes and margins.

Box 2.2
Scope of operating expenditure in the baseline and the Balanced Pathway

The broad scope of operating expenditure is:

- **Energy and fuel costs.** Energy costs are calculated using the fuel-specific LRVC.
- **Routine maintenance costs**. Includes the cost of repairing a car or boiler, cost of maintaining CCS technology, or minor replacement of parts which does not significantly prolong the lifetime of the technology.
- **Direct staffing costs.** Labour required for maintenance or for operations of low-carbon assets. For example, labour costs required to install a heat pump, compared to labour costs required to install a gas boiler.
- **Agricultural additives.** Animal feed and additives for livestock. Compost, fertiliser, and nitrates for use in soils, and inputs to alternative protein production are all considered operating costs.
- **Chemicals and solvents** related to running high-carbon or low-carbon assets (for example, CCS).
- **Changes in material inputs** in industrial and energy settings, including steel, cement, concrete, timber, and plastic.

We do not include:

- **Policy and other intangible costs.** We do not include things that relate to energy prices other than costs (for example, levies and bills), cost of public engagement, costs of early-stage R&D, or costs associated with co-benefits of wider goods (for example, benefits for nature or health).
- **Taxes and subsidies.** These transfer resources between people within the economy rather than being a cost to the economy as a whole.

Box 2.3
Approach to costing changes in demand

We consider the impact of changes in demand for low- and high-carbon products and activities (for example, shifting from meat and dairy towards lower-carbon foods, keeping flying close to today's levels until technology develops, modal shift, and increased household recycling rates) on whole-economy costs.

Our general approach follows the methodology in this chapter. We estimate additional capital and operating expenditure by calculating the difference between the capital and operating costs incurred at the levels of demand in the baseline and the pathway. Where those levels of demand vary, our estimate of the additional cost or cost saving includes costs or cost savings from the change in demand. For example:

- In surface transport, we assume there is more demand for driving (higher vehicle mileage) in the Balanced Pathway than in the baseline. This is because the per mile cost of running an EV is lower (on average) than the cost of running a petrol vehicle. The extra costs of these additional journey miles are included in the costs of the pathway.
- In aviation, we assume that demand for flying in the Balanced Pathway is lower than in the baseline. This means that the cost associated with demand for flying is lower in the Balanced Pathway than the baseline.

We do not attempt to estimate general equilibrium effects of changes in demand (for example, what consumers would otherwise purchase in other sectors of the economy). We do not quantify the impact that relatively more driving or relatively lower flying might have on growth or productivity.

Annualised resource cost

We also present capital expenditure as annualised, where the cost is spread over the asset lifetime (see Figure 4.4 in the Seventh Carbon Budget advice report).

- Additional capital expenditure is annualised (split into equal annual payments). We also add a financing cost, using the Green Book discount rate of 3.5% (in real terms).[5] This means that if we were to take the net present value (NPV) of the yearly payments, applying the same discount rate, the resulting NPV would be equal to the in-year additional capital expenditure.

- When costs are annualised, they are spread forward across the asset lifetime (so spikes in capital expenditure are smoothed) but they are also higher, because we have added a financing cost.

  - For example, if £100 is spent in 2025 for a new asset which has a lifetime of 5 years, the annualised payment at a 3.5% discount rate would be £21.40 each year.*

- Our calculations on annualised costs use the PMT financial function in Excel, which calculates the payment for a loan based on constant payments and a constant interest rate. The end-of-life residual value (cash balance attained at the end of the payment) is 0, and payments are assumed to be due at the beginning of the period.

  - The PMT function uses the following formula:

$$P = \frac{Pv * r * (1+r)^{n-1}}{(1+r)^n - 1}$$

  - Where:

    - *P* is the annualised capex.

    - *Pv* is the present value of the asset.

    - *r* is the discount rate, which in this case is 3.5%.

    - *n* is the number of years over which the cost is annualised.

- The annualised additional capital expenditure is calculated at measure level and then aggregated at subsector and sector level.

- Annualised resource costs combine annualised additional capital expenditure and in-year additional operating costs. Operating costs do not require annualising because they are already in-year.

Abatement costs

At a measure level, the abatement cost is the additional cost (capital and operating expenditure) of the measure compared to the baseline, relative to the direct and indirect abatement that measure results in, expressed in £/tCO_2e.† Calculating abatement costs for each measure indicates

* Calculation uses Excel PMT function = -PMT (3.5%, 5, 100, 0, 1).

† Discussion on the difference between direct and indirect abatement is in Section 1.8.2.

its relative cost effectiveness. For example, one measure's abatement cost might be £300/tCO_2e, which is less cost effective than another measure which costs £100/tCO_2e.

In our analysis, we calculate two types of abatement cost: the new unit abatement cost (NUAC) and the average measure abatement cost (AMAC). More detail on how these variables are calculated is in Box 2.4.

- **NUAC.** This abatement cost captures the cost-effectiveness of a new unit introduced in a given year.
  - For example, the NUAC for EVs in 2040 would reflect the cost effectiveness of a new EV made and sold in 2040.
  - This measure can be compared to carbon values (monetary estimates of the value to society of avoiding emitting 1 tCO_2e), to assess when the measure is cost effective in the Balanced Pathway. The use of carbon values is discussed in more detail in Sections 1.5.1 and 1.7.2.
  - If a measure's abatement cost is equal to or less than the carbon value, this indicates it is technically cost effective to deploy. However, this is not the only consideration when determining the deployment of technologies in the pathway (see Section 1.5).
- **AMAC.** This abatement cost captures the average cost effectiveness of all units operating in a given year. At a measure level, this takes an average of the NUACs of all units operating in the year, weighted by their respective shares of in-year abatement.
  - For example, the AMAC for EVs in 2040 would reflect the cost effectiveness of all EVs which operate in 2040, combining the NUACs of new and existing EVs on the road.
  - The AMAC is used to indicate the cost effectiveness overall for a group of technology units or set of measures in a given year. It can also be compiled at subsector or sector level to show the average cost effectiveness of that group.
  - In Figure 4.6 of the Seventh Carbon Budget advice report, AMACs are used to present the relative cost effectiveness of every measure in the economy in 2050.

Box 2.4
Approach to calculating abatement costs

In order to calculate the abatement costs, the following inputs are required for each measure unit deployed in a given year:

- The measure's lifetime, in years.
- The additional costs (£) of the unit over its lifetime (capital and operating expenditure), compared to the baseline.
- The total abatement (tCO_2e) over the unit's lifetime (direct and indirect).

New Unit Abatement Cost (NUAC):

- The NUAC combines costs and abatement across the lifetime of the unit into a single, comparable abatement cost, using the following equation. Both costs and abatement are discounted to represent their levelised values across the unit's lifetime.

$$NUAC = \frac{£}{tCO2e} = \frac{\sum_{t=1}^{n} \frac{C_t}{(1+r)^{t-1}}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^{t-1}}} = \frac{Additional\ cost\ (discounted)}{Total\ CO_2e\ lifetime\ abatement\ (discounted)}$$

- Where:
  - C_t (£) represents the additional cost of the measure unit compared to the baseline in year *t*. This combines the annualised additional capital expenditure and in-year additional operating expenditure.
  - E_t (tCO_2e) represents the emissions reduction in year *t*.
  - *r* represents the social discount rate (3.5%).
  - *n* represents the lifetime of the unit.

Average Measure Abatement Cost (AMAC):

- The AMAC is calculated using by taking a weighted average of the NUACs of all units operating in the year *t*, using the following equation:

$$AMAC = \frac{£}{tCO2e} = \frac{\sum_{i=1}^{m} NUAC_i \times E_{it}}{\sum_{i=1}^{m} E_{it}} = \frac{Aggregated\ cost\ of\ all\ units\ operating\ in\ year\ t}{Total\ abatement\ of\ all\ units\ operating\ in\ year\ t}$$

- Where (combined with definitions above):
  - $NUAC_i$ (£/tCO_2e) represents the NUAC of each operating unit.
  - E_{it} (tCO_2e) represents the emissions reduction for each operating unit in year *t*.
  - m represents the number of units.
- For measures that do not have clearly defined units (for example, a waste facility that has continuous capital improvements), we assume that the NUAC is equal to the AMAC.

2.1.3 Adjusting for double counting

Rationale

Our whole-economy cost estimates assess the net additional cost of the Balanced Pathway compared to the baseline, by combining the additional capital expenditure and additional operating expenditure across all sectors of the economy. We try to avoid double counting by using social costs as the basis of our analysis, which represent net costs to the economy, rather than costs moving between actors. However, there are still some cases of double counting which need to be adjusted for centrally.

For the purpose of the adjustment, it is useful to split the CCC sectors into 'end-use sectors' and 'energy and fuel sectors':

Table 2.1
Split of sectors for double counting removal

Sector group	End-use sectors Users of energy	Energy and fuel sectors Producers and users of energy
Sectors included	Agriculture Aviation Residential buildings Non-residential buildings F-gases Industry Shipping Surface transport Waste	Electricity supply Fuel supply Engineered removals*

Between these groups, there are two cases of double counting which need adjusting for:

- **Electricity costs.** End-use sectors pay for electricity. This same cost is used by the electricity supply sector in generating electricity to meet the demand. The cost of electricity demanded appears in the end-use sector operating costs, and in the electricity supply sector capital and operating costs (as revenue from electricity sales is used to invest in and operate the expanded system).
  - For example, the surface transport sector includes the cost of electricity to run EVs in their operating costs. The cost of producing electricity, to ultimately run EVs, is also included in the electricity supply costs.
- **Low-carbon fuel costs.** Low-carbon fuels, including hydrogen, biomass, SAF, and synthetic fuels, are made from processes in the fuel supply sector (refineries and processing plants) and the engineered removals sector (DAC feedstock for synthetic fuels). End-use sectors pay for low-carbon fuels, and this cost is used by the fuel supply sector and the engineered removals sector to provide feedstock and generate more fuel. The cost of low-carbon fuels appears in end-use sector operating costs, and in the fuel supply sector and engineered removals sector capital and operating costs.
  - For example, the aviation sector includes the cost of SAF to run low-carbon flights in their operating costs. The cost of producing SAF is also included in the fuel supply sector (through building plants and refineries) and the engineered removals sector (through providing BECCS biofuel and DAC feedstock).

Double counting then arises when we add together the end-use sector and energy and fuel sector costs. The cost of additional electricity and low-carbon fuels are captured twice: in the end-use sector additional operating costs and also in the energy and fuel sector capital and operating costs, where they are produced in the UK.

* We have classified engineered removals as both a user of energy (for example, running DACCS plants requires electricity), and a producer of energy (since it provides the DAC feedstock component in producing synthetic low-carbon fuel, including SAF).

Double counting adjustment for additional costs

To address the instances of double counting set out above, we remove the cost of additional energy demanded from energy and fuel sectors and keep this cost in end-use sector costs. We refer to this as the consumption approach, since it focuses on the sectors which consume energy, rather than produce it.

The steps taken for aggregating costs to whole-economy level using the consumption approach are described below:

For electricity:

- The value of additional electricity demanded in the Balanced Pathway is calculated by multiplying the quantity of additional electricity demanded in each sector by the respective electricity LRVCs used in that sector.*
  - Electricity LRVCs vary depending on whether energy use is residential, commercial, or industrial. There are further breakdowns based on end-use variants (flexible/inflexible, with/without storage, EV charging, HGVs).
- The value of additional electricity demanded is aggregated between end-use sectors (in this case, including fuel supply and engineered removals which also demand electricity), to show the total double counted expenditure in electricity.
- The total double counted electricity value is removed in-year from electricity supply costs, split between additional electricity supply capital and operating costs.
  - The split between the amount removed from capital and operating costs is based on the proportion of capital and operating costs which make up the LRVC (the capital and operating cost required to generate a unit of electricity). This split varies over time, with the proportion of capital expenditure being between 50-70% (higher at the start of the transition and reducing towards the end).

For low-carbon fuels:

- We adjust for double counting for the following low-carbon fuels: SAF, bioenergy, hydrogen, and synmethanol. The value of additional low-carbon fuel demanded in the Balanced Pathway is calculated by multiplying the quantity of additional fuel demanded by its respective LRVC.
- For each fuel type, the value of additional low-carbon fuel demanded is aggregated between end-use sectors, giving a total double counted expenditure for each fuel type.
- This is then removed from the capital and operating costs of the sectors which produce it. This is done differently depending on the fuel type.
  - For hydrogen and bioenergy, the value of double counting is removed in-year from fuel supply costs, split between additional capital and operating fuel supply costs.

* Our energy cost analysis uses long-run variables costs (LRVCs), as set out in Section 1.7.2. LRVCs vary depending on energy type and year. They are calculated using the cost of energy generation, including capital and operating components. Therefore, it follows that the cost of additional energy demanded (using LRVCs) is equal to the additional cost of energy supplied (by energy producing sectors).

  - For SAF and synmethanol, the value of double counting is removed in the years that the fuel-production capex and opex were spent, from various sources within the fuel supply and engineered removals sectors (biojet, BECCS biojet, synfuel, DAC feedstock, and hydrogen).*

After the adjustment, costs in the energy and fuel sectors will represent:

- **Electricity**: The cost of decarbonising the baseline demand for electricity.
- **Fuel supply:** The cost of decarbonising the fossil fuel supply subsector and the baseline demand for low-carbon fuels.
- **Engineered removals**: The cost of engineered removals without the cost of producing synthetic fuel (which is captured in the operating cost of the sectors which use it).

Alternatively, we could have taken a production approach to double counting, where we remove the cost of additional energy from the operating costs of the sectors that demand it, and keep it in the capital and operating costs of the sectors that produce it. The consumption approach was chosen over the production approach. This is because:

- In the baseline, costs of fossil fuels are included in consumption sectors – for example, petrol is included in surface transport. It is therefore consistent to include the cost of electricity for EVs in the surface transport within the pathway.
- It maintains the sector-level cost profile for more sectors. The consumption approach keeps costs the same for the majority of sectors, only changing costs for the electricity supply, fuel supply, and engineered removals sectors. The production approach would require changes to all sectors.
- Importantly, the choice between consumption and production approach does not impact the net cost of the pathway. This is determined by the level of double counting removed, which does not change depending on which approach is used.

In Figure 4.7 of the Seventh Carbon Budget advice report, we include the 'financing requirement' line. This shows the full additional investment required under the Balanced Pathway, including the cost of expanding the electricity and low-carbon fuel systems to account for additional demand (that is, the additional capital expenditure required under the production approach to adjusting for double counting). This would be offset by correspondingly lower operating expenditure under the production approach.

Double counting adjustment in annualised resource costs

The consumption approach is also applied to the whole-economy aggregation of annualised resource costs. This takes the following steps:

- Using the steps set out above, the total double counted expenditure is calculated for each of electricity supply, fuel supply, and engineered removals and split between additional capital expenditure and additional operating expenditure as described.
  - **Additional capital expenditure.** This view of costs annualises capital expenditure, spreading it across the lifetime of the asset. The portion of the double counted

* The timing of the double counting adjustment is an approximation. In reality, some capital spending on energy production precedes the demand for that energy output, making it difficult to allocate the production cost of energy consumed. For example, some of the social cost used in the synthetic fuel LRVC will be in building synthetic fuel production plants, which will precede the demand for synthetic fuel produced at that plant. For most fuels, we have removed the cost of energy demanded in the year it is demanded. Where we have been able to isolate the direct production cost of low-carbon fuels, we have removed the cost of energy demanded in line with when production costs were incurred.

expenditure removed from capital expenditure is annualised before removing, assuming a lifetime of 25 years.

  - **Additional operating expenditure.** The portion of the double counted expenditure removed from operating costs is removed in-year.

2.1.4 Other adjustments

Bioenergy with carbon capture and storage (BECCS) cost allocation

The BECCS measure sits between sectors which use BECCS (industry, waste, and electricity supply) and the engineered removals sector, where the emissions reductions are counted. In sector costs, and the whole-economy cost profile, BECCS costs are allocated to the engineered removals sector, not to the sectors which use BECCS.

BECCS and energy from waste (EfW) electricity generation

Where electricity is generated by measures outside of the electricity supply sector, including BECCS and EfW, this is treated as a free input within the electricity system, with costs reflected in the engineered removals and waste sectors instead.

2.1.5 Scotland, Wales, and Northern Ireland costing methodology

In general, the costing methodology for the Scotland, Wales, and Northern Ireland advice reports follows the same approach as the UK approach set out above. However, there are some variations, set out below.

Legislation-specific changes

For Northern Ireland, adjustments have been made to costs based on differences in the relevant legislation.

- Costs from international aviation and shipping have been removed in line with Northern Ireland's legislated 2050 target, which excludes emissions from these sources.

- In order to bridge the gap between the Balanced Pathway and the Northern Ireland Net Zero Pathway, a proportion of UK DACCS has been added to the Northern Ireland Balanced Pathway, with costs starting in 2033.

  - Due to the lack of CO_2 storage sites in Northern Ireland, an additional cost is incurred for all CCS processes to ship CO_2 to an appropriate storage site elsewhere. The extra shipping cost is expected to be around £10/tCO_2e, adding £250 million in total to the operating costs of industry, waste, and engineered removals in Northern Ireland, between 2025 and 2050.[6]

Allocation of electricity and SAF costs

The cost of electricity in each nation has been adjusted so that imports or exports to other parts of the all-island Irish grid and the Great Britain grid do not lead to skewing the allocation of costs between nations.

- Northern Ireland is part of the all-island Integrated Single Energy Market. As such, the cost profile takes the form of Northern Ireland's contribution to this grid.

- For Wales and Scotland, the UK-wide costs have been scaled down in line with their respective contributions to additional electricity demand within the Great Britain grid.

Scotland, Wales, and Northern Ireland have varying levels of SAF demand, as determined by the activities at their airports. Costs associated with SAF production and consumption are allocated territorially.

Treatment of costs in terms of GDP

Slightly different methodologies and projections have been used to calculate costs in terms of GDP for each report.

- **UK.** We use UK GDP forecast data from the Office for Budget Responsibility (OBR).[7] The average cost in terms of GDP takes the 2025-2050 average of in-year net additional cost as a proportion of in-year GDP.
- **Wales and Northern Ireland.** We use regional data from the ONS from 2022 (the latest datapoint available).[8] The average cost in terms of GDP takes the 2025-2050 average of in-year net additional cost as a proportion of 2022 GDP. GDP for Wales and Northern Ireland is not scaled in line with expected UK-wide growth for these calculations.
- **Scotland.** We use short-term and forecast GDP data from the Scottish Fiscal Commission.[9;10] The average cost in terms of GDP takes the 2025-2050 average of in-year net additional cost as a proportion of in-year GDP.

Box 2.5
Costs in terms of GDP across nations, using a standardised approach

In order to demonstrate the comparability of our GDP calculations, we have repeated the calculations using a standardised approach. This approach assumes that the latest published value for GDP in each nation (from the ONS) grows at the projected UK growth rate (using the OBR forecast). When calculating the average net cost of the Balanced Pathway in terms of this new projection of GDP for each nation, we find:

- **Northern Ireland**: average net cost is equivalent to 0.2% of GDP between 2025 and 2050.
- **Wales**: average net cost is equivalent to 0.4% of GDP between 2025 and 2050.
- **Scotland**: average net cost is equivalent to 0.4% of GDP between 2025 and 2050.

When rounded to one significant figure, these estimates are unchanged from those in each advice report.

2.2 Fiscal impacts

2.2.1 Public expenditure

Scope

In the Seventh Carbon Budget advice report, we set out a quantitative estimate of the range of public expenditure. This is intended as a high-level indication of the range of the potential split of spend between the public and private sector. It is not intended to be prescriptive of what policy levers are required, but rather to give an indication of scale, as the specific mechanisms used to support the transition are a choice for government.

Overall approach

To estimate public expenditure from 2025 to 2050, we calculate an upper and a lower estimate for each potential source of public expenditure included in the analysis. We then sum all the sector

upper estimates to reach an aggregate upper estimate, and we do the same for the lower estimates. This gives us the aggregate range of public expenditure. In Figure 4.7 in the Seventh Carbon Budget advice report, we compare this range to the 'financing requirement' (noting that some items of public expenditure within this range are operating costs or cost savings).

In general, the upper and lower estimates do not represent maximum and minimum spend, but rather a plausible range to illustrate the choices Government will need to make. Where spend inevitably falls to the public sector (such as the cost of decarbonising public sector buildings) we have included it in both the upper and lower estimate.

To assess the appropriate level of upper and lower estimate for each sector or measure, we consider the following:

- Whether households or businesses would have sufficient incentive to adopt a measure without public financial support, and the role that grants can play in supporting early adoption.
- Whether there are distributional considerations that might lead government to publicly fund the measure.
- Whether there are competitiveness risks, or potential impacts on economic growth, that provide a rationale for the measure to be publicly funded.
- The role of public funding in supporting research and development and support for early-stage technologies.
- In some cases, whether there was precedent for public funding in existing or historical public expenditure.

We have not sought to apply our own judgement to potential classification decisions by the Office for National Statistics (ONS), which might affect whether some items of expenditure score to the public sector. So, for example, we have not included the Sizewell C nuclear power station within public expenditure, although it is possible that the ONS will classify it as such in future.[11]

Our upper and lower sector estimates are calculated either using additional whole-economy capital expenditure as a starting point, or in a more bespoke way, depending on the data available and nature of our assumptions. Tables 2.3-2.9 capture the approach in more detail.

- For some measures, we use the estimated additional capital expenditure (before double counting adjustment) for a sector or measure within a sector as a starting point. We then assume a percentage of this is covered by public expenditure, varying the percentage for the upper and lower estimate. This is similar to the approach taken in OBR's Fiscal Risks Report.[12] In some particularly relevant cases, we also included the additional operating expenditure.
- For some measures, we take a deployment trajectory from the Balanced Pathway (for example, heat pump deployment) and assume a unit cost of public spend (for example, unit cost of a heat pump grant) to estimate public expenditure.
- For a few measures, we base assumed public spend on current or previous public spending levels, especially where the costs are not directly captured in our whole-economy cost measures (for example, research and development).

Across all sectors, we undertook a desk-based review of current public spending commitments as a sense-check for our assumed spending commitments from 2025 to 2027. Committed public expenditure was recorded as of November 2024. We have not ensured that committed public

spend always falls within our range, but generally it does (where it is possible to delineate public spend that is specifically to support the transition to Net Zero).

We include the fiscal costs of shifting legacy policy costs off electricity bills within our public expenditure analysis. However, as a transfer payment, this is not included in our whole-economy costs.

We have only undertaken this analysis at a UK-wide level. The analysis does not include changes to tax receipts, and only considers direct changes to public expenditure. For tax receipts from sources such as fuel duty where revenue would be expected to drop in our pathway, we implicitly assume that these losses will be made up elsewhere. It also does not consider potential indirect effects of the transition on public spending (for instance, any decrease in spend on the NHS due to health improvements).

Main drivers of public spending

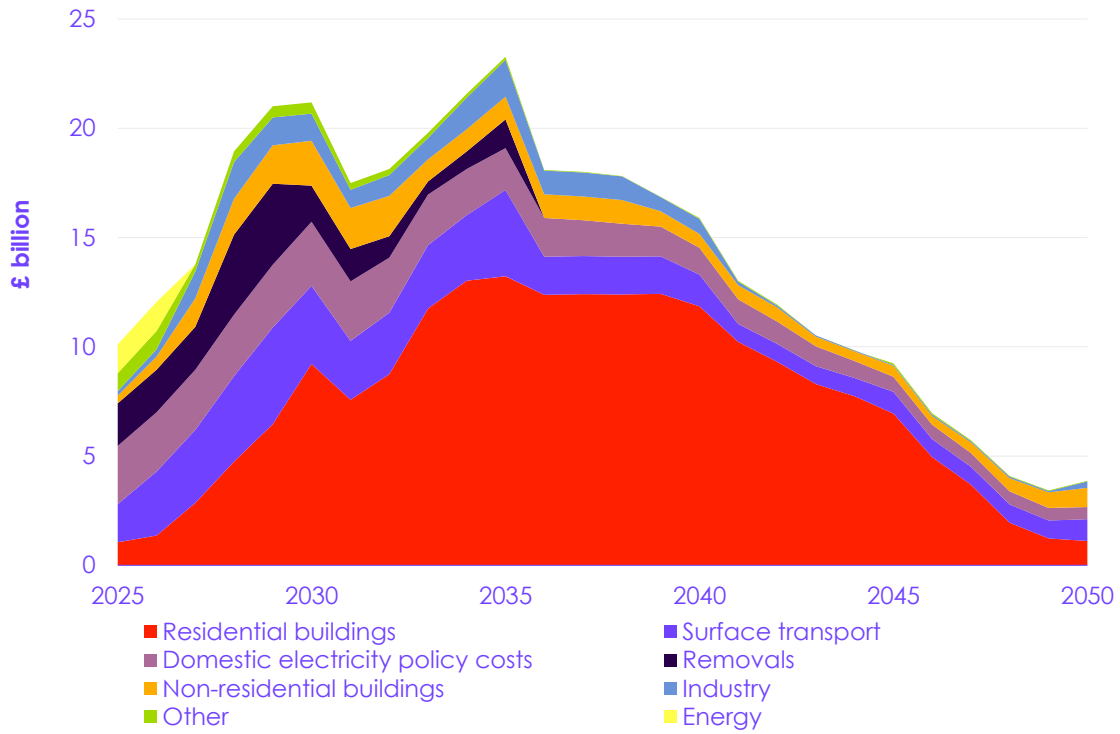
Table 2.2 sets out the main drivers of public spending in our analysis across the whole period, and in the next five years. Figures 2.1 and 2.2 show the composition of public spend in our upper and lower estimate. The section below sets out each sector's assumptions.

Table 2.2 Main drivers of public spend in CCC upper and lower estimates

	Average estimated annual spend (£bn) 2025-2030		Average estimated annual spend (£bn) 2025-2050	
	Upper	**Lower**	**Upper**	**Lower**
Grant support for domestic heat pumps	1.8	0.1	6	0.7
Support for industry	1	0.3	0.7	0.2
Train, bus, and active travel	1.7	1	1.4	0.9
Charge points for cars and vans	0.6	0.1	0.2	0.0
HGVs	0.4	0.2	0.3	0.2
Removing domestic electricity policy costs*	2.8	1.4	1.7	0.8
Engineered removals	2.5	0.7	0.8	0.2
Non-residential buildings	1.3	0.9	1	0.8
Total public spend (including measures not shown here)	16.2	6.2	13.9	4.1

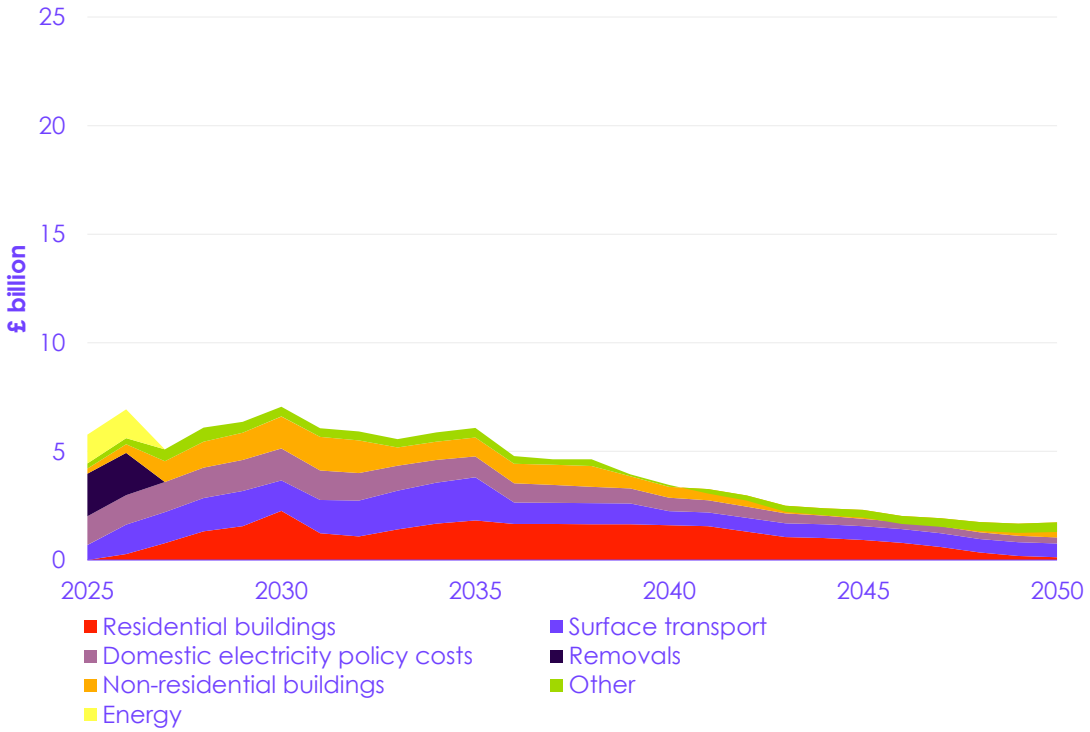
Source: CCC analysis.
Notes: (1) For the lower estimate, estimated savings from avoided subsidies mean land and agriculture public spend is net negative. The total shown here is the 'net' total (i.e. taking those savings into account) of public spend. This is why the average spend for 2025-2050 is similar to the main drivers of spend listed here, despite there being other components of public spend that are positive and not included in this table. (2) *We include removing domestic electricity policy costs as public spend in this analysis, although it is a transfer payment and is not therefore included in our whole-economy costs.

Figure 2.1 Composition of upper estimate of public spend



Description: The main driver of public spend in our upper estimate is residential buildings.
Source: CCC analysis.
Notes: 'Other' includes public spend to support decarbonisation in energy supply, agriculture, land use, waste, aviation, and shipping.

Figure 2.2 Composition of lower estimate of public spend



Description: The main drivers of public spend in our lower estimate are surface transport, rebalancing domestic electricity policy costs, and residential and non-residential buildings.
Source: CCC analysis.
Notes: 'Other' includes public spend to support decarbonisation in energy supply, agriculture, land use, waste, aviation, and shipping.

Detailed breakdown of assumptions for our analysis of impacts on public expenditure

Surface transport

Table 2.3 Surface transport assumptions

	Upper estimate	Lower estimate
Electric cars	We assume a grant of £1,500 – a similar level to the previous plug-in vehicle grant scheme – is available and used for all new small electric car purchases up to 2030.	No public spending.
Electric vans	We assume the continuation of a £2,500 grant for small vans and a £5,000 grant for large vans until 2029. We apply these to our pathway's small and large van deployment and assume 50% of new van purchases use grants in 2025-2026, falling to 25% in 2027-2029.	We assume that the level allocated in the 2024 Budget for van grant support of £120 million is maintained until 2026.
EV car and van private and home charge points	We assume a £350 grant. We use the levels of home charge points in our pathway, and assume 50% access the grant, until 2029.	No public spending.
EV car and van public charge points	We assume that 75% of the cost of installing local public chargers and public chargers along major roads and motorways is covered by public funds until 2029, then it falls to 25% for 2030-2035.	We assume 25% of the cost of installing local public chargers and chargers along major roads and motorways is covered by public funds until 2029.
Trains	We assume all additional capital expenditure is publicly funded.	We assume all additional capital expenditure on the track is publicly funded, but no additional expenditure is committed beyond this.
Bus	We assume 100% of additional capital expenditure is publicly funded until 2039.	We assume 75% of additional capital expenditure is publicly funded until 2039.
HGVs	For 2025-2029, we assume grants of £46,000 for small rigid, £68,000 for large rigid, and £103,000 for articulated HGVs. For 2030-2035 we assume grants at a similar level to the current grant level (see next column) for small rigid, large rigid, and articulated HGVs. For 2036-2040 we assume grants of £11,000 for small rigid and articulated HGVs (and none for large rigid HGVs). From 2041, there are no grants for HGVs.	We assume the continuation of grants at current grant level (£16,000 for small rigid and £25,000 for large rigid and articulated) until 2035.
HGV charge points	We assume 60% of additional costs on mega-chargers is publicly funded until 2040. We assume 50% of additional capital expenditure on depot chargers is publicly funded until 2034, falling to 25% for 2035-2040.	We assume 20% of additional capital expenditure on mega-chargers is publicly funded until 2040. For depot chargers, we assume 25% of additional capital expenditure is publicly funded until 2030.

Active travel	We estimate spend based on historical and committed spend on active travel until 2035. A third of this is then assumed to be publicly funded until 2050.	We estimate spend based on historical and committed spend on active travel, and assume a third of this is publicly funded until 2035, and a ninth of this is public funded from 2036-2050.

Notes: These estimates are illustrative and used as inputs to provide an overall estimate of total public spend. They are not intended as recommendations of appropriate levels of spend for each sector or area.

Residential buildings

Table 2.4 Residential buildings assumptions

	Upper estimate	Lower estimate
Heat pumps*	We assume all households that switch to heat pumps in our pathway receive a grant, with grant levels varying by date: £8,000 from 2025-35, £7,000 from 2036-2040, £6,000 from 2041-2045, and £5,000 from 2046-2050.	We assume households that socially rent and that switch to a heat pump in our pathway receive a £6,000 grant throughout to 2050.
Electric resistive heating	We assume an annual government spend of £500 per household for households that socially rent who switch to electric resistive heating.	We assume an upfront grant of around £2,000 until 2035 for all households that switch to electric resistive heating.
Heat networks	We assume additional capital expenditure is 100% publicly funded.	We assume that the proportion of additional capital expenditure that is publicly funded is based on the split between public and commercial heat networks in our non-residential buildings model. This varies each year, but the ratio over the whole time period is 45%.
Energy efficiency measures	We assume that for households installing large energy efficiency measures, 75% of costs are covered, unless they socially rent in which case 100% of costs are covered.	We assume that for households installing large energy efficiency measures, 25% of costs are covered, unless they socially rent in which case 100% of costs are covered.

Notes: These estimates are illustrative and used as inputs to provide an overall estimate of total public spend. They are not intended as recommendations of appropriate levels of spend for each sector or area. *Grant levels are based on the grant levels modelled in our distributional modelling, with some simplifications and rounding. They are not intended as a recommendation for the appropriate level of grant to set. As set out in Chapter 3, the distributional model grant levels are set based on a calculation to ensure that, on average, households will have a £2,000 incentive (over the lifetime of a heat pump) to purchase a heat pump instead of a gas boiler.

Non-residential buildings

Table 2.5 Non-residential buildings assumptions

	Upper estimate	Lower estimate
Public buildings	We assume all additional capital expenditure is publicly funded.	We assume all additional capital expenditure is publicly funded.
Commercial buildings	We assume that 20% of additional capital expenditure is publicly funded, until 2030. 10% of additional capital expenditure is publicly funded from 2031-2050.	No public funding.

Notes: These estimates are illustrative and used as inputs to provide an overall estimate of total public spend. They are not intended as recommendations of appropriate levels of spend for each sector or area.

Agriculture and land use

For this sector, we make less use of the upper and lower estimate when the additional capital expenditure for each measure is too low to warrant producing a separate upper and lower estimate.

Table 2.6 Agriculture and land use assumptions

	Upper estimate	Lower estimate
Woodlands and hedgerows	We assume that between 50-100% of additional capital expenditure is publicly funded during 2025-2029, varying by specific measure. By 2035, most measures fall to 0-50%, except for hedgerow creation and broadleaf woodland creation which remain at 100% throughout the period.	
Peatland restoration	We assume all peatland restoration is 100% publicly funded, except for cropland peat restoration, which is 100% publicly funded until 2039, then 50% until 2050.	
Restoration of extraction sites	We assume 50% of additional capital expenditure for restoration of industrial extraction sites is publicly funded. 100% of additional capital expenditure for restoration of domestic extraction sites is publicly funded.	
Supporting a change in land use	We use rental value of farmland which is no longer used for livestock in our pathway as a proxy for public spend to incentivise a change in land use.	We use 50% of rental value of farmland which is no longer used for livestock in our pathway as a proxy for public spend to incentivise a change in land use.
Supporting a reduction in average meat and dairy consumption	We assume a small level (around £30 million) of public spend is used on information campaigns and to support alternative proteins, promoting a reduction in meat and dairy consumption.	We assume a small level (around £10 million) of public spend is used on information campaigns and to support alternative proteins, promoting a reduction in meat and dairy consumption.
Avoided subsidies	We assume recent subsidy levels would continue at their current rate in the absence of the Balanced Pathway. We apply this subsidy rate to the farmland which is no longer used for livestock in our pathway and capture this as a reduction in public spend.	
Low-carbon farming measures	We assume no public funding for incorporating legumes into grass swards. For all other measures, we assume between 25-100% of additional capital expenditure is publicly funded throughout, depending on the specific measure.	

Notes: These estimates are illustrative and used as inputs to provide an overall estimate of total public spend. They are not intended as recommendations of appropriate levels of spend for each sector or area.

Energy supply and making electricity cheaper

Table 2.7 Energy supply and making electricity cheaper assumptions

	Upper estimate	Lower estimate
Making electricity cheaper (domestic)	In line with policy package two in our distributional model, we assume electricity policy costs are removed from electricity and put onto a mixture of gas bills and the exchequer, such that a typical overall energy bill is unchanged, with the exchequer covering the policy costs not picked up in gas bills. This implies a public spend of on average £2.6 billion from 2025-2035, falling to on average £1 billion from 2036-2050.	We assume 50% of the public spend implications of the upper estimate. This implies a public spend of on average £1.3 billion from 2025-2035, falling to on average £0.5 billion from 2036-2050.

GB Energy	We assume that the announced commitment at the 2024 autumn budget spreads over the next two years (£125 million). We assume this level of annual spend continues until 2030.

Notes: These estimates are illustrative and used as inputs to provide an overall estimate of total public spend. They are not intended as recommendations of appropriate levels of spend for each sector or area.

Industry

Table 2.8 Industry assumptions

	Upper estimate	Lower estimate
CCS	We assume 100% of additional capital expenditure is publicly funded until 2035, then 50% until 2040, then 25% until 2050.	We assume 25% of additional capital expenditure is publicly funded until 2039, after which there is no public funding.
Electrification (industrial)	We assume 75% of additional capital expenditure is publicly funded from 2025-2030, 50% is publicly funded from 2031-2040, after which there is no public funding.	We assume 25% of additional capital expenditure is publicly funded until 2040, after which there is no public funding.
Hydrogen	We assume 100% of additional capital expenditure is publicly funded until 2040, then 25% until 2050.	We assume 25% of additional capital expenditure is publicly funded until 2040, after which there is no public funding.
Energy efficiency	We assume 5% of additional capital expenditure is publicly funded.	We assume no public funding.

Notes: These estimates are illustrative and used as inputs to provide an overall estimate of total public spend. They are not intended as recommendations of appropriate levels of spend for each sector or area.

Engineered removals, aviation, shipping, and waste

Table 2.9 Engineered removals, aviation, shipping, and waste assumptions

	Upper estimate	Lower estimate
Sustainable aviation fuel	We assume 25% of costs are publicly funded from 2025-2030.	No public funding.
Engineered removals	We assume that from 2025-2035 public funds cover what costs remain after we assume credits for engineered removals are sold at the central carbon value, and after we have included estimated private revenues from selling electricity generated by BECCS. We also assume existing government commitments to support CCUS (£3.9 billion) over the next two years, continuing at the same rate until 2029. After 2035, we assume no public funding.	We assume no public funding, except for existing public commitments to support CCUS (£3.9 billion) over the next two years.
BECCS and energy from waste		
Energy from waste		
Recycling	We assume capital costs of the 'simpler recycling scheme' until 2035. We include costs of the 'extended producer responsibility' scheme from 2025-2026.	We assume capital costs of the 'simpler recycling scheme' until 2035.

Notes: These estimates are illustrative and used as inputs to provide an overall estimate of total public spend. They are not intended as recommendations of appropriate levels of spend for each sector or area.

2.2.2 Tax receipts

In the Seventh Carbon Budget advice report, we use ONS data on environmental taxes in 2023 to source what proportion of government revenue from 'taxes and social contributions' is from environmental taxes. We also use it to calculate what proportion of total environmental taxes each significant environmental tax category comprises.[13]

To estimate the magnitude of revenue lost from fuel duty due to falling demand for fuel for vehicles, we:

- Take the fuel demand (TWh) for transport that is modelled in our baseline and in our Balanced Pathway. We convert this into litres applying conversion rates for diesel blend and petrol blend, weighted based on the proportion of cars owned by fuel type.[14]

- Assume fuel duty remains at the same rate of 53p per litre (in nominal terms), and apply this revenue to each litre demanded in the baseline and in the pathway, from now until 2050.

- Calculate the difference between baseline and pathway revenues in 2030. We divide this by OBR historical revenues in 2023 to calculate what the fall in revenues would be as a fraction of fuel duty revenues today.

2.2.3 Public borrowing

We assume that levels of public borrowing are determined by the UK Government's fiscal rules and by limits on borrowing powers set out in legislation and policy for the Scottish and Welsh Governments and the Northern Ireland Executive.

We therefore assume that changes in public spending or taxation in one area are offset by changes in public spending or taxation elsewhere, with no net impact on levels of public borrowing.

Endnotes

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Chapter 3: Households

Introduction

This chapter describes the methodology behind our analysis of how the Balanced Pathway involves households, presented in Chapter 8 of our Seventh Carbon Budget advice report. We drew on our Balanced Pathway sector models, bespoke CCC models for distributional impacts and co-impacts, and a citizens' panel to inform this analysis.

- **Household low-carbon choices**: we estimate emissions reduction from household choices by assessing whether each measure in the Balanced Pathway relies on a household low-carbon choice. We estimate the emissions footprint for three illustrative individuals from home energy use, travel, and meat and dairy consumption by drawing on published datasets on the distribution of emitting activities across income quintiles, and assuming emissions factors for each activity.

- **Citizens' panel**: we commissioned Ipsos to deliver a citizens' panel, to understand what a group of people representative of the UK population, once they have learnt about the topic, think is needed to ensure Net Zero is affordable and accessible for all households. The process was supported by Sciencewise, evaluated by Ursus, and steered by an Independent Oversight Group.

- **Impacts on household costs and savings**: to assess the impact of the Balanced Pathway on household costs and savings in home energy use and surface transport over the 2025-2050 period, we use our Net Zero Distributional Impacts model (developed by Frontier Economics) to assess the impact of two illustrative policy packages on 15 household archetypes, constructed to be broadly representative of the UK population. We also model expected spend for a 'typical' household in 2025 and 2050 for home energy use, surface transport, and food and drink.

- **Wider impacts**: to assess the non-financial impacts of the Balanced Pathway, we combine Balanced Pathway sector pathways with our Co-Impacts model (developed by PwC). To assess the potential impacts of the Balanced Pathway on groups with protected characteristics, we conducted a mapping exercise to identify priority areas, and then a review of the literature and stakeholder engagement on the priority areas identified.

- **Scotland, Wales, and Northern Ireland**: most of the analysis on household impacts is conducted at a UK-wide level. For our advice to the Scottish Government, the Welsh Government, and the Northern Ireland Executive, we conducted a review of data and literature to advise on any key differential expected impacts and drew out relevant insights from the UK-wide analysis.

Our approach to determining the appropriate roll-out of low-carbon technologies and reduction in demand for high-carbon activities for both households and other actors are detailed in Sections 1.5 and 1.6 of this report respectively.

3.1 Household low-carbon choices

3.1.1 Emissions abatement from household low-carbon choices in 2040

In Chapter 8 of our Seventh Carbon Budget advice report, we outline that around a third of emissions reductions in 2040 rely on household low-carbon choices (see Figure 8.1 in the advice report). This section sets out our analysis on the proportion of abatement in the Balanced Pathway that relies on household low-carbon choices.

To determine the contribution to emissions reduction of each household low-carbon choice, we take the following approach:

- For each measure in the Balanced Pathway, we label whether it involves a household low-carbon choice or not (Table 3.1).
- We only include measures which are directly reliant on household choices. This means we exclude measures that may have wider public implications or where public acceptance is of relevance, but which do not require individual purchasing decisions or changes to lifestyle (for example, construction of energy transmission infrastructure).
- We do, however, include purchasing of low-carbon heating systems and energy efficiency measures for residential use as a household low-carbon choice, even where the purchase may be done by a private landlord or a local authority or social housing provider as homeowners, rather than by households as tenants.
- If a measure does constitute a household low-carbon choice, we also label whether it constitutes a one-off purchase (for example, investment decisions) or a sustained choice (for example, ongoing consumption decisions).
  - One-off purchase of low-carbon measures and technologies: a purchase needs to be made only once (for example, home insulation) or once to transition to a low-carbon technology and then as a replacement purchase at the end of life of the technology (for example, heat pumps).
  - Sustained choices by households to reduce high-carbon activities: these involve households making low-carbon choices which are repeated or sustained in an ongoing way (for example, a reduction in meat consumption).
- Each measure in the Balanced Pathway has abatement assigned to it for a given year. As a result, we are able to quantify in any given year between 2025-2050 the emissions reduction that is reliant on household low-carbon choices (Figure 3.1). Figure 8.1 in the Seventh Carbon Budget advice report is based on this for 2040.
  - This includes abatement from one-off purchases made in earlier years which are being used in 2040 (for example, an electric car purchased in 2035, which is being used in 2040).
  - For sustained low-carbon choices, generally only the abatement from the choices made in that year are shown.*

* The exception is a reduction in average meat and dairy consumption, where we assume a three-year time lag before a reduction in meat and dairy demand will feed through to a corresponding reduction in UK livestock production. Therefore, emissions in 2040 depend on meat and dairy consumption choices in 2037.

- The estimate is focussed on the direct impact on UK territorial emissions in the relevant sectors, and does not cover all emissions impacts, including emissions from imported meat and dairy and emissions from inbound flights.[1]

  - For one-off purchases, the figures show abatement from the use of the low-carbon technology. Emissions from production of technologies are accounted for in the industry sector, where these occur in the UK.

  - A shift away from average meat and dairy consumption towards lower-carbon foods results in reduction in livestock numbers in our modelling. This leads to two sources of emission reductions: a reduction in direct emissions from livestock and soil emissions by releasing land out of livestock production; and the increased land-based sequestration this enables. The impact of releasing land for sequestration is shown for the year in question. As trees take time to grow, this understates the longer-term impact on sequestration of the resulting land release.

These numbers are associated with emission reductions across all households in the UK. Different households have different emission footprints, as set out further below.

Table 3.1
All measures in the Balanced Pathway defined as household low-carbon choices

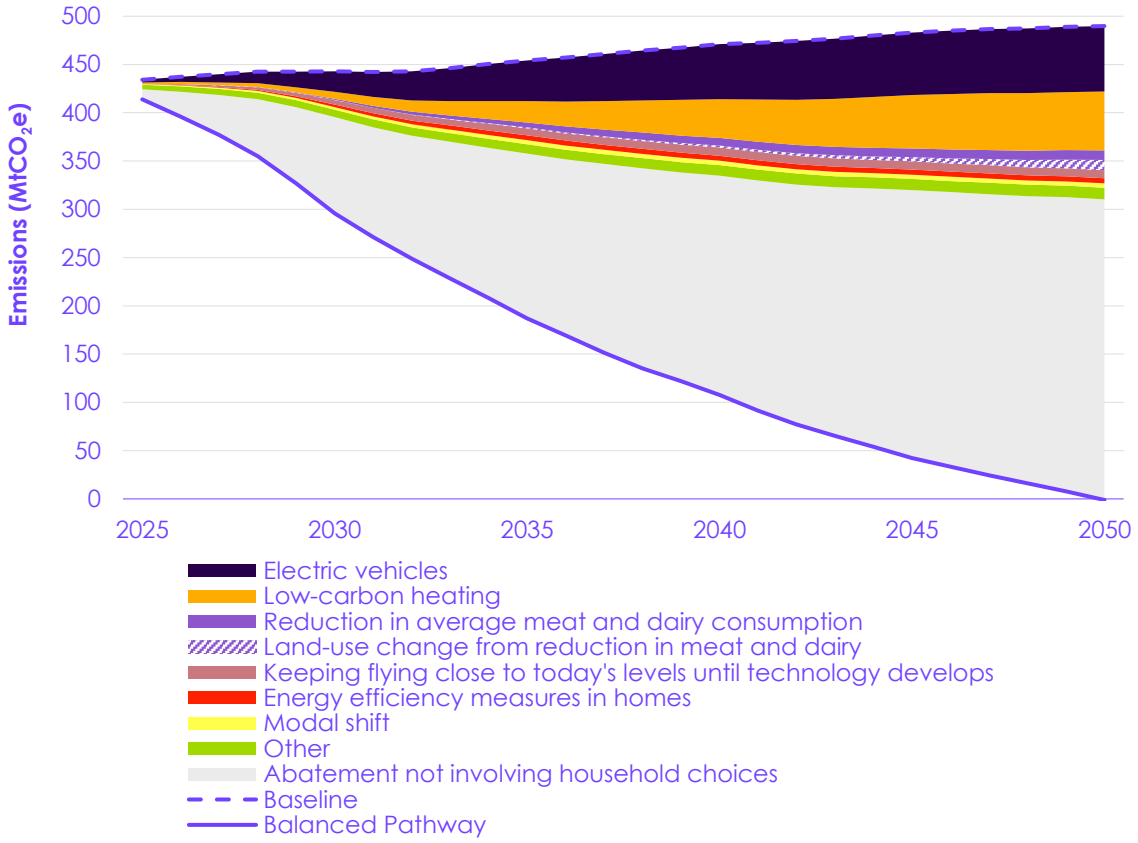
Sector	Measure description	Chart category (in Figure 8.1 in the Seventh Carbon Budget advice report)	Abatement from household choice in 2040 ($MtCO_2e$)	% of measure abatement reliant on household choices	Source for % of measure abatement attributable to households
Agriculture	Reduction in meat and dairy consumption	Reduction in average meat and dairy consumption	8.0	100%	
	Land use change from reduction in meat and dairy*	Land use change from reduction in meat and dairy	2.0	100%	
	Reducing food waste from farm to household	Other	0.2	65%	Proportion of reduction in food waste in Balanced Pathway from households (based on a CCC waste model output - see Chapter 13 for details).
Aviation	Managing the forecasted increase in baseline aviation demand through policy	Keeping flying close to today's levels, until technology develops	8.4	86%	Proportion of terminal passengers in UK airports flying for leisure purposes.[2]

Industry	Deployment of resource efficiency measures across the economy†	Other	0.6	22%	Proportion of reduction in emissions from resource efficiency measures taken by households in the Balanced Pathway.
Residential buildings	Low-carbon heating associated with existing homes	Low-carbon heating	33.3	100%	
	Low-carbon heating associated with new build homes	Low-carbon heating	7	100%	
	Energy efficiency associated with existing homes, relating to insulation measures	Energy efficiency measures in homes	5.3	100%	
	Assuming that a proportion of energy-saving behaviour observed between 2021-2023 is maintained into the future	Other	3.9	100%	
	Decarbonisation of cooking and household machinery (lawnmowers) in all homes	Other	0.7	100%	
	Appliance efficiency associated with all homes, relating to all appliances and machinery efficiencies	Other	0.6	100%	
Surface transport	Introduction of zero-emission battery-electric cars to displace internal combustion engine vehicles	Electric vehicles	51.6	94%	Proportion of distance travelled by car for non-business purposes.[3]
	Introduction of zero-emission	Electric vehicles	4.7	24%	Proportion of distance

	battery-electric vans to displace internal combustion engine vehicles				travelled by van for private use.[4]
	Introduction of zero-emission battery-electric motorcycles to displace internal combustion engine vehicles	Electric vehicles	0.4	98%	Proportion of distance travelled by motorcycles for non-business purposes.[5]
	Reducing overall vehicle-km driven to reduce emissions	Modal shift	4.4	94%	Proportion of distance travelled by car for non-business purposes.[6]
	Improved compliance with speed limits to reduce fuel use through slower locomotion in cars	Other	1.3	94%	Proportion of distance travelled by car for non-business purposes.[7]
	Improved compliance with speed limits to reduce fuel use through slower locomotion in vans	Other	0.1	24%	Proportion of distance travelled by van for private use.[8]
	Improved compliance with speed limits to reduce fuel use through slower locomotion in motorcycles	Other	0.01	98%	Proportion of distance travelled by motorcycles for non-business purposes.[9]
Waste	Biodegradable waste landfill ban, reductions in food waste, increased recycling	Other	2.3	32%	Proportion of reduction in waste arisings from households in the Balanced Pathway.
	Reduction in waste arisings	Other	1.2	32%	

Notes: (1) *The proportion of land use change emissions reduction which results from diet change was calculated separately. Several land use change measures feed into this. (2) †Household resource efficiency measures include no further growth in average vehicle size, abatement from a reduction in household food waste in the food manufacturing sectors, and the continuation of current trends in several smaller measures including the use of car clubs. (3) A source for the % of measure abatement attributable to household choices is provided only where this is assumed to be less than 100%.

Figure 3.1 Abatement from household low-carbon choices in the Balanced Pathway



Description: The household low-carbon choices with the largest emissions abatement are electric vehicles and low-carbon heating.
Source: CCC analysis.
Notes: This only includes abatement directly associated with household low-carbon choices. For example, the shift to electric vehicles by businesses are not included. It does not include emissions from imports or inbound flights. There is a time lag between reducing meat and dairy consumption and the subsequent emissions reduction from land-use change, which means that some further emissions reduction from this land use change occur after 2050.

Comparison with approach in our Sixth Carbon Budget advice

This typology differs from our quantification of the role of households in our advice on the UK's Sixth Carbon Budget.

- In our Seventh Carbon Budget analysis, we find that in 2040, around a third of emissions reductions are due to household low-carbon choices, with 72% of this abatement from a switch to electric cars and to low-carbon heating.

- In our Sixth Carbon Budget advice, our analysis showed that 41% of abatement in the Balanced Pathway relied on upstream changes (for example, renewable electricity generation) that do not require consumer choices, 16% of abatement in the Balanced Pathway in 2035 relied primarily on demand-side choices (for example, a reduction in meat and dairy consumption), and a further 43% relied on measures which require businesses and consumers to purchase low-carbon technologies with societal or behavioural changes, such as driving an electric vehicle (EV) or installing a heat pump.

- While the broad categories are comparable to our current labelling of sustained choices and one-off purchases, the Sixth Carbon Budget typology did not distinguish between the purchase of technologies and behavioural changes made by households and by businesses, and therefore is not directly comparable. For the Seventh Carbon Budget, we

developed a more specific typology for household low-carbon choices and have disaggregated the abatement associated with households from other actors.

Household low-carbon choices in Scotland, Wales, and Northern Ireland

Our analysis of household impacts was undertaken at a UK level - we do not explicitly calculate the contribution of household low-carbon choices to achieving the Balanced Pathway for Scotland, Wales, and Northern Ireland.

- However, in Chapter 4 of our advice reports for Scotland, Wales, and Northern Ireland, we draw out key insights from this UK-wide analysis that apply to each nation.

- Household choices made in one part of the UK affect emissions in other parts. For example, agricultural emissions are proportionally higher in rural regions but will depend on households across the UK reducing average meat and dairy consumption rather than just households in that area.

3.1.2. Current household emissions across income groups

Low-carbon choices vary by household. For example, many households do not fly and switching to public transport may be more feasible for urban households.[10] To illustrate this, in Figure 8.2 in the Seventh Carbon Budget advice report, we estimate how current emissions associated with the highest impact low-carbon household choices vary across three illustrative individuals.

This figure illustrates current emissions from home energy, driving, meat and dairy consumption, and flying, for three illustrative individuals with activity levels representative of the lowest-income, median-income, and upper-income quintiles. It is based on analysis of a range of datasets on activity levels across income groups and emissions factors:

- **Home energy:** data on household gas and electricity consumption across income deciles are from the National Energy Efficiency Data Framework, which we average into income quintiles.[11] Greenhouse gas conversion factors were used to calculate emissions from gas and electricity use. We used the emission intensity of electricity and gas in the Balanced Pathway in 2025 (see Chapter 10 and Section 1.8.2). To show emissions on an individual basis, we divide by the average household occupancy (2.36).[12]

- **Driving:** data on average distance travelled per person across income quintiles by car or van are from the National Travel Survey.[13] Car-kilometres were scaled so the average across all income groups aligns with per-capita road traffic estimates for the UK (based on road traffic estimates for Great Britain, scaled to include Northern Ireland).[14] We use CCC modelled emissions factors for a medium-sized petrol car in 2025, based on Society of Motor Manufacturers and Traders (SMMT) historical data on test-cycle emissions intensities of new vehicles, an assumed 2% annual efficiency improvement for new vehicles since the latest historical data, and our modelled estimate of the uplift required to convert these into real-world emissions intensities (based on analysis of test-cycle inadequacy from the International Council on Clean Transport (ICCT)).[15;16]

- **Meat and dairy**:

  – Data on average consumption of meat and dairy per person per week across equalised income decile groups are from the Family Food Survey, which we average to convert into income quintiles.[17] We use the published three-year average dataset, from financial years 2019-20 to 2021-22. We categorise consumption of meat and dairy into different meat types, cheese, and milk, and include foods eaten both at home and outside the home.

- For meat-based composite dishes (such as ready meals), the data does not specify what proportion is meat or in some cases which type of meat is included. For these, we assume that 30% of the content is meat, based on an internal CCC estimate of meat content found in commonly purchased supermarket ready meals.* We then assign the most likely meat type based on the product. We checked that the aggregate consumption levels per meat type that this implies align with FAO food balance sheet statistics.[18]

- To estimate the share of each meat type, milk, and cheese consumed in the UK that comes from imports or from domestic production, we use data on imports, UK production, and exports of meat and dairy from agriculture in the UK, and milk supply and utilisation statistics.[19;20]

- We then estimate the emissions per person for each meat type, milk, and cheese consumption using emissions factors from Poore and Nemechek (2018).[21] We apply their emissions factors for the UK to the proportion of consumption we estimate comes from UK-produced meat and dairy. For consumption of imported meat, we apply emissions factors from the largest import country for each meat type, milk, and cheese. We assess the largest import country using UN Comtrade data.[22] The trade data may not accurately capture the country of origin of all products. However, this is unlikely to significantly change the estimate of emissions.

- **Flights**:

  - Data on the number of international flights taken by income group are from the National Travel Survey.[23] We do not show the modal number of flights taken by individuals in each income quintile, which is zero across all quintiles, due to the unequal distribution of flying. In 2019, 20% of the highest-income quintile flew four or more times a year, compared to just 3% of the lowest-income quintile. We illustrate this distribution by showing the individual representing the lowest-income quintile as flying zero times, the individual representing the median-income quintile as taking one short haul flight per year, and the individual representing the upper-income quintile as flying four times per year (three short haul and one long haul).

  - We choose two of the most common long and short haul flight destinations from the UK to represent the range in emissions from long and short haul flights. For short haul, we show a flight from London Gatwick to Alicante, Spain, and for long haul we show a flight from London Heathrow to New York.[24]

  - We use the International Civil Aviation Organization (ICAO) carbon emissions calculator for emissions data from 2024.[25]

  - The National Travel Survey shows outbound journeys from the UK to another country. We assume that flights are taken as a round trip, and therefore we also include an inbound journey, represented separately as imported emissions (see below).

- We show emissions from inbound flights and meat and dairy imports, which are not included in the UK's carbon budgets or the Balanced Pathway, but contribute to imported emissions (see Chapter 10 of the Seventh Carbon Budget advice report for further discussion of imported emissions).

- This analysis does not capture the full emissions impact of individuals, as emissions from other sources are excluded (for example, emissions associated with household waste). This is to

* This differs from our approach to calculating meat consumption indicators. When calculating indicators, we do not disaggregate the meat content of composite dishes and use the whole weight of the dish in order to make our indicators more easily comparable to the official statistics reported based on the underlying FFS data.

align this assessment of the emissions by individuals with the key household low-carbon choices we discuss.

- The analysis for this figure is distinct from the sector-level abatement analysis that informs the Balanced Pathway.

3.2 Citizens' panel

We convened a citizens' panel to inform our advice around household low-carbon choices in the Seventh Carbon Budget. A citizens' panel is a group of citizens, broadly reflective of the UK population, convened to explore the preferences and opinions of the public – once they have been informed and discussed a topic together in depth. The panel focused on what is needed from government to make low-carbon choices accessible and affordable for all households in four areas: home heating, car use, meat and dairy consumption, and flying.

Alongside wider evidence on public attitudes and preferences, the panel findings have informed our advice on how household low-carbon choices can be made affordable and accessible by government. They indicate the perspectives of a diverse and informed group of citizens, once they have had time to deliberate on these questions. In Section 3.3, we present the outcomes of the citizens' panel's discussions around the policy packages we have developed.

- The panel was delivered by Ipsos, and a detailed outline of the panel methodology can be found in their report, Citizens' Panel for an accessible and affordable household vision of Net Zero. The panel was co-funded by Sciencewise and adhered to the Sciencewise guiding principles and quality framework on the essential elements of a public dialogue on policy involving science and technology.[26]

- The project involved an oversight group to provide independent advice on the process and ensure a wide range of perspectives are involved in shaping the work. An independent evaluation (due to be published in 2025) has also been conducted by Ursus Consulting to assess how the project's governance, design, delivery, and impact have performed in relation to best-practice standards.

3.3 Distributional impacts

In Section 8.3 of our Seventh Carbon Budget advice report, we assess the main costs and savings related to household spending, focusing on changes in home energy use and transport in detail and summarising impacts on food and flying. We assess impacts for a typical household, as well as the distribution of costs and savings across different household archetypes. There will also be some indirect impacts on households from other sectors, however, the impacts of these indirect effects on households are uncertain and are not included in our households analysis.

3.3.1 Home energy and transport

Net Zero Distributional Model overview

We assess changes to home energy use and transport using our Net Zero Distributional Model. The Net Zero Distributional Model was developed for the CCC by Frontier Economics, whose more detailed summary of the model is on our website. We updated the model after it was commissioned from Frontier, with key changes as outlined below.

- The model calculates the distributional effect on household costs and savings of selected policies for decarbonisation in residential buildings and surface transport, for a set of 15 representative household archetypes.

- The model estimates household costs under our baseline scenario. The model also estimates household costs in a scenario in which households take up low-carbon technologies in line with the Balanced Pathway, calculated as additional costs or savings relative to the baseline scenario. The costs of climate inaction (such as costs of extreme weather) are not factored into the model.

- The starting point in the model is that each household using a technology bears the costs and benefits of taking up and using that technology. This results in an estimate for a 'no policy action' scenario, where technologies are purchased, with impacts on the distribution of household costs and savings. We do not consider this a realistic scenario on its own (as policy is likely to be required to ensure uptake of certain low-carbon technologies), but use it as a point of comparison.

- We then add on policies to assess the distributional consequences, relative to this 'no further policy action' starting point. We have selected two combinations of policies ('policy packages') to drive decarbonisation measures in line with our Balanced Pathway.

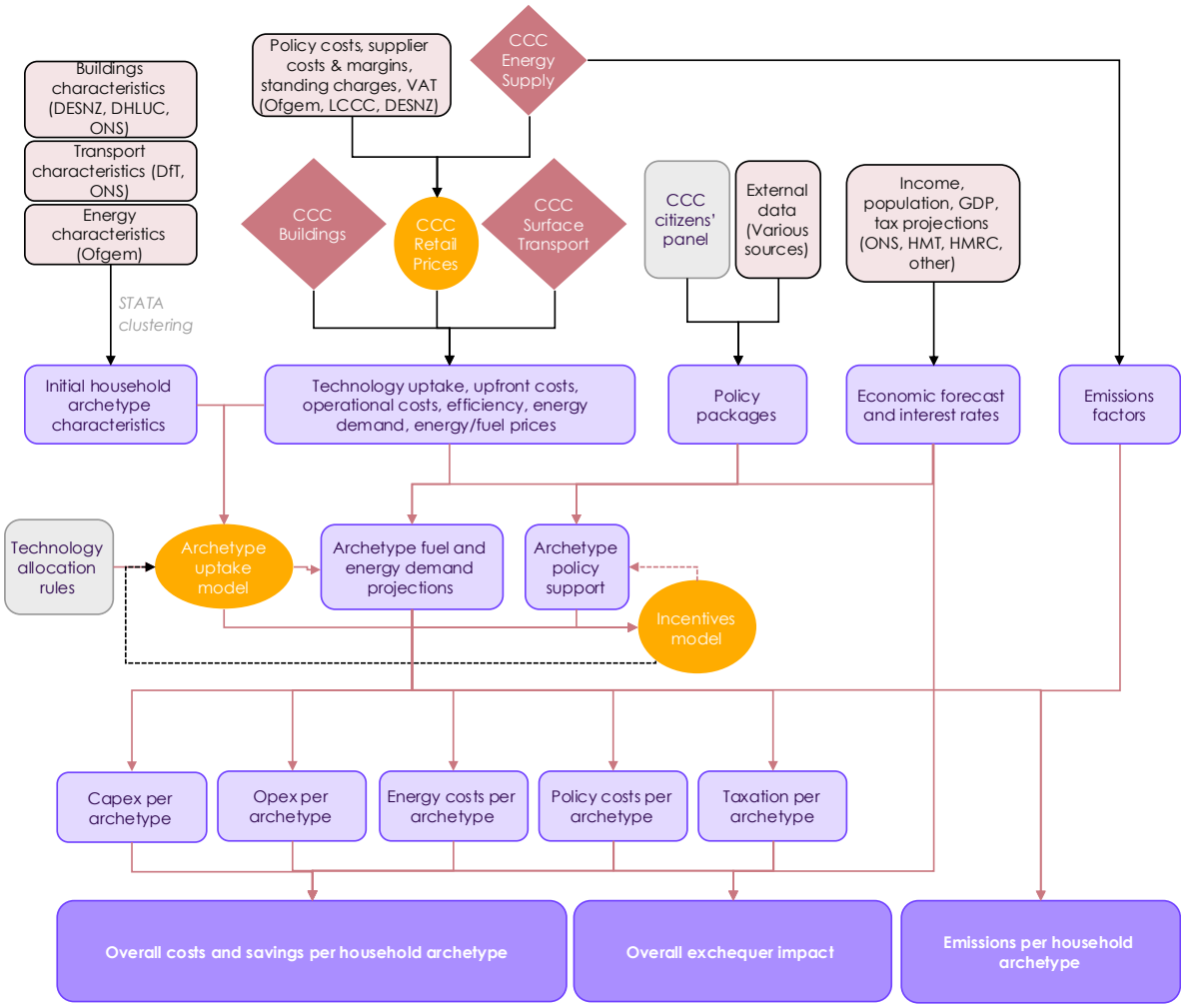
- The model calculates the total costs (or revenues) associated with providing these policies to all eligible households and distributes these across archetypes. The model calculates the change in household costs for each archetype and snapshot year (in 5-year intervals from 2025 to 2050), relative to the baseline. The change in costs includes upfront capital costs of technologies and retrofits, ongoing non-fuel costs (for example, maintenance), energy costs (for example, electricity, gas, petrol, or diesel), and additional costs and benefits such as changes in grants or general taxation (due to policy selection).

- The model also calculates the impacts of different policy combinations on Exchequer spending and revenues. We assume that new spending or revenue collection is distributed across households in line with the current allocation of taxes.[*] This assumes that Government continues to adjust the tax system to keep distribution of tax (net of welfare) constant.

Key inputs and outputs of the model are outlined in Figure 3.2 and discussed in the sections below.

[*] Modelling of the current allocation of taxes includes all major taxes and benefits, such as income tax, national insurance, VAT, council tax, and income support, by income decile.

Figure 3.2 Net Zero Distributional Model schematic



Description: The figure illustrates the structure the Net Zero Distributional Model. The model combines inputs from sector pathways, a household archetype model, and illustrative policy packages to estimate the costs and savings faced by different households over time.
Source: Frontier Economics (2025) *Net Zero Distributional Model*; CCC analysis.
Notes: Infographic developed by CCC based on Frontier Economics' Net Zero Distributional Model.

Household archetypes

We commissioned Frontier Economics to develop 15 household archetypes to show the range of impacts faced across the UK.[27] The aim of this analysis is to highlight the range of impacts and opportunities experienced by different types of UK household as a result of Net Zero, as many households will face significantly different impacts compared to the 'typical' UK household.

- The model has capacity to assess a wide range of different household types, however, for the purposes of this report we assess 15 representative archetypes.
- These archetypes represent distinct groups of households in the UK population, and vary according to physical building characteristics (including house size and EPC rating), travel characteristics (for example, car ownership and mileage), socioeconomic characteristics (for example, income and tenancy status), and other characteristics (such as level of rurality).

- The archetypes were selected by carrying out a clustering analysis in STATA to develop a set of 15 archetype 'clusters'. A set of systematic rules were then applied to allocate characteristics to a 'representative household' in each cluster. For example, clusters with the highest proportion of households off the gas grid were allocated as 'off-gas grid' until the total number of households off the gas grid was in line with the UK-wide figure.

Following Frontier's construction of 15 archetypes, we adjusted some archetype characteristics to ensure an appropriate spread of characteristics. The key characteristics of each archetype are shown in Table 3.2 below.

- We adjusted archetype incomes to ensure coverage of all income deciles. Archetypes are shown in order of increasing income, from A1-A15, in Table 3.2 below.

- We introduced an additional allocation rule to concentrate social housing in low-income household clusters, as is reflective of the UK's housing stock.

- When taken together, these 15 archetypes broadly represent the population of the UK. However, by their nature archetypes do not represent the full extent of diversity within the UK population. The approach of clustering households according to key characteristics means that not every combination of household characteristics that exists in the underlying population will be included.

We also assess impacts for a 'typical' UK household. This is calculated based on median UK levels for numerical characteristics such as income and car mileage, modal values for discrete characteristics such as heating system and housing type, and energy consumption in line with Ofgem's typical dual fuel consumer, as shown in Table 3.2 below.

Most household characteristics remain constant over time, however, there are some baseline characteristics that change in both the baseline and the pathway, based on Office for National Statistics (ONS) projections:

- **Net income** rises by 2% annually to 2050 in real terms, based on ONS data on the median income growth rate between 2004 and 2019.[28]

- **House value** rises by 0.7% annually to 2050 in real terms, based on ONS data on the average house price growth between 2005 and 2019.[29]

- **Population** increases by 6% between 2025 and 2035 and by 11% between 2025 and 2050, based on ONS data and Frontier Economics assumptions.[30]

Some characteristics are also changed over time as part of the Balanced Pathway (for example, a household switches from a gas boiler to a heat pump). This varies by archetype, but in aggregate terms these changes align with the pathway in terms of heating technology, car type, energy demand (heating and non-heating), and car mileage, as outlined in the section below.

Table 3.2
Net Zero Distributional Model archetype starting characteristics, in 2025*

Label	% of total HHs	Heating system	EPC	Income decile	Housing type	Tenure	Car mileage†	# and type of cars	Access to parking
A1	8%	Gas boiler	C	1	Mid Terrace	Social renter	None	0	Street
A2	8%	Gas boiler	C	1	Semi Detached	Social renter	High	2 diesel cars	Off-street
A3	9%	Gas boiler	E	2	Flat	Private renter	None	0	Street
A4	3%	Gas boiler	C	3	Mid Terrace	Owner occupier	Medium	2 petrol cars	Street
A5	12%	Gas boiler	D	3	Mid Terrace	Private renter	High	2 diesel cars	Street
A6	2%	Gas boiler	B	4	Detached	Owner occupier	Medium	1 diesel car	Off-street
A7	2%	Gas boiler	C	5	Semi Detached	Owner occupier	Medium	1 diesel car	Off-street
A8	6%	Gas boiler	D	5	Semi Detached	Owner occupier	Medium	2 petrol cars	Off-street
A9	10%	Gas boiler	D	6	Detached	Owner occupier	Low	1 petrol car	Off-street
A10	3%	Electric heating	E	7	Detached	Owner occupier	High	1 diesel car	Off-street
A11	5%	Oil boiler	E	7	Detached	Owner occupier	High	1 diesel car	Off-street
A12	9%	Gas boiler	C	8	Semi Detached	Owner occupier	Low	1 petrol car	Off-street
A13	8%	Gas boiler	C	9	Flat	Private renter	None	0	Street
A14	8%	Gas boiler	D	9	Mid Terrace	Private renter	High	2 petrol cars	Off-street
A15	7%	Gas boiler	D	10	Detached	Owner occupier	Low	1 petrol car	Off-street
'Typical' household		Gas boiler	D	5	Semi Detached	Owner occupier	Medium	1 petrol car	Off-street

Notes: (1) *The table includes key archetype characteristics. There are further characteristics that have been considered in our model that are not included here such as housing size, rurality (rural/urban status), house value, gas grid connection, and heating technology. (2) †Car mileage is defined based on total car mileage across both cars, where households have two cars. Mileage is categorised into low (under 13,000 km per year), medium (13,000-20,000 km per year), and high (over 20,000 km per year). Each archetype has a specific car mileage number in the model, but here we present mileage grouped into low, medium, and high for simplicity and to correspond to the chart labels.

Technology uptake allocation

Total levels of uptake and use of low-carbon technologies in the modelling are not determined by the policies chosen and are instead set to broadly align with the Balanced Pathway.

- Uptake of low-carbon technologies is consistent with the starting characteristics of the archetypes. For example, archetypes that start with high building efficiency do not take up insulation, and archetypes with no vehicles do not take up electric cars.

- Uptake across archetypes results in household numbers with each technology that are broadly consistent with the overall Balanced Pathway in terms of uptake rate and technology mix. Because the archetype households are representative rather than average, and because grouping households into 15 archetypes entails a loss of granularity, the aggregate uptake numbers in the pathway do not exactly match our archetypes.

While overall uptake and use levels are fixed in the model, the order of uptake across different household archetypes varies. The choice of uptake technology and timing are determined by households' eligibility and incentive to take up technologies.

- The model first assesses the level of uptake available each year, in line with the Balanced Pathway. For example, if 450,000 air source heat pumps are installed in existing homes in the pathway in 2030, then there are 450,000 air source heat pumps available for installation in the model.

- Each archetype is tested for eligibility. For example, archetypes living in flats are not eligible for ground source heat pumps in the Balanced Pathway, so ground source heat pumps are not assigned to flats in the model.

- Each eligible archetype is also given a weighting, based on their relative incentive to take up each measure.

  - For buildings, uptake is weighted evenly between eligible households and assumed to be the same across archetypes.*

  - For transport, uptake is calculated based on the additional upfront cost of uptake, as a proportion of income. Where the additional upfront cost is a smaller proportion of income, households are given a higher weighting and therefore take measures up earlier. If the additional upfront cost is negative (that is, the low-carbon option is cheaper than the baseline), uptake is weighted evenly between eligible households.

- Technologies are then allocated to household archetypes based on eligibility and incentive weighting. Once the number of households within a household archetype taking up a certain technology reaches a minimum threshold (we set this at 70% in our modelling), the representative household archetype is determined to have taken up the technology.

- Effectively, this approach results in eligible household archetypes taking up low-carbon heating and energy efficiency relatively evenly in terms of income, while electric car uptake is income dependent (with higher-income households modelled as taking up electric cars first).

The model also only includes the first 'switch' to low-carbon technologies, and does not include replacements, either in the pathway or the baseline. Once an archetype has switched to a low-

* As discussed in more detail below, the incentives to switch to low-carbon heating (in net present value terms, over the lifetime of the technology) are the same in both policy packages.

carbon technology, we assume that they do not switch again to another technology. For modelling purposes, we allocate uptake in line with the Balanced Pathway.

Energy retail prices

For our distributional analysis, we model real-world retail prices faced by consumers. These are calculated using long-run variable cost (LRVC) outputs from our energy supply modelling (see Section 1.7.2) and adding on policy costs, supplier costs and margins, VAT, and other charges as outlined below.

- **Long-run variable costs** include the cost of generating electricity, as well as network costs, and capacity markets. These are modelled as part of our energy supply modelling, as outlined in Section 1.7.2 and Chapters 10 and 12 on electricity and fuel supply.

- **Supplier costs and margins** include the operating costs and profit margins of energy retailers. These are calculated based on a weighted average of margins (£ per kWh) across the 'big six' energy retailers from 2014-2022 and assumed to remain constant over time.

- **Policy costs** are additional costs levied on electricity and gas bills, to fund other energy-related investment. These are modelled based on historical price cap data from Ofgem, as well as projected future policy costs as outlined below.

  - **Renewables Obligation and Feed-in Tariff** costs are modelled based on projected electricity generation from individual generating stations, based on project start year, lifetime, capacity, and load factors, falling to zero by 2046 and 2039 respectively. These are currently levied on the unit price of electricity.

  - **Contracts for Difference** (CfDs) are modelled based on published strike prices for generating stations from Final Investment Decision Enabling for Renewables (FIDER) and allocation rounds one to six (AR1-AR6), relative to the modelled Market Reference Price in each year of generation. It is assumed that strike prices fall over time, such that the net exchequer cost of allocation rounds beyond AR6 is zero, and the overall impact of CfD payments on bills is zero by 2045. These are currently levied on the unit price of electricity.

  - **Energy Company Obligation** costs are based on historical costs and assumed to remain constant until the scheme ends in 2027. Extension or replacement of the scheme is included separately in our policy packages. These are currently levied on the unit price of electricity.

  - **Smart Meter** roll-out costs are based on projections by the Department for Energy Security and Net Zero (DESNZ) for the total cost of roll-out from 2019 to 2034. These are currently spread across electricity and gas, on both unit and standing charges.

  - **Nuclear Regulated Asset Base** costs are based on Ofgem projections for the cost of the policy, from 2028 to 2040. This is expected to be levied on the unit price of electricity.

  - **Warm Homes Discount** costs are based on historical Ofgem price cap data and assumed to remain constant on a per-household basis until 2050. These are currently levied on standing charges for both electricity and gas.

  - **Other future policies** such as the British Industry Supercharger or potential Hydrogen levies have not been modelled in this analysis.

- **Standing charges** include the daily cost of connection to electricity and gas grids. These include a portion of network and operating costs, as well as some policy costs, as outlined above. Network costs are split between unit rates and standing charges in line with current

proportions, and this proportion is assumed to remain constant over time. Households who switch away from gas-powered heating and cooking systems no longer pay gas standing charges.

- **VAT** is value-added tax, charged at a rate of 5% for domestic energy consumption.

- **Gas grid decommissioning** costs have not been included in our retail price modelling. It is not clear where any costs will fall.

As current policy costs are disproportionately levied on electricity rather than gas, our policy packages include rebalancing of policy costs from electricity onto gas and/or general taxation. This is discussed further in Table 3.3 below.

Selection of policy packages

We have developed two policy packages to illustrate a range of policy choices and their distributional outcomes. **These packages are not intended to be prescriptive or distinct policy options, but to highlight the key trade-offs and consequences of different policy choices**.

The two policy packages aim to show a range of impacts based on type of policy mechanism (for instance, price-based or other), level of public expenditure, focus on running costs or upfront costs, and funding mechanism. A full list of policies that are included can be seen in Table 3.3.

- Both policy packages include core elements that are considered necessary to deliver the transition. This includes public investment in expanding EV charging infrastructure, decarbonising public transport, and supporting active travel, as well as making electricity cheaper by removing policy costs and providing grants for low-income households. Both packages also assume a phase-out of new high-carbon technologies and deployment of energy efficiency improvements in line with the Balanced Pathway.

- Beyond this, policy package one focuses mostly on running costs, through shifting electricity policy costs onto gas and taxing fossil fuels. Upfront support for households installing energy efficiency and low-carbon heating is limited to low-income households. Overall, this package involves low levels of public expenditure, with support provided mostly through market-based mechanisms and funded through bills.

- Policy package two focuses more on upfront costs, with grants provided for all households installing low-carbon heating. Electricity policy costs are shifted partially onto general taxation and partially onto gas bills (enough for the average dual fuel bill to face no net change from rebalancing). Overall, this package involves higher levels of public expenditure, with support provided mostly through public sector funding, funded through general taxation.

- We have also shown the impacts of our pathways for households without policy support ('before policy'). We do not consider this to be a realistic scenario, as households likely do not have sufficient incentive to take up heat pumps without policy support in many cases, but we use this as an illustrative comparison to show the relative impacts of policy packages.

Our policy packages are designed to have a financial incentive for a household to adopt a low-carbon technology, and to be fiscally neutral.

- Both policy packages have been designed so that the low-carbon option is cheaper for households than the high-carbon alternative. Within the model, this has been done by calculating lifetime costs of low-carbon measures deployed in each year, and providing policy support such that the low-carbon heating option is at least £2,000 cheaper than the baseline alternative over its lifetime, in net present value terms. For surface transport, this is

not required as households already save over £2,000 when switching to electric cars, over the lifetime of the technology. These calculations are based on average UK energy demand and upfront costs, and therefore may not be applicable to all households.

- Both policy packages have also been designed to be fiscally neutral. This means that all public spending is funded, either through bills or general taxation. In practice, Government may choose to fund policies through other mechanisms such as borrowing or reallocating departmental spending. However, we have not modelled this. Levies placed on companies are assumed to be passed on to consumers.

- Both policy packages have been tested and iterated with our citizens' panel and selected through consultation with Government, academic, and industry experts, as well as a wider review of literature on past and present policies implemented in the UK and elsewhere.

- Households are assumed to take up eligible policy support. In practice, additional policy action will be needed to ensure that households are aware and able to take up grants and other policy support, and government would need to monitor the effectiveness of policies. This is discussed further in our supplementary research on the impacts of the Seventh Carbon Budget on groups with protected characteristics.

Table 3.3
Policy package description, by policy lever

Policy	Policy package 1	Policy package 2
Rebalancing electricity and gas policy costs	Renewable Obligation, Feed-in Tariff, Energy Company Obligation, Warm Homes Discount and early Contracts for Difference (FIDER and Allocation Rounds 1-2) are shifted entirely on to gas bills until 2040, and general taxation after this. Carbon pricing is additionally levied on heating gas and oil until the combined impact with rebalancing reaches the price of carbon.*	Renewable Obligation, Feed-in Tariff, Energy Company Obligation, Warm Homes Discount and early Contracts for Difference (FIDER and Allocation Rounds 1-2) are shifted partially to gas bills (so that the average dual fuel bill reaches price parity with the counterfactual) and partially to general taxation until 2040, and entirely to general taxation after this.
Taxes on heating gas and oil		
Renewable Transport Fuel Obligation	Yes (~1p per km)	No
Increase in Vehicle Excise Duty for petrol and diesel cars	Yes, £80 per car per year†	No
Upfront grants for heat pumps	Targeted grant for low-income households only	Universal grant
Upfront grants for communal heat	Targeted grant for low-income households only	Universal grant
Upfront grants for insulation	Targeted grant for low-income households only	Targeted grant for low-income households only
Upfront grants for electric cars	No	No

* Here we use the carbon value as outlined in the HM Treasury Green Book, starting at £292/tCO_2e in 2025, and rising to £426/tCO_2e in 2050 (in 2023 prices).

Obligations on boiler manufacturers‡	Yes, phasing out by 2035	No
Investment in public transport, active travel, and EV charging infrastructure	Yes, funded by taxation	Yes, funded by taxation
Phase out new fossil fuel boilers	Yes. In line with Balanced Pathway – new sales of high-carbon technologies are phased out in line with phase-out dates, but phase-out dates alone do not directly impact household costs and savings.	Yes. In line with Balanced Pathway – new sales of high-carbon technologies are phased out in line with phase-out dates, but phase-out dates alone do not directly impact household costs and savings.
Home energy efficiency standards		
Phase out new petrol and diesel cars		
Notes: (1) †The standard rate of VED in our model is £195 per year, although this varies for different types of vehicles. This analysis was carried out before changes to VED were announced in the Government's 2024 Autumn Budget Statement. (2) ‡Obligation on boiler manufacturers is modelled as increasing boiler costs and reducing heat pump costs to reach price parity over their lifetime.		

Other key assumptions

Price year: All prices, costs, and rates are expressed in real terms (2023 prices), using GDP deflators.

Cost of capital: We apply varying costs of capital depending on purchase type and household characteristic, based on a review of existing commercially available interest rates.

- For vehicle purchases, we assume an 8.9% APR for low- and middle-income households, who are assumed to fund purchases through loans. For higher-income households funding capital expenditure through savings, we assume a standard 3.5% cost of capital.
- For home upgrades, we use a range of 3.5% to 7.0% APR based on income, with lower-income households paying higher interest rates. For rented properties, we use the lower rate of 3.5% as we assume home upgrades are funded by property owners rather than tenants.

Fuel duty: we exclude fuel duty from all calculations for petrol, diesel, and electric cars. This is because we assume there will be policy in place to maintain current levels of taxes, but we leave the approach as a choice for government.

Tax: when policy costs are funded through general taxation, we assume the proportion of tax contribution from each income decile remains constant, with the same applying for revenues generated from policies. This includes both direct (for example, income tax) and indirect taxes (for example, VAT), based on published ONS data.[31]

Used car markets: we have not modelled used car markets in detail. We assume that the upfront cost differential between petrol/diesel and electric cars is the same for both new and used cars at any point in time.

Charging points: we assume that households without access to off-street charging pay higher charging costs for EVs. The additional cost of charging at public charge points (on top of domestic retail prices) starts at 25 p/kWh in 2025, falling over time to reach 5 p/kWh by 2045 as charging infrastructure develops.[32]

Indirect cost impacts: we do not capture any impacts of measures on house prices.

Landlord cost pass-through: we assume that landlords pass through costs of installation to tenants on an annualised basis, and that tenants receive costs and savings related to changes to bills.

Costing per archetype

We calculate costs and savings for each archetype relative to a 'no further decarbonisation' baseline.

- Annualised costs are calculated at five-year intervals from 2025 to 2050, as well as an annual average for the period 2025 to 2050 (undiscounted). We annualise costs over the lifetime of the technology.
- For heat pumps, we split costs into longer-term home upgrades (for instance, upgrading radiators) and technology costs (for example, heat pumps), with varying lifetimes.
- Costs for each archetype are disaggregated into capital expenditure, maintenance costs, energy costs (including energy policy costs), grants, changes in general taxation, and additional transport policy costs (for example, vehicle excise duty). Costs can be further disaggregated into spending by sector (that is, comparing spending on buildings versus that on transport).

3.3.2 Change in household costs for a typical household

In Figure 8.3 in the Seventh Carbon Budget advice report, we compare a 'typical' household's bills in 2025 and in 2050, based on median UK consumption in 2025 and 2050. This is separate from the 15 archetypes included in our distributional analysis, and has characteristics as outlined in Table 3.2.

- The chart represents the typical annual spend for a 'typical' household on home energy bills, heating system maintenance, driving bills (petrol or electricity), other driving costs (car maintenance, insurance, and vehicle excise duty), public transport, food, and drink, as well as annualised capital investment in cars and heating systems (for example, gas boilers and heat pumps).
- The 'typical' UK household is modelled based on median and modal household characteristics for the UK - a semi-detached, owner-occupied house with a gas boiler and one petrol car. This household has energy consumption in line with Ofgem's average dual fuel bill household for 2025, median car mileage and median income for the UK, and average food and drink costs in line with the Family Food Survey (for both groceries and eating out).
- We annualise technology costs over their lifetime, including financing costs in line with typical commercially available rates. Heating system costs include heat pump installation costs, heat pump technology costs, and basic energy efficiency measures such as draught-proofing around windows and doors and hot water tank insulation. Home energy costs include heating, cooking, lighting, and other energy use, excluding car charging costs as these are included in transport (bills).
- Estimates for annual household energy bills are modelled based on CCC projections for retail prices in 2025, and are shown in real terms in 2023 prices. As such, figures may not directly match other published sources such as Ofgem's quarterly price cap publications.
- Food and drink costs show annual household food and drink spending, including groceries and eating out. The approach to calculating food and drink costs is outlined in Section 3.3.4.

3.3.3 Energy retail prices

In Figure 8.4 of the Seventh Carbon Budget advice report, we compare the energy bill of a typical household using a gas boiler to an equivalent household using an air source heat pump.

- The 'energy bill with a gas boiler' is based on Ofgem's average dual fuel bill household in 2025, consuming 2,700 kWh electricity and 11,500 kWh gas per year.[33] The energy bill includes both heating and non-heating (for example, lighting and cooking) energy consumption, and includes both standing and unit charges.

- The 'energy bill with a heat pump' is based on the same household heating their home with an air source heat pump instead of a gas boiler. This includes a coefficient of performance (COP) of 2.94, in line with our residential buildings pathway (see Chapter 7). It includes an energy demand uplift of 15% as heat pumps require the heating system to be operated more continuously than with a gas boiler, which can increase the energy demand for space heating. It is assumed that this household disconnects from the gas grid, meaning it no longer needs to pay a gas standing charge.

The three charts in Figure 8.4 show how these two households' bills compare under different policy cost rebalancing scenarios.

- Chart (a) shows energy bills under the current configuration of policy costs.

- Chart (b) shows energy bills when some policy costs (Renewables Obligation, Feed-in Tariff, Energy Company Obligation, Warm Homes Discount, and early Contracts for Difference payments from FIDER and Allocation Rounds 1-2) are shifted from electricity to gas bills. Beyond 2045, to avoid levying residual policy costs on a rapidly decreasing number of gas users, policy costs are phased off gas bills and onto general taxation, until in 2050 all remaining policy costs are funded through general taxation.

- Chart (c) shows energy bills when the same policy costs are levied partially onto gas bills, and partially onto general taxation. Policy costs are levied onto gas bills until the Ofgem average dual fuel bill user faces no net costs from rebalancing (that is, until the increase in gas bills matches the decrease in electricity bills), and remaining policy costs after this are shifted onto general taxation.

We do not include any costs related to decommissioning of the gas grid in energy bills. To the extent these occur, they are captured in our fuel supply sector costing. Effects of other policies in policy packages (such as additional taxes on gas beyond rebalancing of policy costs from electricity) are also not included here.

Modelling of energy prices involves a significant degree of uncertainty and depends on a number of factors that are difficult to precisely model. As such, figures in this chart should not be used as a precise estimate for bills in each given year, but to show the overall trend and relative effect on incentives of different rebalancing options.

3.3.4 Impacts across archetypes

In Figure 8.5 of the Seventh Carbon Budget advice report, we set out the impact of both policy packages on the 15 household archetypes outlined above.

- To create the charts, we use the Net Zero Distributional Model (as outlined above) to calculate the change in average annual household costs for each archetype over the 2025-2050 transition period.

- Each dot on the chart represents the total additional costs for each household per year under the Balanced Pathway from 2025 to 2050, compared to a 'no further decarbonisation' baseline. Costs are expressed as a proportion of household net income.

- We first calculate these costs without policy support, represented with grey dots. This includes the net costs and savings for households when meeting the Balanced Pathway (compared to the baseline scenario), but without any policy support. We do not consider this 'before policy' scenario to be a realistic scenario as in many cases households are likely to lack sufficient incentives to make changes without policy support, meaning it is presented for reference only.

- We then apply policy packages one and two in the model, as outlined above. The orange dots show the change in costs as a proportion of income under policy package one and the purple dots under policy package two.

- The breakdowns of the cost and cost saving components of the orange and purple dots, and the explanations behind these, are outlined out below for transport (Figure 3.3 and Box 3.1), buildings (Figure 3.4 and Box 3.2), and transport and buildings combined (Figure 3.5 and Box 3.3).

Box 3.1
Impacts across archetypes under each policy package for transport costs

The two policy packages are relatively similar for transport. Impacts in terms of energy costs/savings, maintenance costs/savings, and annualised capex, all of which are similar for each archetype across both policy packages (see Figure 3.3). Differences only arise from different levels of general taxation, whether vehicle excise duty (VED) applies, and the Renewable Transport Fuel Obligation (RTFO).

Under policy package one:

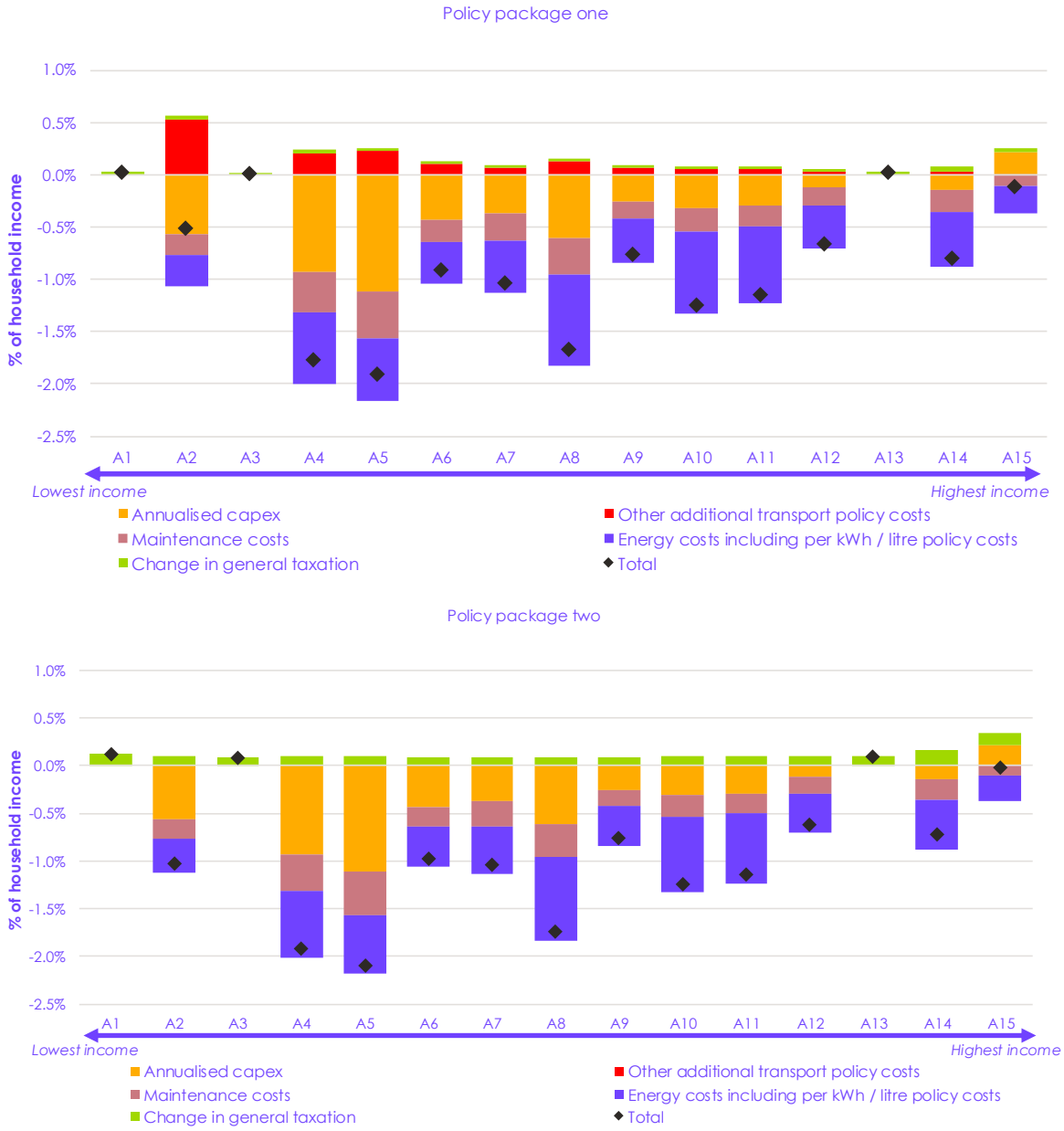
- Archetypes A1, A3, and A13 see relatively small changes in transport costs as they are assumed not to purchase a car during the transition. Additional exchequer investment in public transport, active travel, and EV charging infrastructure is mostly balanced by exchequer receipts from VED on internal combustion engine (ICE) cars, meaning changes in general taxation are minimal.
- Archetype A2 faces greater additional policy costs levied via increased VED rates on ICE cars and RTFO costs than other archetypes because it replaces both its ICE cars with electric cars later on in the transition. It still saves overall on transport costs as it benefits from lower upfront car costs once it does replace its ICE cars with electric cars.
- Archetype A15 also experiences less savings in transport costs compared to other archetypes because it switches to an electric car earlier in the transition, in 2025, when upfront costs are higher than those faced by archetypes switching from 2030 onwards. It also has a lower mileage than most other archetypes, which leads to more limited savings in running costs.
- All other archetypes save between 0.7% and 1.9% of net income per year over the transition period, with variation based on when they purchase an electric car, how many cars they own, the amount they drive, and the proportion of their income that this spending represents. In general, those with higher mileage, or those purchasing more cars after electric cars reach upfront price parity with ICE cars, save the most as a proportion of their income.

Under policy package two, most archetypes face lower energy costs and slightly higher taxation as a proportion of their income, compared to policy package one.

- Archetypes A1, A3, and A13 experience some transport costs as they are assumed not to purchase a car during the transition. Under policy package two, they face higher taxation to fund public investment in EV charging infrastructure, public transport, and active travel, as unlike in policy package one, there are not exchequer tax receipts from increased VED for ICE cars to balance this public spend.
- Archetypes A2, A4, and A5 experience larger savings in transport costs under policy package two as they do not face additional costs of VED or RTFO when switching to electric cars later in the transition, unlike in policy package one.
- All other archetypes face similar costs to policy package one, apart from facing slightly higher costs of general taxation as described above.

All archetypes face slightly higher costs in both policy packages than in the 'before policy' scenario, because both policy packages include some public investment in EV charging infrastructure, public transport, and active travel, funded by higher levels of general taxation.

Figure 3.3 Transport costs and savings by archetype and policy package



Description: The figure illustrates the breakdown of transport costs for each archetype, under policy package one (at the top) and policy package two (at the bottom). Under both policy packages, most household archetypes save over the transition period, apart from households A1, A3, and A13 who do not have cars.
Source: CCC analysis.
Notes: 'Other additional transport policy costs' include costs arising from changes to Vehicle Excise Duty and the Renewable Transport Fuel Obligation. Maintenance costs include car insurance and routine maintenance.

Box 3.2
Impacts across archetypes under each policy package for buildings costs

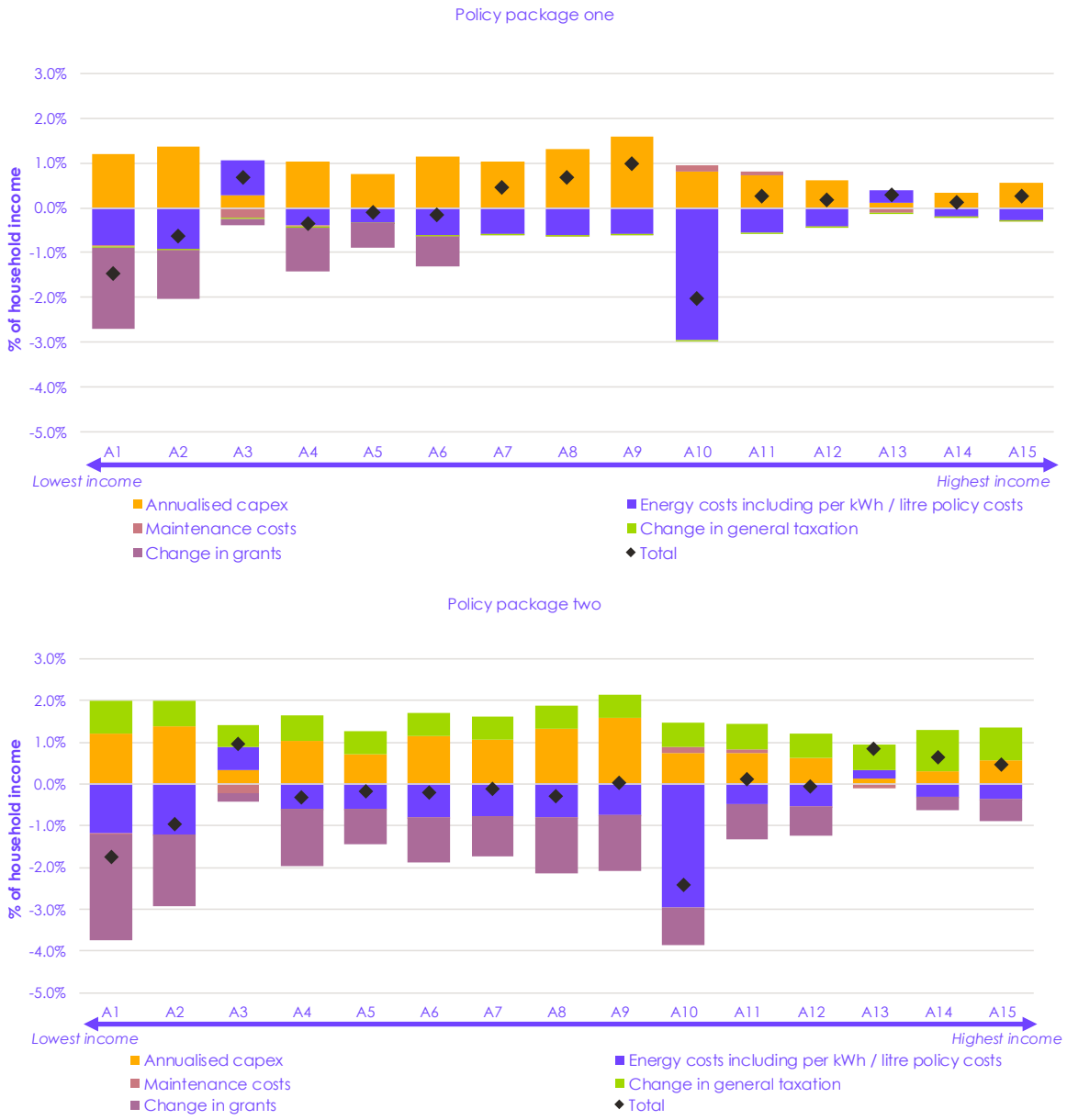
Under policy package one:

- Archetypes A1, A2, A4, A5, and A6 experience savings as they receive upfront grants when switching to air source heat pumps or communal heating, and some savings in energy costs.
- Archetypes A3 and A13 face net costs as they install electric resistive heating, resulting in higher energy costs than other technologies due to lower efficiency (despite lower upfront costs).
- Archetypes A7, A8, A9, A11, A12, A14, and A15 face some costs from switching from gas or oil boilers to heat pumps, particularly due to high upfront costs and not receiving grant support. This is despite some savings in energy costs.
- Archetype A10 sees the largest savings as a component of income compared to the other archetypes as it switches from electric resistive heating (which has lower efficiency and so relatively high energy bills) to a heat pump in 2035.

Under policy package two:

- Archetypes A1, A2, A4, A5, and A6 experience savings as they receive upfront grants when switching to air source heat pumps or communal heating. They pay higher levels of general taxation to fund universal grants compared to policy package one, however they pay less in levies on energy bills. For archetypes A1 and A2, energy bills represent a larger proportion of income than taxation, meaning they save more under policy package two, compared to both policy package one and the 'before policy' scenario.
- Archetypes A3 and A13 face costs for a similar reason to in policy package one. However, they face higher costs than in policy package one and in the 'before policy' scenario because they pay higher levels of general taxation, without significant savings from grants as electric resistive heating costs are dominated by energy costs rather than upfront costs.
- Archetypes A7, A8, A9, A10, A11, and A12 face lower costs, and even net savings in the case of A7, A8, A10, and A12. This is because the savings from receiving upfront grants and lower energy bill levies outweigh the additional general taxation required to fund these policies.
- Archetypes A13, A14, and A15 face higher costs than in policy package one as they pay a larger proportion of the increase in general taxation due to their higher incomes, and this outweighs any savings from reduced energy bill levies and upfront grants.

Figure 3.4 Buildings costs and savings by archetype and policy package



Description: The figure illustrates the breakdown of buildings costs for each archetype, under policy package one (at the top) and policy package two (at the bottom). About half of the 15 archetypes see net savings as a result of the transition, with the exact number varying by policy package.
Source: CCC analysis.

Box 3.3
Impacts across archetypes under each policy package for overall costs

Under policy package one, most archetypes experience savings. Total impacts range from costs of 0.7% to savings of 3.3% of household income.

- For all archetypes except A3, A9, A13, and A15, combined buildings and transport changes lead to net savings overall.
- For low-income households, this is because upfront grants for home heating and savings in transport costs generally outweigh any other cost increases, apart from archetype A3 (who does not have a car).
- For middle- and higher-income households, this is because transport cost savings generally outweigh buildings costs and increased levels of general taxation, apart from archetypes A9, A13, and A15.

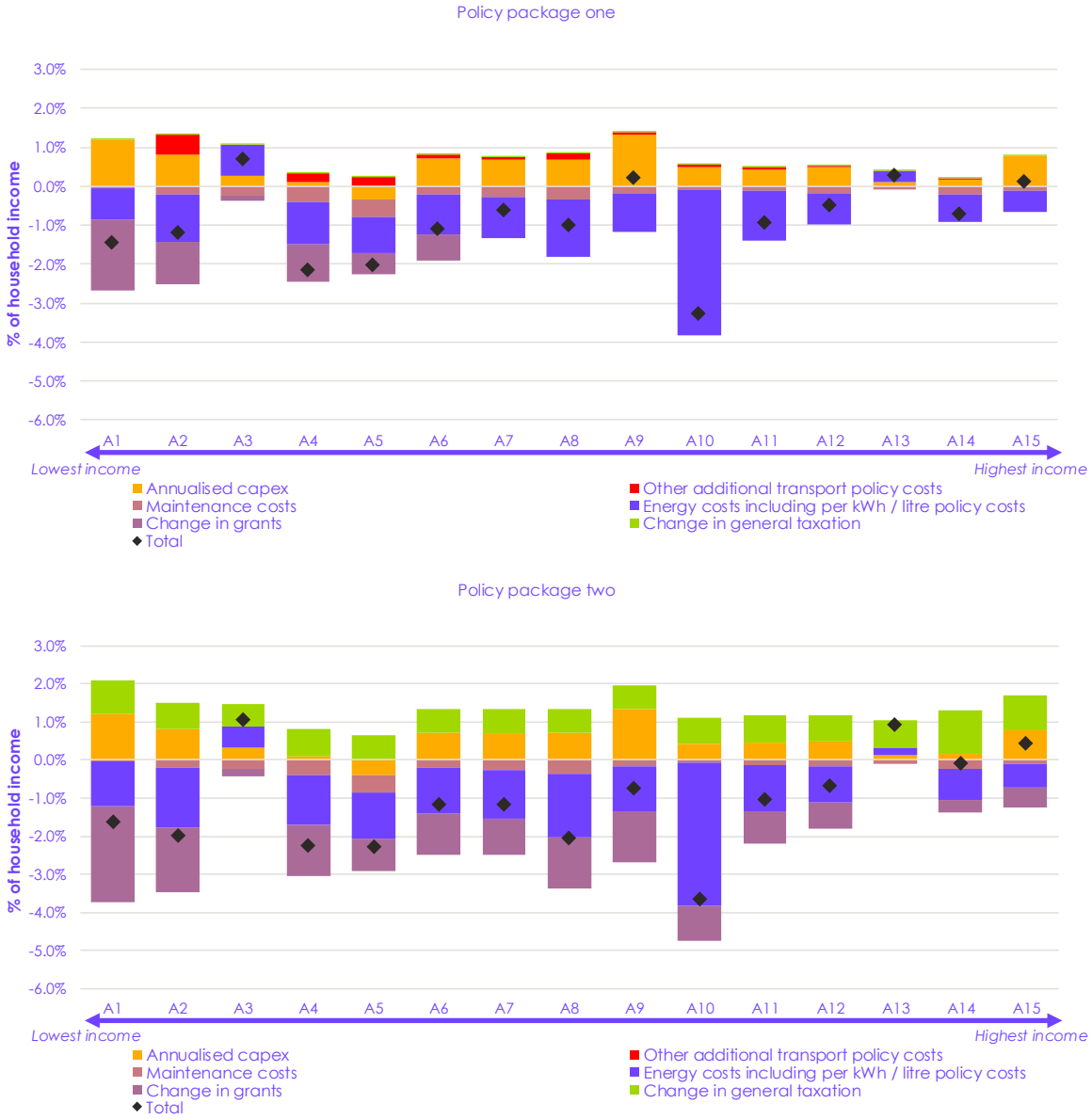
Under policy package two, most archetypes experience savings. Total impacts range from costs of 1.1% to savings of 3.6% of household income.

- For all archetypes except A3, A13, and A15, combined buildings and transport changes lead to net savings overall.
- For low- and middle-income households, this is because upfront grants for home heating and savings in transport costs generally outweigh other cost increases, apart from archetype A3.
- For higher-income households, this is because transport cost savings generally outweigh buildings costs and increased levels of general taxation, apart from archetypes A13 and A15.

There are some key characteristics that lead to households facing net costs overall.

- Across both policy packages, households who both have no car and cannot install a heat pump or access a heat network, and therefore install direct electric resistive heating (A3 and A13), tend to face net costs. These characteristics tend to appear in similar household types (for instance, households living in flats).
- Archetype A1 makes net savings overall in both policy packages despite not having a car, as it receives a grant for home heating and faces relatively low levels of taxation due to its lower income.
- Conversely, archetype A15 experiences net costs in both policy packages as it is in the highest income decile, meaning it faces a higher proportion of costs that are funded through general taxation. A15 also purchases electric cars early, before they reach upfront price parity with ICE cars, meaning savings on transport are lower than for other archetypes.
- Archetype A9 faces net costs in policy package one as it does not receive a grant but still faces higher upfront costs from installing energy efficiency measures and a heat pump, as well as facing increased levels of general taxation to fund grants for low-income households and smaller savings on transport costs due to their low mileage.

Figure 3.5 Total (buildings and transport) costs and savings by archetype and policy package



Description: The figure illustrates the breakdown of overall costs for each archetype, under policy package one (at the top) and policy package two (at the bottom). Most household archetypes save across both policy packages, with some exceptions for households without cars and/or installing direct electric resistive heating (A3 and A13), the highest-income household archetypes (A15), and in policy package one only, households with high upfront costs who do not receive grants (A9).
Source: CCC analysis.
Notes: 'Other additional transport policy costs' include costs arising from changes to Vehicle Excise Duty and the Renewable Transport Fuel Obligation. Maintenance costs include car insurance and routine maintenance.

Citizens' panel

As described in Section 3.2, we convened a citizens' panel to inform our advice around household low-carbon choices in the Seventh Carbon Budget, with a focus on understanding what is needed from government to make household low-carbon choices accessible and affordable for all households.

We tested our two policy packages with our citizens' panel to explore which combination of policies were considered accessible and affordable. During panel discussions, participants deliberated whether they supported elements of one of the policy packages over the other, discussed changes they wanted to see made to policies, raised policies they wanted to add, and deliberated more widely principles that would make the transition in home heating and transport accessible and affordable for all households.

In some cases, our policy packages were updated to include considerations from the citizens' panel. For example, participants suggested that they were unlikely to invest in low-carbon technologies that had higher upfront costs, even if they paid themselves back in lower running costs over their lifetime – participants suggested that they needed an additional incentive, or shorter payback period, to be encouraged to invest. As such, our policy packages ensure households receive a £2,000 saving when installing a heat pump instead of a gas boiler, over the technology lifetime.

In addition, we constructed a 'citizens' policy package' based on principles and policy preferences that emerged during deliberations. Our modelled citizens' policy package took the policy package participants landed on during discussions as a starting point and utilised more general principles from panel discussions as a guide to adjust model parameters that were not discussed by participants explicitly.

Figure 3.6 shows the policy package that the citizens landed on during discussions and Table 3.8 outlines how this package and wider discussions have been used to establish model parameters for our modelled citizens' policy package. The citizens' policy package included the following elements, with comparisons made to the final policy packages one and two published in our Seventh Carbon Budget advice report:

- Means-tested tapered grants for home heating and energy efficiency available to almost all households, with low-income households receiving the largest grants and high-income households the smallest. In policy package one, these grants are targeted at low-income households while in policy package two, these are universally applied.

- Smaller targeted grants for electric cars, with zero-interest loans and scrappage schemes. In policy packages one and two, grants for electric cars are not included.

- Rebalancing of electricity and gas costs funded through general taxation, with some costs on gas once low-carbon heating systems are affordable. In policy package one, costs are shifted to gas bills until 2040 and general taxation after this. Taxes are additionally levied on heating gas and oil until the combined impact of rebalancing and taxes reaches the price of carbon. In policy package two, they are shifted partially to gas bills (so that the average dual fuel bill reaches price parity with the counterfactual), and partially to general taxation until 2040, and entirely to general taxation after this.

- Phase-out dates and energy efficiency standards for new and private rented properties, but with some form of protections for renters and low-income households. In policy packages one and two, phase-out is included, but phase-out dates alone do not directly impact household costs and savings.

We modelled the distributional impacts of this citizens' policy package, in line with the distributional analysis above. The impacts of this package are shown in Figure 3.7. These graphs do not perfectly

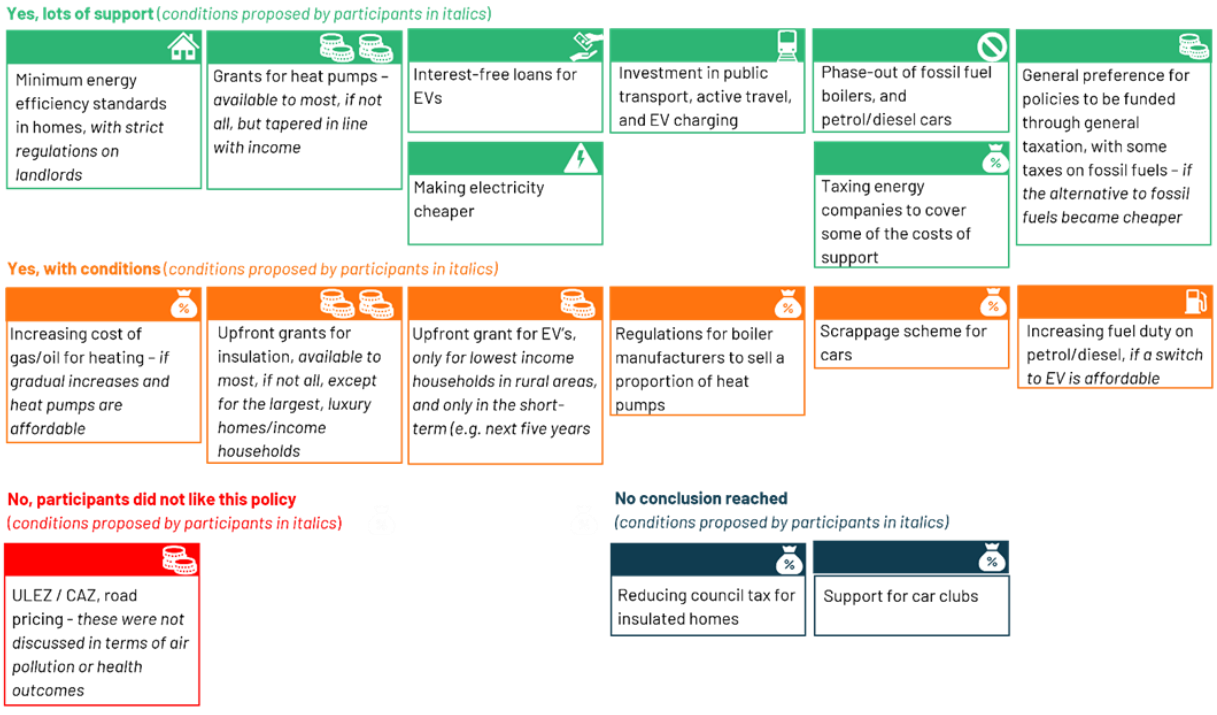
capture the impacts of this policy package, as there are some components such as tapered grants and energy company contributions that are too complex to model precisely.

- The impact on buildings costs for archetypes under the citizens' policy package is similar to that of policy package two overall. Generally, archetypes A7-A9 face greater savings than in policy package one, as unlike in policy package one they receive a grant. Conversely, archetypes A1, A2, A5, and A10-A15 save less than in policy package two. For archetypes A1, A2, and A5, this is because in the citizens' policy package, lower grant levels compared to policy package two are not fully offset by greater savings in energy costs compared to policy package two. For archetypes A10-A15, this is because in the citizens' policy package, unlike in policy package two, there are no grants.

- With respect to transport costs, the impact on archetypes under the citizens' policy package is close to that of policy packages one and two, although archetypes A4-A12 experience larger savings in the citizens' policy package due to the provision of zero-interest loans, in particular archetypes A4 and A5 as they also receive small upfront EV grants. Under the citizens' policy package, archetype A2 experiences savings between the levels it experiences in policy packages one and two, as it faces greater VED costs than in policy package two but less than in policy package one, which are more pronounced as it switches to EVs later than other archetypes.

- With respect to the change in overall costs, under the citizens' policy package, middle-income household archetypes experience more savings than under policy packages one and two, due to the broader provision of upfront grants for home heating and zero-interest loans for EVs. Low- and high-income households face a mixture of differences, as they generally experience higher levels of taxation to fund grants for low- and middle-income households but also receive zero-interest loans for EVs.

Figure 3.6 Citizens' level of support for CCC policy package elements



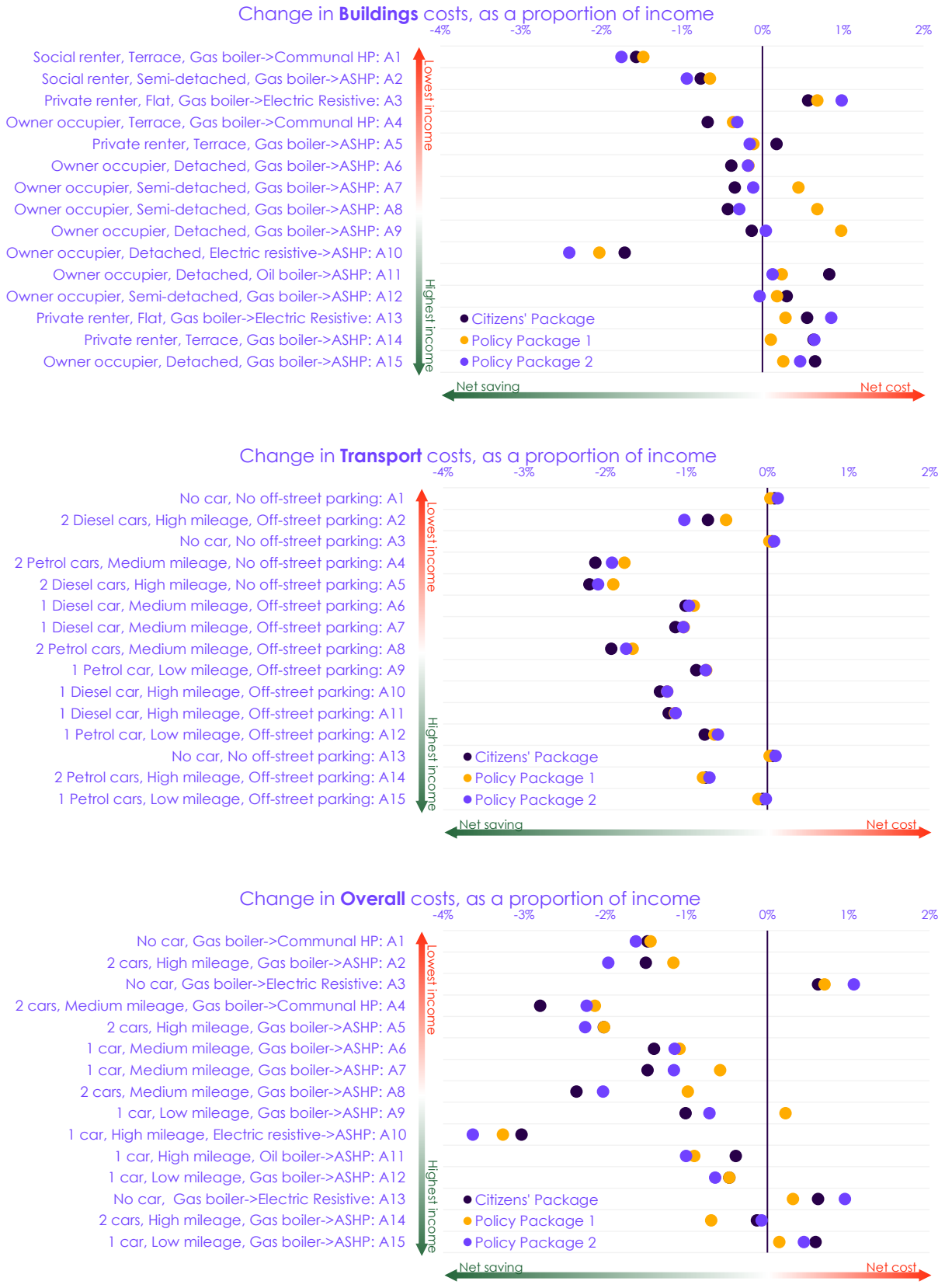
Description: There was a lot of support from the citizens' panel for grants for heat pumps, making electricity cheaper, and minimum energy efficiency standards, among other things. The panel was supportive of increasing the cost of gas/oil for heating only if increases are gradual and heat pumps are affordable. The panel was not supportive of ultra-low emission zones, although these were only discussed in terms of their impacts on emissions.
Source: CCC (2025) *Citizens' Panel Report*

Table 3.4
Policies included in the modelled 'citizens' policy package'

Policy	Citizens' policy package	Reasoning	Modelling approach
Grants for heat pumps, communal heating, and insulation	Targeted grant	Participants thought everyone should be supported financially with upfront costs of low-carbon heating, but support should be tapered. The tapering should generally be in line with income, though participants recognised differences between building and insulation type.	In the model, grants for heat pumps are assumed to be targeted at low- and middle-income households (A1-A9) and the cost is borne by increases in general taxation. All households are provided with zero-interest loans (modelled by removing the cost of capital).
Grants for EVs	Small targeted grant and interest-free loans	Given the expectation that soon an EV would cost the same as a petrol/diesel car, participants felt these was needed only for the lowest-income households in rural areas who really needed it, and only in the short term. Many suggested zero-interest loans as an alternative, to help those who otherwise would not buy a car to benefit.	In the model, small grants (£500-£800) for EVs are assumed to be targeted at low-income households (A1-A5) and the cost is borne by increases in general taxation. All households are provided with zero-interest loans.
Obligations on boiler manufacturers	Yes	Participants generally liked obligations and taxes on companies.	In the model, obligations on boiler manufacturers are applied without targeting, phasing out by 2035.
Taxes on heating gas/ oil	Yes (but only as a transitional process)	Participants were generally less accepting of increased taxes on gas as they said this would disproportionately impact lower-income households who couldn't afford to switch to electricity straight away. But they were open to a transitional process where taxes on gas were raised gradually over time, electricity was made more affordable, and households were supported to switch to electrified low-carbon heating.	In the model, taxes on heating gas and oil are gradually raised over time, such that the combined impact of policy cost rebalancing and taxes on heating gas/oil leads to the price of carbon of gas/oil being added to bills by 2050.
Renewable Transport Fuel Obligation	No	Not discussed.	In the model, the RTFO is not applied as it was not specifically discussed with the panel.
Increased VED on petrol/ diesel cars	Yes (but only if EVs are affordable)	Participants understood the importance of increasing the running costs of petrol/diesel cars to encourage change. But they thought it would disproportionately affect lower-income households or those who had to drive for work in lieu of good public transport, and they wanted to see this happen only when EVs are affordable to households or good public transport is made more widely available.	In the model, increased VED on petrol and diesel cars is applied after 2030, once electric cars have reached price parity with petrol cars in terms of upfront costs.
Rebalancing electricity/ gas prices	Yes (but any changes to gas bills should be phased in over time)	Participants felt reducing the price of electricity was a necessary step for incentives to switch to low-carbon heating to function. They were conscious of the impact on lower-income households of an immediate and sharp rebalancing, so said there should be a transitional period and it would require that the switch to low-carbon heating is made affordable. In the end, participants leaned more towards a	In the model, legacy policy costs (Renewable Obligations, Feed-in Tariffs, Energy Company Obligations, Warm Homes Discount, and early Contracts for Difference (FIDER and Allocation Rounds 1-2)) are removed from electricity bills. These are initially moved onto general taxation, with an increasing portion shifted

		combination of rebalancing policy costs onto gas and general taxation.	onto gas bills over time until legacy policy costs are rebalanced onto gas bills by 2045. Beyond 2045, these are shifted back to general taxation to avoid exponential increases in policy costs per household as the number of gas users declines.
Investment in public transport, active travel, and EV charging infrastructure	Yes	Participants supported investment in public transport and charging infrastructure. There was not much discussion on how this should be funded, but participants generally were more supportive of funding through general taxation. Windfall taxes on energy companies were suggested throughout.	In the model, investment in the decarbonisation of public transport, in cycling and walking infrastructure, and in EV charging infrastructure is applied and assumed to be funded by increases in general taxation.
Phase out of new fossil fuel boilers and petrol/diesel cars	Yes	Participants supported a phase-out date, provided that support with upfront costs was available for households. They thought a phase-out date would enable government, business, and households to prepare for the change. Participants supported phasing out petrol/diesel cars. For many this was an essential pre-requisite to encourage the necessary change.	In the model, fossil fuel boilers and petrol and diesel cars are phased out in line with the Balanced Pathway.
Home energy efficiency standards	Yes (but with landlord regulation)	Participants wanted to see improvements to the energy efficiency of rental properties, but were concerned about the cost being passed through to renters.	In the model, energy efficiency is installed in line with the Balanced Pathway.

Figure 3.7 Citizens' policy package distributional impacts



Description: The three graphs show the impacts on buildings, transport, and combined costs as a proportion of income for household archetypes under policy package one, policy package two, and the citizens' policy package.
Source: CCC analysis.
Notes: In the transport costs chart, the citizens' policy package dot is not visible for archetypes A1, A3, A13, A14, and A15. This is because these archetypes face total costs that are the same as under policy package two. In the overall costs charts, the citizens' policy package dot is not visible for archetypes A5 and A12, which experience the same total savings as in policy package one.

Food and drink costs

In the Seventh Carbon Budget advice report, we state that costs of food and drink are expected to change by less than 5% as a result of Net Zero. This is based on modelling of the impact of reducing meat and dairy consumption on household food spending. This analysis is less detailed than our buildings and transport distributional modelling, but is intended to indicate the likely scale and direction of changes to food costs due to our Balanced Pathway.

- We take historical food prices from the Family Food Survey, which documents food consumption and expenditure by category over time.[34]
- Meat and dairy expenditure made up 19% of the average weekly UK per-capita food and drink shop in 2019/20 (including both in home and out of home consumption).[35]
- We assume that households reduce average meat and dairy consumption in line with the Balanced Pathway, which includes a 35% reduction in average meat consumption and a 20% reduction in average dairy consumption by 2050. We assume that, on average households increase consumption of legumes, plant-based meats, alternative proteins (precision fermentation and cultivated meat products), and dairy alternatives such that total protein consumption remains constant.
- We assume that households initially switch to legumes and existing plant-based meat products, until prices for alternative proteins fall. We model alternative meat prices starting at current commercial rates, and falling over time until they reach parity with current plant-based meat prices, undercutting meat products. The rate of price reduction has been modelled in line with historical price reductions in other foods whose price has fallen over time due to technology developments, such as extruded goods (for example, dry pasta).[36]
- We assume that all other food prices remain constant, in real terms. This is an assumption used in our modelling and is not a prediction of future food prices. We have also not modelled food price changes due to climate-related events such as droughts or extreme weather, and have not modelled potential price-based interventions.
- If we use the same assumptions above about changes in product prices and average shifts in consumption, and apply these to the existing consumption and spend on food by different groups (including income quintile, age, employment status, rurality, ethnicity, and region), we find impacts of a similar scale. However, we have not done an in-depth review of differences in changes in prices for products that are typically bought by different groups.

Flying costs

Box 11.3 in Chapter 11 on aviation sets out our analysis of impacts on ticket prices and the distribution of flying across groups, based on characteristics such as income.

3.4 Wider costs and benefits

3.4.1 Co-impacts

Beyond direct financial costs and savings, we have also assessed a number of co-impacts of the transition for households and the economy, which are summarised in Section 8.4 of our Seventh Carbon Budget advice report. We have modelled these quantitatively where possible and discussed impacts qualitatively where benefits are harder to quantify.

Co-impacts model

We assess a number of health and other non-financial impacts with our Net Zero Co-impacts Model. The model was developed for the CCC by PricewaterhouseCoopers (PwC), whose more detailed summary of the model is on our website. The model converts levels of uptake and use of low-carbon technologies and behaviours in the Balanced Pathway into impacts for households and wider society.

- We assess impacts from outdoor air quality, excess cold and dampness in homes, congestion, noise pollution, time costs related to modal shift, road safety, road repairs, physical activity, and diet, as shown in Figure 3.8 below.

- The model takes low-carbon actions from the Balanced Pathway such as changes in technology uptake, demand, and household consumption, and converts these into impacts (health, social, economic, or environmental impacts) for households. For example, a reduction in petrol car mileage due to a switch to electric cars leads to a reduction in petrol combustion, which improves air quality and provides a health benefit to households.

- The model then converts these impacts into monetary values. Where possible, this is done using HM Treasury Green Book valuation methods, and elsewhere this is supplemented by published academic evidence.[37] For example, the model uses UK air quality damage costs (developed by Ricardo for Defra) to value the monetary impact per unit of pollutant emitted.[38]

- For more information, see The distribution of climate action co-benefits, which sets out the full methodology.

- The model's scope is not comprehensive - it does not include all co-impacts, and is focussed on those that are most material, reliable to quantify, and supported by evidence. There were a number of other co-impacts that we did not quantify. In some cases. this was due to a lack of sufficient evidence (for example, indoor air quality), whereas for others this was due to lack of robust methodology for quantifying co-impacts in monetary terms (for example, increased connectivity, or wellbeing effects of access to green space).

In our Seventh Carbon Budget advice report, we only present the findings of the model in terms of economy-wide benefits and costs, as we assessed this as the most robust estimate. Figure 8.6 in the Seventh Carbon Budget advice report shows the total quantified co-impacts across the economy in the Balanced Pathway, with and without a rebound effect as a result of the transition to EVs.

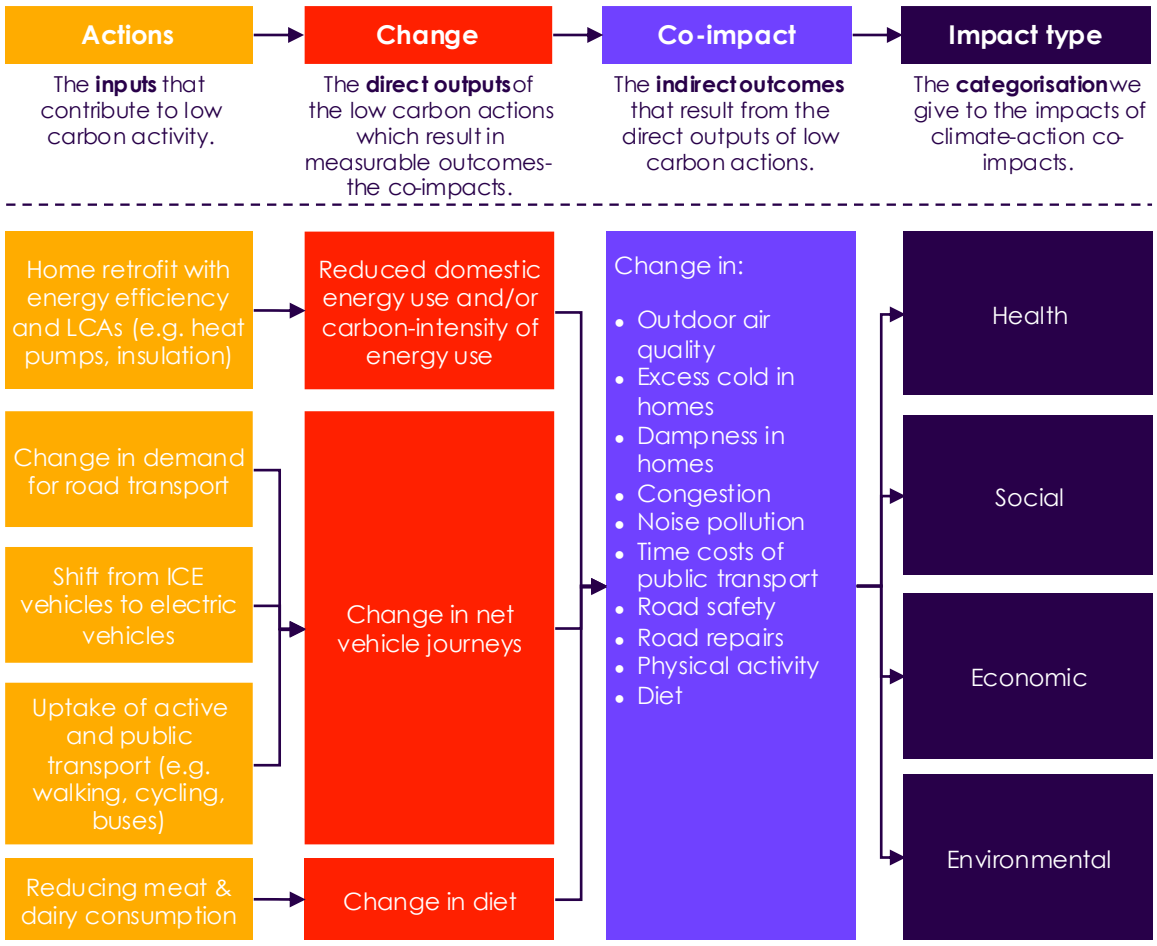
- The rebound effect refers to the potential for car mileage to increase as households and businesses respond to cheaper driving costs when switching to EVs. In our surface transport modelling (and therefore the pathways used in our distributional model), we assume this rebound effect occurs, but it is uncertain and will depend on government policy decisions (see Chapter 6).

- The figure shows the level of co-impacts experienced with and without the level of rebound modelled in the Balanced Pathway. The main co-impacts associated with an increased rebound effect are changes to congestion levels, road safety, and noise, with smaller impacts on road repairs and air quality (due to residual brake and tyre pollution from EVs).

- In terms of home heating, we assume in both our co-impacts model and our residential buildings sector pathway (and therefore in our distributional model) that people don't heat their homes more in general when energy bills fall. However, we do assume that households with heat pumps increase heat output energy demand by 15% compared to a gas boiler, due to load profiles of heat pumps compared to gas boilers, leading to a small health benefit (see Chapter 7).

Further co-impacts relating to land use, agriculture, and nature were quantified in a separate Land Use Archetypes project, published alongside this methodology report.[39]

Figure 3.8 Simplified pathways for co-impacts analysis



Description: The co-impacts model takes low-carbon actions, such as a shift from ICE vehicles to EVs as inputs. It then calculates the direct outputs of these actions, such as a change in net petrol/diesel vehicle journeys. It then estimates the co-impact that results from this, such as an improvement in outdoor air quality. These impacts are grouped into impact types, such as health or economic impacts.
Source: PwC (2025) *Co-impacts model*.

3.5 Impacts on protected and vulnerable groups

3.5.1 Fuel poverty

In Box 7.2.3 of our Seventh Carbon Budget advice report, we discuss impacts of our pathway on fuel poverty in the UK. This is in line with requirements laid out in the Climate Change Act to take into account 'the likely impact…on fuel poverty'.[40]

Definitions of fuel poverty vary across the UK, by nation:

- In England, households are considered in fuel poverty if they are living in a property with a fuel poverty energy efficiency rating of band D or below, and when they spend the required amount to heat their home, they are left with a residual income below the official poverty line.[41]

- In Scotland, households are considered in fuel poverty if:
  - More than 10% of the household's adjusted net income after housing costs would be needed to pay for reasonable fuel needs.
  - After deducting fuel costs, benefits received for a disability or care need, and childcare costs, their remaining adjusted net income is insufficient to maintain an acceptable standard of living, defined as being at least 90% of the UK Minimum Income Standard (MIS).[42]
- In Wales, households are considered in fuel poverty if they would have to spend more than 10% of their income on maintaining a satisfactory heating regime.[43]
- In Northern Ireland, households are considered in fuel poverty if in order to maintain a satisfactory level of heating (21°C in the main living room and 18°C in other occupied rooms), they are required to spend over 10% of household income on fuel use.[44]

We calculate fuel poverty impacts using our residential buildings sector archetypes. As outlined in Chapter 7, these archetypes include almost 12,000 archetypes representing the UK housing stock, with characteristics such as property size, type (for instance, semi-detached or terraced), energy demand, energy efficiency characteristics (for example, EPC rating), and fuel poverty status.

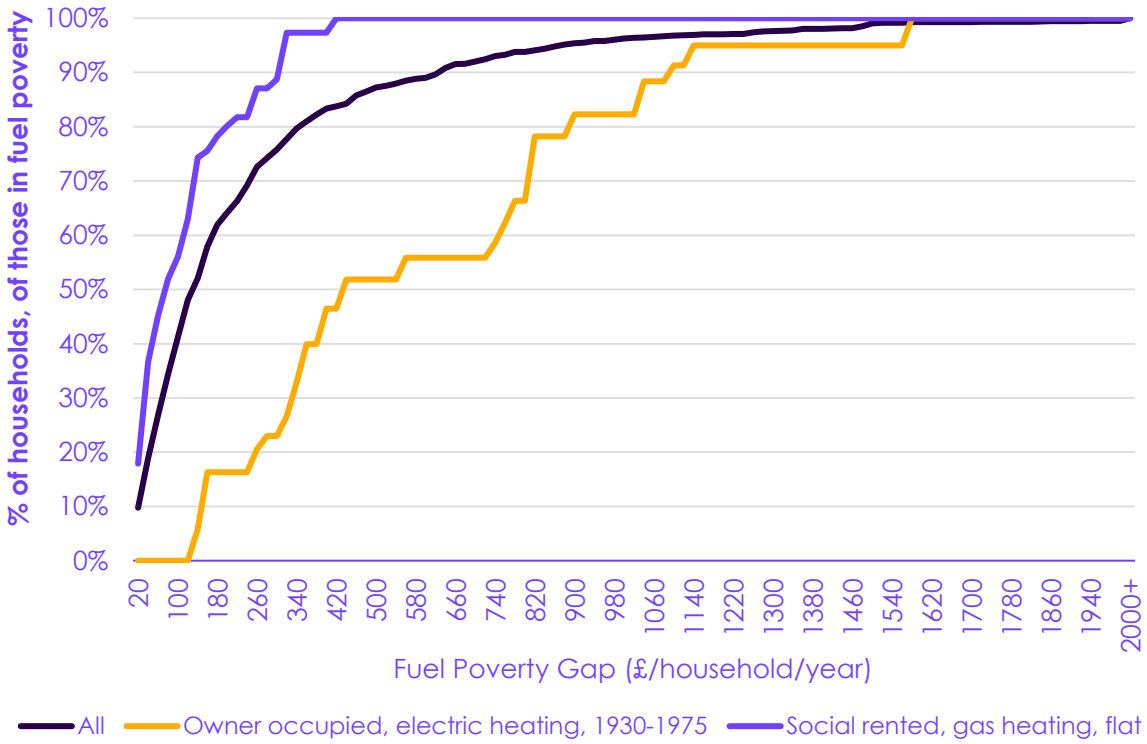
Based on the definitions above, for a household to no longer be in fuel poverty, they must either overcome a 'fuel poverty gap' (by increasing income or by spending on energy decreasing), or in England they can also move out of fuel poverty by increasing the EPC rating of their property.

Modelling impacts on fuel poverty: fuel poverty gap approach

We model fuel poverty gaps based on published data from the English Housing Survey (EHS).[45]

- We map the key characteristics in this dataset to characteristics in our residential buildings archetypes in order to calculate a fuel poverty gap distribution for each archetype in our CCC buildings dataset (Figure 3.9).
- Fuel poverty gap data inputs include households in England only, as equivalent data are not available for Scotland, Wales, and Northern Ireland. To address this, archetypes in the EHS data are mapped to equivalent archetypes in the CCC buildings data, to produce a distribution of archetypes reflective of the different household compositions in each nation.
- Using Balanced Pathway data on energy demand and internal retail price modelling (see Section 3.3.3), we calculate the total annual energy bills for each CCC buildings archetype and how they vary between 2025 and 2050 in the baseline and Balanced Pathway.
- Using this data, we calculate the annual change in energy bills for each CCC buildings archetype, and the proportion of households within each archetype grouping that this bill saving takes out of fuel poverty (by reducing energy bills) each year, as well as any that are brought into fuel poverty.
- As we have the starting number of households in fuel poverty across the UK, we can therefore calculate the total number of households taken out of fuel poverty by our pathway, based on reducing energy bills.
- This analysis assumes no changes in real income over time. In practice, increases in real income over time, in line with other CCC modelling, may reduce the number of households in fuel poverty.

Figure 3.9 Fuel poverty gap distribution by house type



Description: The figure shows the proportion of households in fuel poverty, by size of fuel poverty gap (the amount of money a household would need to no longer be classed as fuel poor). Lines represent different household groupings – '1930-1975' represents the property age band, and 'electric heating' here refers to direct electric resistive heating.
Source: CCC analysis of EHS data.

Modelling impacts on fuel poverty: EPC approach

In England, households are also no longer considered in fuel poverty if their Energy Performance Certificate (EPC) rating improves to a grade C or higher.[46] EPC ratings are based on Standard Assessment Procedure (SAP) scores, with an EPC rating of C defined as a SAP score of 69-80.[47]

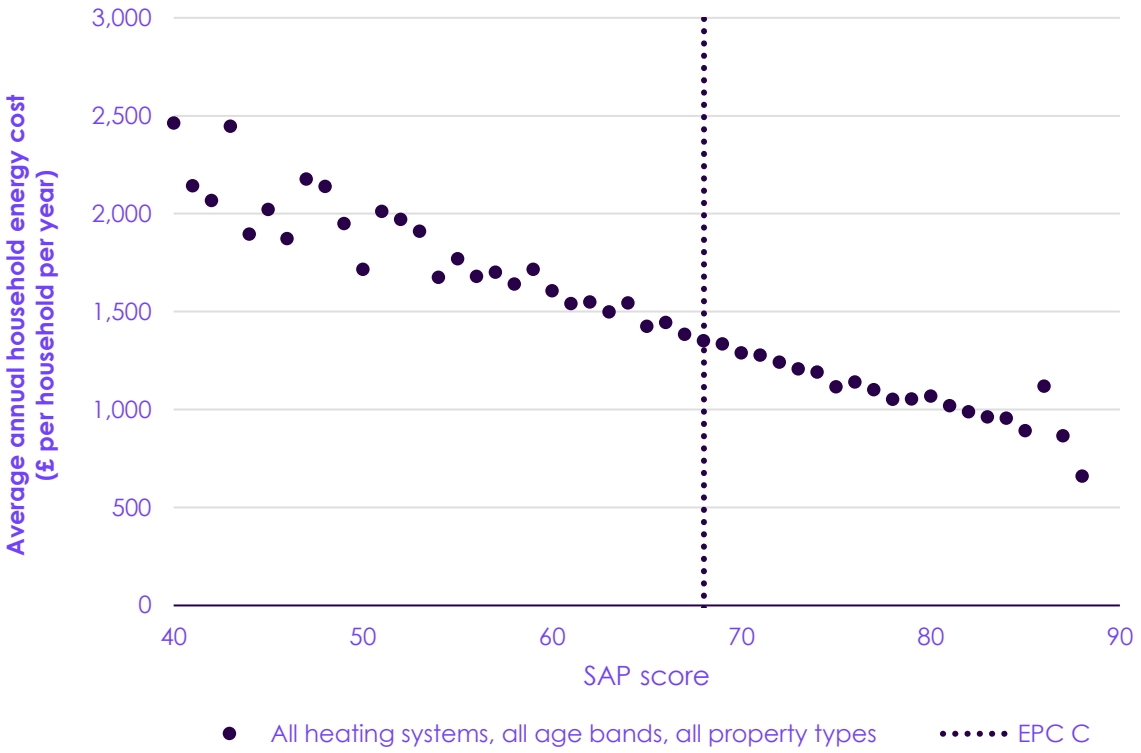
Based on the same published data on archetypes and fuel poverty gaps, we plot the correlation between SAP score and overall energy spend, shown in Figure 3.10.

Using EHS buildings archetype data, we estimate an initial SAP score (and therefore EPC rating) for each CCC buildings archetype, and how this varies with modelled energy consumption. We then use Balanced Pathway data for energy consumption to estimate the change in SAP score, and therefore change in EPC rating, for each CCC buildings archetype over time.

Based on these EPC ratings, we then calculate the number of fuel poor CCC buildings archetypes, and households associated with each archetype, whose EPC rating improves to a grade C or higher between 2025 and 2050.

It should be noted that energy consumption in the original EHS dataset is based on modelled energy consumption, which is likely to overestimate energy consumption in fuel poor households, as these households often respond to cost pressure by reducing energy demand below modelled levels. This is consistent across both EHS and CCC datasets, meaning that absolute numbers of fuel poor households are difficult to estimate, but relative changes can be more accurately assessed.

Figure 3.10 Average energy consumption by SAP score



Description: The figure shows average household energy cost as a function of SAP score, across all households in the English Housing Survey (EHS) dataset, with each dot representing the average household energy cost for each SAP score, averaged across all archetypes with that SAP score.
Source: CCC analysis of EHS data.
Notes: Energy costs are modelled costs. The dotted line shows the minimum SAP score required to achieve an EPC grade C or above. This data is available by heating system type, property size, property age, and property type, and the relationship between household energy cost and SAP score has been modelled for each category based on this data.

Combining the two approaches

By combining these two methods, we can calculate the number of households brought in and out of poverty by changes to bills in our Balanced Pathway. We carry out this method for the UK as a whole, and for Scotland, Wales, and Northern Ireland,

In Scotland, Wales, and Northern Ireland, only the fuel poverty gap approach is used as only England includes an assessment of EPC rating in its definition of fuel poverty.

In England, CCC buildings archetypes are assessed in terms of both the fuel poverty gap approach and the EPC approach. For each archetype in the CCC buildings archetype dataset, if households in the archetype are brought out of fuel poverty through the EPC approach, the archetype is not assessed under the fuel poverty gap approach to avoid double counting.

3.5.2 Groups with protected characteristics

In Section 8.5 of our Seventh Carbon Budget advice report and in our supplementary research, we set out our assessment of the potential impacts of the Balanced Pathway on groups with protected characteristics.[48]

The Public Sector Equality Duty

The Public Sector Equality Duty (PSED) integrates consideration of equality and good relations into the day-to-day business of public authorities.[49] With respect to protected characteristics, this means the CCC must pay due regard to:

- Eliminating unlawful discrimination, harassment, victimisation, and other conduct prohibited by the Act.
- Advancing equality of opportunity between people who share a protected characteristic and those who do not.
- Fostering good relations between people who share a protected characteristic and those who do not.

Approach to identifying risks and opportunities

In line with requirements laid out in PSED, we have assessed the impacts of the Balanced Pathway for groups with protected characteristics. We initially undertook a screening process to identify priority areas for research, including a mapping exercise to identify potential risks and opportunities for groups with protected characteristics across all key analytical areas and sectors. Key areas identified are presented in Table 3.5 below. These potential impacts were discussed with stakeholders and prioritised based on a number of selection criteria:

- Is the impact directly due to CCC pathways (higher priority) or due to Government policy choice or design (lower priority)?
- How significant is the impact (in terms of number of people affected and severity of impact)?
- Is it the secondary effect of an underlying factor (for example, is it part of a wider issue)?
- Could the impact require action in the short term (are there any time-sensitive interventions required)?

Based on this, we focussed a more detailed review of the literature and data analysis on four priority areas: home decarbonisation, surface transport, diversity in the workforce, and air quality.

Table 3.5
Key topics identified by CCC PSED process

Impact	Category	Description of effect	CCC approach
Building type impacts	Direct pathway impacts	Some groups disproportionately live in different building types (for example, ethnic minorities renting, older people in rural areas) and will face different impacts/access to measures.	We conducted a further review of literature, which is summarised in the supplementary research briefing.
Impacts of changes to driving	Choice availability	Some groups (for example, people with disabilities or dependents) have greater reliance on petrol/diesel cars, and may find it more difficult to switch to electric cars or public/active transport.	We conducted a further review of literature, which is summarised in the supplementary research briefing.
Changes to diets	Cost impacts	Some groups have restricted diets (for example, due to religion or disability) or spend a larger proportion of their income on food.	Different diets and incomes were assessed as part of our food price analysis.
Changes to costs	Cost impacts	Some groups tend to be on lower incomes, so are more impacted by changes to costs such as for heating bills, transport, or flying.	The analysis of impact based on incomes is captured in our distributional impacts work.
Employment impacts	Direct pathway impacts	Changes to employment in certain sectors will affect some groups differently (for example, some Net Zero growth sectors have limited ethnic/gender diversity).	This had been assessed in our Net Zero Workforce Report. We summarised findings from this, supplemented with a rapid literature review.
Air quality impacts	Direct pathway impacts	Certain groups with protected characteristics disproportionately live in areas affected by air pollution.	We conducted a further review of literature, which is summarised in the supplementary research briefing.
Grappling challenges	Choice availability	Some older people and those with disabilities may struggle to grapple with a number of changes, especially digital/technological changes.	We conducted a further review of literature, which is summarised in the supplementary research briefing.
High consumption	Cost impacts	Some groups consume more utilities (for example, people with disabilities tend to consume more energy) or services.	Variable consumption levels are modelled in our distributional analysis, although these are not assigned to specific protected groups or characteristics.
Accessibility of technology	Access	People with disabilities may be left out of EV markets if technology is not accessible. EV chargers could also block pavements.	We conducted a further review of literature, which is summarised in the supplementary research briefing.
Access to nature	Access	Changes to land use could make nature more accessible for groups who may currently have limited access (for example, ethnic minorities).	This was noted but we did not conduct a further review.

Calculations in the supporting research briefing on PSED

In our supplementary research briefing on impacts on groups with protected characteristics, Figure 1 shows the proportion of income spent on energy in the UK by characteristic. This was calculated using the following approach:

- For income, disability, age, tenure, and number of dependents, we use the ONS 2023 Living Costs and Food Survey for the financial year ending 2022.[50] We obtain the proportion of disposable income spent on energy by dividing the sum of mean household gas and electricity expenditure by the mean disposable income.

- For ethnicity, we use the ONS average household disposable income and energy expenditure dataset for the financial years ending 2019, 2020, and 2021 combined.[51] These are the most recently available datasets. As they are in a different year, we present these on a different graph.

- Energy prices have risen faster than incomes since this period, meaning this data likely underestimates both the proportion of income spent and the difference in proportion spent by different groups.

The annual distance travelled in England by characteristic (Figure 2 in the supplementary research briefing) was calculated using the following approach:

- For UK average mileage, income, disability, and number of dependents, we use the 2024 National Travel Survey data, which presents distance travelled in 2023 in miles.[52]

- For ethnicity, we use the 2019 National Travel Survey travel data, which presents the five-year average between 2015 and 2019 of distance travelled in miles by ethnic group. [53]

- We expect there to be less variation by year in travel (as compared to energy spend), and so we show data on ethnicity on the same graph as data on other characteristics, adjusted to 2023 levels in order to ensure that distance travelled by all groups is comparable. This adjustment has been calculated by multiplying the distance travelled by each ethnicity group, by mode, by the ratio between the average distance travelled in 2023 and in the original 2015-2019 dataset.

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Chapter 4: Economy, businesses, and workers

Introduction

This chapter covers methodology relating to Chapter 9 in the Seventh Carbon Budget advice report on what the Seventh Carbon Budget means for the economy and businesses. Our analysis is informed by a review of published literature and macro-economic models, and analysis of data on emissions, economic, and trade contributions of sectors, businesses, and products. Our findings were tested in discussions with economic experts.

- Our analysis of impacts on workers is largely based on our Net Zero Workforce Report, which includes details of the methodology, so this chapter focusses only on our methodology for economy and businesses.

4.1 The economy and businesses

4.1.1 Macroeconomic impacts

To assess the impact of Net Zero on the UK macroeconomy, we conducted an analysis of key factors affecting the UK economy more generally, drawing on a body of external literature and testing our hypotheses with experts.[1;2;3;4;5;6]

- We conducted a review of literature summarising the findings of published macro-economic models quantifying the impact of the UK Net Zero transition on GDP in 2050 (Table 4.1).
- We reviewed published literature more broadly on the potential impacts of the Net Zero transition on key economic indicators.
- We tested our approach and conclusions with economists and business organisations.

Table 4.1
Summary of impacts on UK GDP in macroeconomic models

Model name	Model approach	GDP % change by 2050*	Author (year)
ThreeME	Neo-Keynesian	1.1-1.8%	Pareliussen, J. et al. (2022)
GIBM	System dynamic	-0.9-1%	Hafner et al. (2021)
UK TIMES	Partial equilibrium	1-2%	BEIS (2021)
E3-ME	Neo-Keynesian	2-3%	Chewpreecha, U. and Summerton, P. (2020)
GEM-E3	Neo-classical, Walras's law	-0.5%	Ekins, P. et al. (2020)
E3-MG	Neo-Keynesian	2-5%	Dagoumas, A.S. and Baker, T.S. (2010)

Notes: (1) Most studies tend to find a small positive or negligible negative impact on GDP. Generally, this is due to investment brought forward into capital-intensive (rather than energy-intensive) technologies, falling costs of energy due to renewables, and a net increase in employment. However, models often rely on assumptions such as low interest rates, near-perfect allocation of resources, and unlimited access to finance. Percentages indicate percentage point changes comparted to the baseline. (2) This is not a comprehensive review of all models.

4.1.2 Impacts on sectors of the economy and businesses

We have assessed evidence of the potential impacts on different segments of the economy of the transition to Net Zero, drawing on established methodologies and an extensive body of external literature.

- We analysed the emissions, economic, and trade contributions of business sectors and of specific products to identify potential opportunity and risk activities, using established metrics such as gross value added (GVA), revealed comparative advantage (RCA), and emissions intensity.

- We grounded our analysis in a review of a wide body of literature, including previous CCC publications (such as our Net Zero Workforce Report and advice on the Sixth Carbon Budget), as well as external literature such as HM Treasury's Net Zero Review and recent work by economic consultants and institutions.[7]

- We tested our approach and conclusions with economists and business organisations and held discussions in several communities where opportunities and risks to particular industries are likely to be more pronounced.

We consider the main factors which determine how a given sector/activity might be impacted by the transition to Net Zero in terms of:

- **Whether the activity is emissions intensive.** We consider this on the basis that the most emissions-intensive sectors will face more fundamental changes which are likely to involve more significant costs (or face exposure to higher carbon prices), compared to sectors with low emissions intensity.

  - We calculate emissions intensity of UK sectors by dividing their emissions footprint by their contribution to UK Gross Value Added (GVA). We use production-based economic activity emissions data from the Organization for Economic Co-operation and Development (OECD) (to align with trade categories) and GVA data from the

Office for National Statistics (ONS) – taking an average between 2015 and 2020, given the OECD data were only available up to 2020.[8;9]

  - We consider sectors with an emissions intensity of less than 100 tonnes of carbon dioxide equivalent per £1 million of GVA to have relatively low emission intensity. This benchmark is used in an indicative way to characterise different economic activities and should not be taken as a definition of what is high or low emissions intensity. Emissions intensity is relative and is expected to decline as the UK transitions to Net Zero.

- **Whether demand for the activity is likely to increase or decrease, relative to a world without climate action.*** We consider this as it affects the revenue streams of particular industries.

  - We use our assessment of the products and services needed to decarbonise the economy, and our 2023 Net Zero Workforce Report assessment, to guide our assessment of whether demand for a given activity will grow or decline.

- **Whether the activity in question is internationally traded or domestic.** We consider this when assessing the risk of carbon leakage and opportunities for low-carbon exports, because traded goods and services are more exposed to international competition but also able to access a bigger international market.

  - We use global data (an average of 2015 to 2020) on value added to exports from the OECD to identify which activities are traded, and which ones are not.[10] We used the global average GVA contribution to exports as the threshold for identifying traded and non-traded sectors.

- **Whether the UK is specialised in a given activity.** The UK has strengths which make it competitive in providing particular traded goods and services to an international market.

  - We use the established metric of revealed comparative advantage (RCA) to identify areas of UK specialism. We use UK and global export data (the average of 2015 to 2020) from the OECD Trade in Value database at a sector level, and similar data (we take the latest year of data from 2023) from the UN Trade and Development statistics database at a product level.[11]

  - RCA is calculated by taking the share of UK exports from a given sector or product category and dividing it by the share of exports from that sector/category globally. If the RCA is greater than one, then it can be said that the UK has a comparative advantage in providing that good or service, as it is implied that the UK is relatively more productive in these activities. The approach we take to assessing competitiveness is outlined in more detail below.

Assessing areas of potential growth opportunity

We used the RCA metric to identify potential opportunities for the UK to capture growing markets in low-carbon goods and services and supplemented this with a review of relevant literature.

- Where the UK has a comparative advantage in providing a particular good or service, then we consider it to be well positioned to realise export opportunities from the international market.

- We use the sector-level RCA scores to indicate the broad areas of the UK's existing strengths across the economy. We verified and supplemented this by reviewing relevant literature.

* This was considered in order to understand business-level impacts, rather than to identify structural changes in the economy.

We have limited historical trade data with which to calculate RCA scores in new or emerging products and services. For these sectors, we identify where the UK has a comparative advantage in the incumbent sector today that points to underlying capabilities and specialisms which could be applied to producing low-carbon goods and services. However, we note limitations in this indicative approach:

- Where the UK has a strength in an activity today, this does not automatically translate to an advantage in the low-carbon equivalent in the future. This is dependent on how effectively a sector adopts low-carbon alternatives relative to its competitors. New market entrants can be more effective at seizing opportunities in emerging markets than incumbents, as they are not burdened by retrofitting outdated supply chains and business models. Equally, therefore, the UK may be able to succeed in new industries that are not current strengths.

- RCA is a proxy metric based on observed trends and does not fully reflect the full nature of a country's particular strengths and weaknesses in a given activity, which is dependent on a range of factors including physical conditions, the labour market, and the overall investment landscape. For example, the RCA metric does not reveal the UK's favourable geological conditions that make it well placed to develop carbon capture and storage capabilities.

- Insights based on trade data (as well as other economic datasets such as GVA and employment) are highly sensitive to how sectors and activities are defined and aggregated.

Figure 9.2 in the Seventh Carbon Budget advice report indicates different products produced in the UK which may have a low-carbon application and which have an RCA above one.

- To construct Figure 9.2, we assessed RCA at a product level.

- To assess which products to include in the figure, we made a judgement about whether those products or activities have a potential low-carbon application. This is an illustrative assessment.

Assessing competitiveness and carbon leakage risks

To assess the risk of carbon leakage for emission-intensive traded products, we reviewed relevant literature and supplemented this with a high-level analysis of the UK's top export destinations and competitors.

- We reviewed external literature including work for previous CCC advice and HM Treasury's Net Zero Review.

  - In 2017, the CCC commissioned Cambridge Econometrics to look in depth at the impact of decarbonisation policies on three emissions-intensive sectors (steel, aluminium, and cement).[12]

  - Our 2019 advice on the Net Zero target built on this assessment by looking at an updated estimate of the cost of decarbonising emissions-intensive industries in line with Net Zero.

  - For our 2020 Sixth Carbon Budget advice report, we updated these cost estimates again, and also commissioned the Energy Systems Catapult to assess a range of policy measures to mitigate the risk of carbon leakage.[13]

  - The 2021 HM Treasury Net Zero Review considered the risk to UK industry from carbon leakage by looking at emissions embodied in trade and assessing the impact of illustrative carbon pricing scenarios.[14]

- We supplemented this review by examining the UK's key export markets and competitors for a selection of emissions-intensive products.
  - We focused on the broad categories of emissions-intensive products under the proposed scope of the UK Carbon Border Adjustment Mechanism (CBAM) – aluminium, ceramics, cement, fertiliser, glass, and steel (we did not include hydrogen).[15]
  - We drew on trade matrices from the UN Trade and Development statistical database to assess the share of exports in these products traded within a given region or trading block.[16] We then identified the UK's top three export destinations for those products, and further identified the top two importers to those markets.

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Chapter 5: Uncertainty and contingency

Introduction

This chapter presents our methodology for analysing uncertainties in the Balanced Pathway and identifying potential contingency measures. Our analysis examines both economy-wide and sector-specific uncertainties that could affect the UK's progress towards its emissions targets.

- The methodology focuses on quantifying key sources of uncertainty that could materially impact emissions reductions in the pathway to 2050. These include macroeconomic variables such as GDP, emissions accounting methodologies, and costs of key technologies and fuels.

- Our approach standardises uncertainty bounds where possible to enable comparison across different sources, typically using one standard deviation (1-sigma) confidence intervals. However, given the inherent challenges in precisely quantifying long-term uncertainties, these results should be interpreted as indicative rather than as statistically rigorous probability distributions. This limitation notwithstanding, the analysis provides insights into the relative importance of different uncertainty sources and their potential combined effects on pathway outcomes.

- This chapter describes the methodology behind uncertainties that impact transition rates across multiple sectors. In addition, a range of sector-specific uncertainties have been undertaken that impact the pathways for individual sectors and do not have cross-economy impacts on emissions. The methodologies underpinning these sensitivity tests are covered in the relevant sectoral chapters.

- Section 5.5 summarises the contingency options that we have considered, which could be used to go further or to catch up if emissions reductions fall off track. The methodologies used to estimate the emissions savings from these contingencies are set out in the relevant sectoral chapters.

5.1 Our approach to uncertainty and contingency analysis

We have chosen to base this advice on a single modelled pathway, supported by a range of modelled uncertainties and contingencies, as opposed to the five decarbonisation pathways considered in our previous Sixth Carbon Budget advice.

- This partly reflects our assessment that the best way forward in many areas is now clearer (notably electrification of most aspects of key end-use sectors, enabled by rapid decarbonisation and expansion of the electricity system), and there is value in narrowing the option space to emphasise the urgency of delivering the key actions required in these areas.

- Options remain in some sectors (for example, the optimal balance of choices across low-carbon fuels, engineered removals, and demand to address residual emissions remains uncertain in some areas, in particular aviation). In these areas, we consider a mix of solutions in our pathway, reflecting the importance of leaving several options open at this stage.

- Development of contingency options is important to enable the potential risks from these (and other) uncertainties to be addressed effectively, ensuring a robust and adaptive approach to achieving Net Zero.

- In Chapter 6 of the Seventh Carbon Budget advice report, we have set out our assessment of the potential impact that uncertainties in a range of key underlying factors (for example, population and GDP, emissions accounting, and technology and fuel costs) could have on our pathway. In addition, the sectoral chapters of this report set out a range of sensitivity tests that we have performed to understand the robustness of our key assumptions and identify important delivery dependencies. These include considering delivery risks and opportunities (for example, the possibility of slower EV uptake or faster scale-up of heat pump installation supply chains). Sensitivity tests on these variables have been undertaken at sector level to understand the robustness of our sectoral pathways.

- We have modelled a range of additional actions which could provide contingency options to go further or to catch up if emissions reductions fall off track. Appropriate contingencies vary depending on the period under consideration, as well as the timescales available for implementation.

  – We discuss the range of contingency options available and the factors that should be considered in developing and implementing them in Chapter 6 of the Seventh Carbon Budget advice report.

  – Contingency options appropriate for the targets we have advised for Scotland, Wales, and Northern Ireland are discussed in their respective advice reports.

- It will be important to proactively monitor indicators of each of the key sources of uncertainty considered, to identify risks of emissions reduction falling off track at an early stage and enable contingency options to be implemented to mitigate the potential impact on meeting emissions targets. We have discussed our approach to progress monitoring in Chapter 5 of the Seventh Carbon Budget advice report.

- Our quantitative analysis of uncertainties and contingencies is undertaken at a UK-wide level, assessing the impact of variations in assumptions or additional actions on emissions across the UK.

  – While we have not directly assessed the impacts on emissions in Scotland, Wales, and Northern Ireland separately, in most cases the relative impact of a given uncertainty or contingency on the pathway for the sector that it affects is expected to be similar.

  – For this reason, when we present the results of our sensitivity tests and contingencies in Chapters 6-18, we include the percentage impact on sectoral emissions as well as the absolute emissions change.

5.2 Key sources of uncertainty

Our uncertainty analysis considers a range of trends in contextual background factors and specific assumptions within our sectoral modelling. This section examines each type of uncertainty in detail, explaining our methodology for quantifying the uncertainty range and estimating the impact on emissions in our pathway.

- In our cross-economy uncertainty analysis, we quantify the combined impact of a range of key sources of long-term uncertainty on our emissions pathway. In addition, we separately examine the impact that key sources of short-term uncertainty could have on emissions

during NDC target years or carbon budget periods. The results of this analysis can be found in Chapter 6 in the Seventh Carbon Budget advice report.

- For most uncertainty sources, we have developed estimates or proxy measures to quantify their likely ranges. However, it is important to acknowledge that some potentially significant sources of uncertainty remain outside the scope of this analysis. Additionally, data limitations affect our ability to fully characterise certain uncertainties.

- Consequently, while our analysis provides insights into key drivers of pathway variation, it should not be considered an exhaustive assessment of all uncertainties affecting the Balanced Pathway.

5.2.1 Population and GDP

Population

Population is strongly linked to levels of emissions in some sectors, so it is important to assess the uncertainty in future population. The population estimates used in our Balanced Pathway are based on Office for National Statistics (ONS) population projections and align with the assumptions used in the Government's 2023 Energy and Emissions Projections (EEP) (see Section 1.7.2).

- The ONS provides population projections up to 2050, based on trends in fertility, mortality, and net migration, which are updated every other year based on demographic changes over time.

- Our central population projection uses the ONS 2020-based data released in January 2023, which underpins the Government's 2023 EEP. However, as this was an interim release and because future ONS projections would be able to incorporate Census 2021 data, this dataset did not include any variant projections to account for the impact of different assumptions on factors such as birth and death rates.

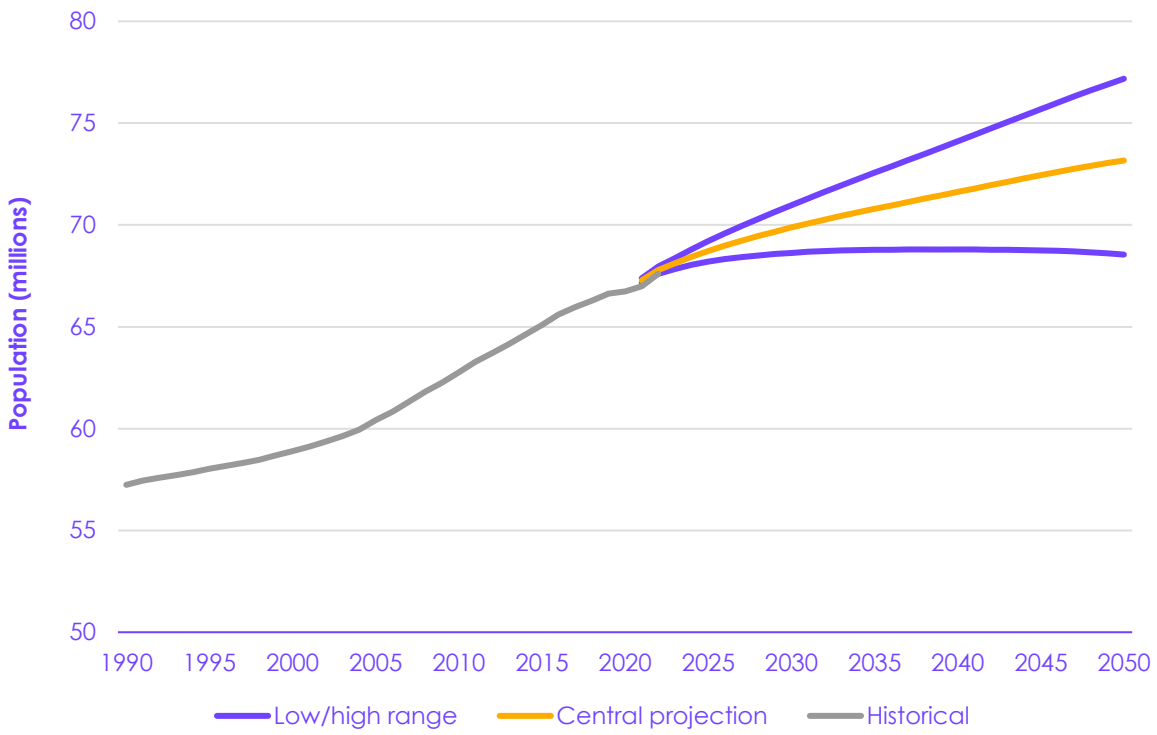
- The ONS 2018-based release includes several variants assessing the impact of different core assumptions on its central projection; however, the ONS emphasises that these are not formal confidence intervals but rather different high and low population scenarios (based on differing assumptions on fertility, mortality, and migration), which offer an indication of variation in future population trends.[1]

- To estimate the overall uncertainty in the future UK population, the high and low variants from the 2018-based release are each combined using root-sum-of-squares on the variants for each input. Comparing these to the 2018-based central projection allowed us to calculate the percentage differences between the resulting combined high and low scenarios and the central projection.

- This degree of variation was then applied as a scaling factor to the 2020-based data used as the central assumption, to define the high and low bounds of population uncertainty (Figure 5.1).

A second interim ONS dataset was issued, out of sequence, in January 2024. Due to higher migration estimates, this 2021-based projection deviated significantly from previous projections. However, for the Seventh Carbon Budget period, the 2021 projection is within our uncertainty margins.

Figure 5.1 Population projection range



Description: Our central population projection grows over time, while for our uncertainty analysis we also test a low/high range which grows out to 2050.
Source: ONS (2019) *National population projections, variant projections – 2018 based*; ONS (2023) *2020-based interim national population projections: year-end June 2022 estimated international migration variant*. CCC analysis.
Notes: (1) The central projection shown is our central assumption for use in our Balanced Pathway modelling, which uses the 2020-based ONS population projection published in January 2023. (2) The low/high range is derived from scaling the low and high scenarios from the 2018-based ONS dataset to the 2020-based dataset being used in our Balanced Pathway.

GDP

Gross Domestic Product (GDP) relates to the amount of economic activity occurring, which for some sectors is closely related to emissions. Our central GDP estimate is based on Office for Budget Responsibility (OBR) projections and long-term economic determinants and aligns with the assumptions in the 2023 EEP (see Section 1.7.2).

- As part of the economic and fiscal outlook, the OBR produces GDP forecasts. These forecast monthly GDP up to five years into the future. Beyond five years, an assumed trend rate of GDP growth is applied.
- OBR working paper 17 evaluated forecast uncertainty on the rate of GDP growth with stochastic simulations as an alternative to the historical forecast error approach traditionally used to represent uncertainty.[2]
- The OBR report does not cover uncertainty for the predictions beyond the five-year period from 2021 to 2026. To generate our uncertainties up to 2050, we take the average of the OBR stochastic uncertainty result for GDP growth rate and use this to extrapolate upper and lower uncertainty bounds for GDP out to 2050.
  - Uncertainties from 2021 and 2022 were excluded from the average due to the pandemic impact and the rebound impact in 2022. The OBR's estimates over the

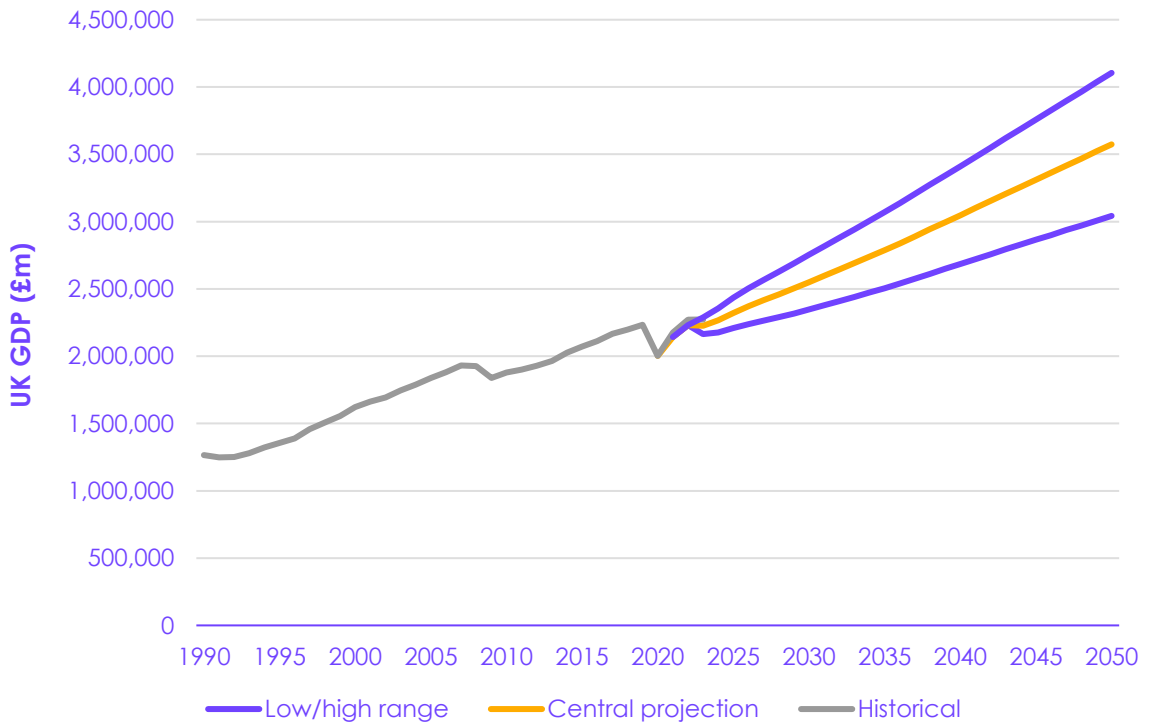
period from 2023 to 2026 average out to a two-sided 80% uncertainty range for GDP growth with a width of 7.2 percentage points.

  - Scaling this to a 1-sigma level of uncertainty gives an uncertainty for GDP growth in a particular year of ±2.8 percentage points.

  - This represents the uncertainty for growth in a particular year. For simplicity, we assume that GDP growth in one year is independent of that in the next. Therefore, we combine growth uncertainties for successive years by root-sum-of-squares, which has the effect of reducing the rate at which our GDP uncertainty range expands from the full 2.8 percentage points in the first year in proportion to the square root of the number of years (Figure 5.2).

- For the aviation sector, we also consider uncertainty in foreign GDP and the elasticities with which demand reacts to prices. Further details of the approaches to these uncertainities can be found in Chapter 11.

Figure 5.2 GDP annual growth uncertainty



Description: Our central GDP projection grows over time, while for our uncertainty analysis we also test a low/high range which grows out to 2050.
Source: OBR (2021) *Working paper No. 17: evaluating forecast uncertainty with stochastic simulations*; OBR (2023) *Long-term economic determinants – March 2023 Economic and fiscal outlook*. CCC analysis.
Notes: The central projection shown is our central assumption for use in our Balanced Pathway modelling.

This analysis is used to derive a general uncertainty for long-term trends in GDP, covering general variation but not major shocks (for example, the economic impact of a global pandemic). In our Seventh Carbon Budget advice report, we discuss the potential impact of economic shocks in qualitative terms in a separate section considering short-term uncertainties.

5.2.2 Greenhouse gas inventory

Emissions accounting

Our analysis of carbon budgets relies on current measurements of UK emissions, which are subject to ongoing refinement as measurement and accounting methodologies evolve. All emissions data in our analysis are based on the final 2022 inventory of emissions (see Section 1.7.2).

- The 2022 UK greenhouse gas (GHG) emissions inventory, published by Ricardo, provides relative uncertainty estimates for emissions across different sectors and subsectors.[3;4]
  - We validated that these uncertainty ranges adequately capture historical variations in inventory emissions resulting from methodological changes. This was done by assessing how the uncertainty ranges published in a given year performed against future inventory changes after that year.
  - We then apply these fixed relative uncertainties to emissions in all future years.
- For sectors where the proportion of emissions from different subsectors remains relatively stable over time, we apply the quoted sector-level uncertainties.
- However, for sectors experiencing significant changes in subsector emissions composition through to 2050 – specifically agriculture, land use, and waste – we use more granular subsector-level uncertainties to better reflect changing emission patterns. In some cases, the subsectors used in the inventory do not align to those used by the CCC. Here, judgement was used to decide whether to use uncertainties from an adjacent sector or subsector or whether to neglect the uncertainty in inventory emissions from the subsector in question.
- In the land use sector, emissions result from the complex make-up of sources and sinks. For grassland emissions, which are currently close to zero due to a cancellation of sources and sinks (see Chapter 17), it is therefore more appropriate to use the absolute grassland emissions uncertainty in 2022 instead of the relative uncertainty.

On top of inventory uncertainties based on the UK's GHG emissions inventory, we also apply dedicated emissions factor uncertainties for soil emissions in the land use sector and wastewater emissions in the waste sector, as the emissions factors for these sources are under review and may potentially change in future. More detail about these sector-specific inventory uncertainties can be found in the corresponding sectoral chapters.

Hydrogen

Hydrogen is not a GHG, but it can have an indirect warming effect, for instance by increasing the lifetime of methane in the atmosphere, altering ozone distribution in the atmosphere, and increasing the concentration of water vapour. If hydrogen use increases greatly as part of the transition to Net Zero, this could justify its inclusion within the inventory in future as leakage of hydrogen could contribute to global warming.

- Several studies have attempted to quantify the impact of hydrogen in the atmosphere using the GWP100 metric, so that it can be directly compared with GHGs such as methane that it could replace in some sectors (Table 5.1).
- Due to the uncertainty of many of these indirect impacts, there is a relatively wide spread of potential GWP100 values for hydrogen, ranging from 3.3 to 11.6. Supplementary material for the Intergovernmental Panel on Climate Change's (IPCC's) Fifth Assessment Report cited the 5.8 GWP100 value given in Derwent et al. (2006).[5;6] This is the value we have used for our uncertainty estimate.

- There is also uncertainty about the rate of leakage that would arise from the use of hydrogen.[7]
  - As a smaller molecule than methane, hydrogen leakage might be expected to be a bigger issue, but some studies have indicated similar leakage rates to methane for pipeline transportation and distribution.[8;9]
  - Different areas of the economy will be susceptible to disparate rates of hydrogen leakage, however, there is not yet a consensus on levels for all production, pipeline, or trucking transportation and use case scenarios. A published estimate for cross-economy leakage rate in the United States suggests a range from 2.9% to 5.6% in 2050.[10]
  - For our uncertainty analysis, we have assumed a 5% cross-economy rate for hydrogen leakage.

Table 5.1
GWP100 values for hydrogen

Source	GWP100	Methodology	Publication year
Derwent et al *Int. J. Nuclear Hydrogen Production and Application*	5.8	Single Lagrangian chemistry transport model	2006
Derwent et al[12] *Int. J. Hydrogen Energy*	5±1	Single Lagrangian chemistry transport model	2020
Field & Derwent[13] *Int. J. Hydrogen Energy*	3.3±1.4	Single global chemistry transport model	2021
Warwick et al[14] UK Government policy paper	11±5 7.9±3.6 (troposphere only as previous studies)	Single global chemistry transport model (including stratosphere)	2022
Derwent[15] Int. J. Hydrogen Energy	8±2	Sensitivity analysis using single chemistry transport model	2023
Sand et al[16] *Commun Earth Environ*	11.6±5.6	Five-member ensemble of global chemistry transport models	2023

Source: Referenced articles in the table.
Notes: Hydrogen has a short lifetime in the atmosphere, so GWP20 estimates are considerably higher than GWP100.

5.2.3 Global warming potentials

A further source of uncertainty in the Balanced Pathway stems from the global warming potential (GWP) values used to convert non-CO_2 emissions into their carbon dioxide equivalent (CO_2e). In our Balanced Pathway, we use GWP100, which compares the warming effects of GHGs over a 100-year time horizon (see Section 1.8.2). Changes to GWP values could alter the impact of emissions estimates from non-CO_2 GHGs, which could impact the ability to meet future emission targets.

Our uncertainty analysis incorporates the uncertainties in the GWP100 emissions factors as published in the IPCC's Sixth Assessment Report (Table 5.2).

Table 5.2
Uncertainties in GWP100 emissions factors

Greenhouse gas	GWP100 uncertainty
CH_4	20%
N_2O	24%
F-gases	18%

Source: IPCC (2021) *Sixth Assessment Report, Chapter 7 Supplementary Material of Working Group I.*
Notes: Uncertainties for different F-gases have been averaged. Reported 2-sigma uncertainties have been converted to 1-sigma values.

5.2.4 Fuel and technology costs

Fuel costs

Variation in fuel costs is one driver that can play a role in the cost effectiveness of the move to low-carbon technologies and in consumers and businesses choosing them. If factors delay or accelerate the point at which these become cost competitive, this will have a direct impact on emissions along the pathway. We have performed a range of sensitivity tests in our sectoral models to assess the impact of fuel cost uncertainties on the emission pathway.

- Uncertainty ranges for fossil fuel costs up to 2050 are based on the high and low variations for long-run variable costs (LRVCs) included in the supplementary guidance on valuing energy costs in HM Treasury's Green Book. These variations are based on the alternative scenarios in the Department for Energy Security and Net Zero (DESNZ) fossil fuel cost assumption forecasts.[17] The impact of these uncertainty tests varies by fuel. For example:
  - Fossil fuel cost uncertainties are relatively large. The uncertainty range for gas in 2040 is -60% to +106%, while that for petrol is -45% to +90%.*
  - Currently, the cost of generating electricity depends in large part on the cost of gas. Therefore, electricity cost uncertainties are closely linked to the uncertainty on gas costs early in our pathway. However, as renewables replace more of the gas in the electricity supply sector, this reduces this link. This is taken into account in our gas price uncertainty, with the uncertainty range for gas costs translating to a corresponding uncertainty range for electricity costs which falls in magnitude along our pathway. In 2040, this uncertainty range is -10% to +20%.
- In addition, the long-term uncertainty on electricity technology costs is estimated by varying the cost of generating electricity in our electricity system model by ±25%.
- For synthetic fuels in shipping, variants are based on the estimated differences in cost between importing and domestic production of these fuels. Additionally, international fuel standards and carbon pricing are considered in these tests (see Chapter 15 for further details).

* The uncertainty ranges here are for residential use cases. As we have separate LRVCs for other use cases (such as industrial), the magnitude of the uncertainty ranges for these use cases may be slightly different.

- For aviation, synthetic fuel costs are not included in our uncertainty analysis as changes in the costs of synthetic fuels would also shift the balance between their use and the use of engineered removals, but we were not able to model this trade-off.

- The derived high and low cost projections for each fuel are then run in the sector models to provide an estimate of the sensitivity of emissions in each sector to these costs.

Technology costs

Our sectoral models depend on a variety of technology cost assumptions. Details of the assumptions underpinning these, as well as the sensitivity tests that have been performed, can be found in Chapters 6-18. We incorporate uncertainties on the costs of two of the most significant technologies in our pathway within our cross-economy uncertainty analysis – electric vehicles (EVs) and heat pumps.

- The EV and heat pump sensitivity tests look at the impact on emissions of higher/lower prices changing the pace of the transitions to these low-carbon technologies.

Table 5.3 summarises the cost uncertainties that have been included within our analysis.

Table 5.3
Cost variables included within cross-economy uncertainty analysis

Type of cost uncertainty	Sector	Uncertainties considered
Fuel cost	Surface transport	Oil cost; electricity cost
	Residential buildings	Electricity cost; gas cost
	Industry	Electricity cost; gas cost
	Aviation	Oil cost
	Non-residential buildings	Electricity cost; gas cost
	Shipping	Synthetic fuel cost
Technology cost	Surface transport	Electric vehicle cost
	Residential buildings	Heat pump cost

5.2.5 Climate impacts

There are uncertainties around long-term climate trends, which could impact temperatures and consequently energy demand for heating in the buildings sector. In our Balanced Pathway, we assume that the warming climate leads to a gradual reduction in the number of heating degree days (HDD), in line with the average of the 11 scenarios in the Met Office's 2009 UK Climate Projections as used in the 2023 EEP.[18]

- To account for uncertainty in the extent of projected climate change in the UK, the Met Office's probabilistic projection decadal mean annual temperature anomaly data, based on the RCP4.5 emission scenario, was used to create a climate change-adjusted temperature baseline up to 2050.[19] The decadal trends were linearly interpolated to create an annual temperature time series.

- The 10th and 90th percentile anomaly data from the same data set was used to produce high and low uncertainty scenarios in the same way, which we then normalised to a 1-sigma level to provide our climate uncertainty range.

- We then performed a linear regression between historical annual average temperature data and HDD data to estimate how changes in assumed temperature might affect the HDD assumptions applied within our buildings modelling.[20;21]

- Regression analysis between HDD and historical building emissions data (residential and non-residential separately) then provides scaling factors for future emissions from the buildings sectors based on the climate uncertainty range. These scaling factors are then applied to the residential and non-residential buildings emissions pathways to estimate the potential impact on emissions.

This uncertainty reflects the impact of long-term variation in temperatures due to uncertainties in the extent of projected climate change. In addition, we consider the possible effect of year-to-year weather variation on emissions in the buildings and electricity supply sectors. This analysis is presented in the section of our Seventh Carbon Budget advice report covering short-term uncertainties.

- In the buildings sector, we look at the impact of variable year-to-year temperatures on buildings emissions, based on an analogous approach to that described above but considering expected inter-year variability rather than projected long-term uncertainty.

- In the electricity supply sector, we consider the impact of adverse weather (days with low wind) on electricity supply emissions. This analysis is described in Chapter 10.

5.2.6 Carbon capture rates

Carbon capture and storage (CCS) capture rates determine the proportion of CO_2 in a stream of gas that is captured, and therefore feed into calculations of sector emissions for industry, electricity supply, fuel supply, waste, and engineered removals. Capture rates vary for different applications (see Section 1.7.2), so exact details of the sensitivity tests that are undertaken vary by sector.

- Our low capture rate sensitivity fixes the capture rates at the 2028 values throughout the pathway.

- Our high capture rate sensitivity keeps the 2028 capture rates the same, but sets the 2050 capture rates all to 98%, with a ramp-up for the intervening years.

5.3 Application to sectors

The uncertainties described in the previous section are used to obtain uncertainty estimates on emissions in one of the following ways:

- To determine which sectors should incorporate population and GDP uncertainties, we assessed the significance of the relationship between these variables and historical emissions in each sector.

  - We employed a two-tailed Student's t-test to assess the significance of the slope of the linear model between change in annual GDP and emissions changes. For the t-test, the p-value represents the probability that the relationship is down to chance, so low p-values indicate significant relationships.

- Aviation, industry, and surface transport showed significant slopes ($p<0.01$), while other sectors showed slopes that were compatible with no correlation ($p>0.1$). The R^2 values for aviation, industry, and surface transport also indicated a significant correlation. We therefore apply a GDP uncertainty in these sectors.

- For sectors without a significant GDP correlation but expected population relationships, we apply a direct proportional response between population and emissions. This approach is used for fuel supply, electricity supply, waste, and F-gases.

- For several types of uncertainty, we apply relative uncertainties directly to scale the sector emissions. This approach is used for population uncertainties (where relevant, as discussed above), inventory uncertainties, GWP uncertainties, climate uncertainties, and CCS capture rate uncertainties.

- For industry emissions, we developed a linear regression model to quantify the relationship between GDP and emissions changes. This model uses historical data from 1990-2019, analysing year-on-year percentage changes in both GDP and emissions from industry. We use this first-differencing approach (examining year-on-year changes rather than absolute values) to remove the confounding effect of both GDP and emissions having independent long-term trends over time. This allows us to better isolate the direct relationship between GDP fluctuations and emissions responses.

- For all other uncertainties in Table 4, we generate emissions uncertainty estimates through sensitivity testing by re-running sector models with high/low input assumptions and using the resulting emissions ranges to quantify uncertainty bounds.

Table 5.4 lists which uncertainties are applied to which sectors.

Table 5.4
Uncertainties applied to each sector

Sector	Cross economy	Sector specific
Agriculture	Inventory, GWP	
Aviation	Inventory, GWP, GDP, oil costs	Price elasticities (impact on demand from price changes), foreign GDP
Electricity supply	Inventory, GWP, population	CCS capture rates
Engineered removals		CCS capture rates
F-gases	Inventory, GWP, population	
Fuel supply	Inventory, GWP, population	CCS capture rates
Industry	Inventory, GWP, GDP, gas costs, electricity costs	CCS capture rates
Land use	Inventory, GWP	Soil emissions factor
Residential buildings	Inventory, GWP, gas costs, electricity costs	Heat pump costs, climate uncertainty
Non-residential buildings	Inventory, GWP, gas costs,	Heat pump costs, climate uncertainty
Shipping	GWP	Synfuel costs
Surface transport	Inventory, GWP, GDP, oil costs, electricity costs	EV costs
Waste	Inventory, GWP, population	Wastewater emissions factor, CCS capture rates

5.4 Combining uncertainties

In aggregating the impact of the uncertainties described above, we adopt the following approach:

- Where uncertainties stem from common external drivers, we treat them as correlated across sectors. For example, GDP uncertainty affects emissions across multiple sectors in a coordinated way, as do fuel cost uncertainties.
- Similarly, we account for the relationship between gas and electricity costs, where gas cost uncertainty affects both direct gas prices and electricity prices through its influence on marginal electricity generation costs. We incorporate an additional, independent electricity cost uncertainty to capture other factors affecting electricity prices (see Section 5.2.4).
- We also recognise the relationship between population and GDP uncertainties, conservatively treating them as correlated in our analysis.
- Conversely, where uncertainties are intrinsic to individual sectors – such as inventory uncertainties arising from sector-specific measurement and accounting challenges – we treat them as uncorrelated across sectors.
- Although different sectors face varying challenges to implement carbon capture, the majority of CCS processes are shared across sectors, so this uncertainty has been treated as correlated.

This methodology allows us to combine uncertainties in a way that reflects known relationships while avoiding over-specification of correlations where evidence for such relationships is limited. The resulting aggregate uncertainty provides a structured assessment of potential pathway variations, while acknowledging the inherent limitations in quantifying long-term projections.

- While our analysis provides valuable insights into potential variations in the Balanced Pathway, it is important to emphasise that it represents only an approximation of the underlying uncertainties. Some potential sources of uncertainty remain unquantified.
- Consequently, the resulting uncertainty ranges should be interpreted as indicative of possible pathway variations rather than as formal statistical confidence intervals.

5.5 Contingency actions

We have identified a range of contingency actions that could be implemented either as options to go further in reducing emissions or to make up shortfalls in emissions reductions if the UK begins to fall behind the Balanced Pathway (Table 5.5).

- Contingencies are modelled according to the approaches described in the relevant sectoral chapters.
- The assessment of potential emissions savings and the summary considerations of implementation timescales presented in Table 5.5 should be viewed as initial estimates of the contingencies that could be available. A fuller assessment would be necessary to include these within a robust delivery plan.
- These contingencies all represent actions that are not included in the Balanced Pathway.

Table 5.5
Contingency actions for the UK's emissions reduction targets

Sector	Contingency option	Implementation timescales	Potential average annual emissions savings ($MtCO_2e$, % of sector emissions)			
			2030	CB6	CB7	2050
Surface transport	Incentives for EV cars and vans	• Assumed to start in mid-2026. • Diminishing value over time as almost all new sales are EVs anyway from 2030.	4.7 7%	3.5 9%	2.2 15%	
	Scrappage of older cars and vans	• Assumed to be voluntary: incentives would be offered for scrappage. • Only appropriate once EVs are nearing 100% of new sales (assumed from 2030 for 500,000 vehicles per year). • A larger scheme could be implemented later, but impacts may be limited or delayed by market capacity.	0.8 1%	2.6 7%	1.9 12%	
	Increased measures to enable modal shift	• Multiple-year lead-time for investment in additional public transport services. • Measures to reduce driving could be implemented more quickly.	0.6 1%	0.6 2%		
Residential buildings	Earlier action to scale up residential heat pump markets	• Would need immediate action to scale up training and supply chains and increase awareness and incentives to scale up demand. • Modelled as delivering market scale-up at a pace in line with best international comparators.	4.7 26%	4.8 14%	4.7 26%	
	Scrappage of older residential gas boilers	• Assumed to be voluntary: incentives would be offered for scrappage. • Only impactful once supply chain scale-up achieved.	0.3 1%	2.4 7%	4.4 25%	
Industry/ waste	Increased resource/ energy efficiency in industry/waste*	• Could start to take effect before 2030.	0.4	1.2	1.9	2.2
Agriculture	Higher reduction in meat consumption	• More immediate action could be possible through additional support for more novel alternative proteins, but dependent on scale-up potential and regulatory approval.			0.4 1%	1.9 7%

		• Lag time between reductions and these translating into reduced livestock numbers and land release.				
	Additional use of livestock feed additives (Asparagopsis)	• Deployment from 2035; time needed to address environmental concerns on its use.			1.3 4%	1.7 6%
Electricity supply	Accelerated deployment of low-carbon power	• Planning and deployment timescales would require action to begin now. • Five years to construct one additional low-carbon dispatchable power plant.	2.2 22%	0.7 12%	0.8 18%	
Aviation	Additional aviation demand management	• May need to be phased in over time.	1.4 4%	1.7 6%	2.1 7%	1.7 8%
Waste	Additional investment in wastewater treatment	• Could be implemented quickly, but costs lower the earlier this is done as benefitting from natural replacement cycles.			0.3 4%	0.8 16%
Non-residential buildings	Faster heat pump roll-out in commercial buildings	• Modelled as delivering market scale-up at a pace in line with best international comparators.	0.5 3%	0.6 10%	0.5 18%	
Shipping	Stronger regulation of domestic shipping vessels	• Impact slow to develop due to alternative fuels initially not being widely available.	0.5 5%	0.7 10%	0.5 10%	
Land use	Planting higher-yielding trees from 2035 onwards	• Long lead-time – significant abatement benefits realised only around 10-20 years after planting.				1.7 -6%
Engineered removals	Increased DACCS deployment	• Maximum build-out rates constrain deployment to around 0.5 $MtCO_2$/year.		0.5 -4%	2.0 -9%	15.6 -44%
Engineered removals/ fuel supply	Less reduction in bio imports, allowing more BECCS H_2	• Slower reduction in biomass imports, allowing 10% of blue hydrogen production to be displaced by bio-hydrogen.		0.8	1.5	1.5

Notes: (1) For context, the total emissions in the Balanced Pathway in each period shown in the table are as follows: 295.8 $MtCO_2e$ in 2030; 188.8 $MtCO_2e$ on average in the Sixth Carbon Budget (CB6) period; 106.6 $MtCO_2e$ on average in the Seventh Carbon Budget (CB7) period; and -1.1 $MtCO_2e$ in 2050. (2) We have blanked out cells where the contingency measure in question is estimated to deliver less than 0.3 $MtCO_2e$ in potential emissions savings, to focus on high-yield options. (3) The percentages of land use and engineered removals emissions are negative because land use and engineered removals emissions are negative during the relevant time periods. (4) The percentages are not included for actions that affect emissions across multiple sectors. (5) *The emissions impacts for the 'increased resource/energy efficiency' contingency in the industry and waste sectors could be an overestimate because we calculated these savings based on a direct scaling from the DESNZ research rather than being able to do a full re-run of the sectoral models.

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Part 2:
Sectoral methodology

Chapter 6: Surface transport

Introduction

The surface transport sector includes emissions from road vehicles (cars, vans, heavy goods vehicles (HGVs) buses, coaches, and motorcycles), passenger and freight rail, as well as minor sources such as airport support vehicles.

The Balanced Pathway for surface transport is determined by assessing the extent, pace, and cost of deploying various measures to reduce emissions from today through to 2050, against a counterfactual baseline with rising vehicle use and no further decarbonisation across the UK economy (maintaining the current mix of vehicles in the fleet). Multiple analyses contributed to the pathway:

- **Road transport**. We model the mileage, size, and turnover of vehicle fleets, as well as the uptake of measures to reduce emissions. First, measures which reduce mileage (modal shift) or improve efficiency of the fleet are applied based on what we have assessed to be feasible. However, the vast majority of emissions savings are achieved by the transition to battery electric vehicles (EVs) replacing petrol or diesel vehicles (ICEs) in the fleet at the end of their lives.*
  - For cars, vans, and motorcycles, the uptake of new vehicles is based on a model of expected consumer choices between ICE vehicles, EVs and (in the case of cars) plug-in-hybrid alternatives (PHEVs), considering factors such as purchase price, running costs, and reliability and consumer preferences. These vehicle types are already cost effective compared to the Government's carbon value.
  - For HGVs, coaches and buses, the uptake of new vehicles is determined firstly by assessing the technical capability of different zero-emissions models technologies (EV, hydrogen-fuel cell, pantograph) and the number of vehicles available in the market. ZEVs are then chosen based on the relative total cost of ownership (TCO) of different technology options, with the cheapest zero-emission models purchased first.[1] The (large) proportion of the fleet for which ZEVs are deemed technically capable reaches 100% ZEV sales by 2035 so that diesels are replaced by 2050. Cost and roll out of charging infrastructure also influences zero-emission HGV, bus, and coach uptake.
- **Passenger and freight rail.** We model the transition of diesel rolling-stock to a range of zero- and low-emission alternatives. This is based on the feasibility of different rail journeys and parts of the network to be serviced by certain locomotive types, with an increasing proportion becoming electrified in our pathway.

Our analysis is based on a series of in-house models, including our Road Transport Model and underlying models for zero- and low-emission car and van uptake, and modal shift. Our zero-emission HGV and bus uptake trajectories are based on modelling the CCC commissioned from Environmental Resources Management (ERM).[2] We use in-house passenger and freight rail models, as well as an in-house model for aircraft support vehicles. Model assumptions were developed through reviewing relevant literature and engagement with stakeholders in industry, as well as academic experts.

* Electric vehicles (EVs) is short-hand for battery-electric vehicles (BEVs), while petrol and diesel vehicles are referred to by their internal combustion engines (ICE).

6.1 Baseline emissions in surface transport

The baseline represents a scenario in which there is no further decarbonisation action by either the Government or the market in the surface transport sector – so we effectively hold today's mix of technologies constant but increase overall mileage in line with increases in population and GDP. In this scenario, emissions would rise by 11% from 2023 levels by 2040 (the middle of the Seventh Carbon Budget period) and by 17% by 2050 (Figure 6.1). See Chapter 1 for our general approach to baselines.

The technology mix in the baseline for surface transport includes assumptions on the share of vehicle types through to 2050:

- The EV transition for cars, vans, and buses is already well underway. In the baseline we assume that the mix of EV, PHEV, and ICE in 2023 is fixed to 2050 to reflect a baseline in which there is no additional decarbonisation. There are no zero-emission HGVs in the baseline, to reflect the current lack of zero-emission HGV uptake at scale.

- Fleet turnover is based on empirical fleet survival rates. These are calculated using the Department for Transport's (DfT) vehicle licensing statistics (VEH0111) which gives the number of vehicles that were registered in a given year that remain in the fleet each year.[3] This is combined with historical new registration data (DfT's VEH0150 and VEH0153) to determine vehicle survival rates.[4;5]

  - We apply these survival rates to determine how many vehicles in each year of each age will survive into the next year, and how many will reach the end of their lifetime and fall out of the fleet. The proportion of drivetrain types in the baseline are fixed to 2023 shares.

  - The number of new vehicles entering the fleet is determined by the size of the new car market, which increases in line with projections from the DfT's National Transport Model.[6]

We use a starting point of the market in 2023 (around 1.9 million units per year), which is smaller than before the COVID-19 pandemic (around 2.3 million per year).[7]

- We assume a recovery in the market to pre-pandemic levels by 2026 and thereafter project the sales required to deliver the fleet size projections given the assumed vehicle survival rates. We have considered the impact of a permanently reduced new car market on emissions as part of our sensitivity tests (see Section 6.4).

- We assume capital costs of ICE vehicles increase in our baseline in line with observed trends in prices. In parallel, we assume the capital costs of EVs reduce and eventually the two technologies reach price parity, after which point their respective costs continue to diverge through to 2050. See Box 6.2 for more detail regarding our car, van, and motorcycle price assumptions.

  - We used central CCC assumptions for fuel and electricity prices (see Section 1.7.2). ICE operational costs decrease throughout the pathway due to their increased efficiency.

- For passenger and freight rail, we assume that the split of locomotive technologies remains at 2023 levels through to 2050. Electrification of the network linearly increases from 39% of route-kilometres to 51% by 2050, in line with current Government plans.[8;9]

- There is already use of biofuels for road transport in the UK and our baseline assumes that current levels of E10 bioethanol blending in standard petrol is continued out to 2050.[10]

The baseline levels of vehicle mileage are based on the following assumptions:

- For road vehicles, we use the latest year of DfT's road traffic statistics at the time of analysis (2023) to determine the starting number of vehicle-km by vehicle type.[11] We use quarterly traffic estimates for the beginning of 2024 to provide an annual estimate of that year.[12] These estimates for Great Britain (GB) were scaled to include Northern Ireland based on the latest data from 2014 which was uplifted in line with annual changes at a GB level.[13] Baseline demand for 2025 was based on DfT's National Road Traffic Projections (NRTP) core scenario, adjusted from 2024 based on the average percentage growth in vehicle-km in a typical year from 2015-2019.[14] From 2026 onwards the vehicle-km baseline was based on the NRTP percentage change scaled to the modelled value for 2025.

- In the DfT's core scenario, car, van and HGV kilometres grow based on the main drivers of road traffic demand including population, GDP, employment, households, fuel prices and fuel efficiency. We model motorcycle and bus demand to remain constant.

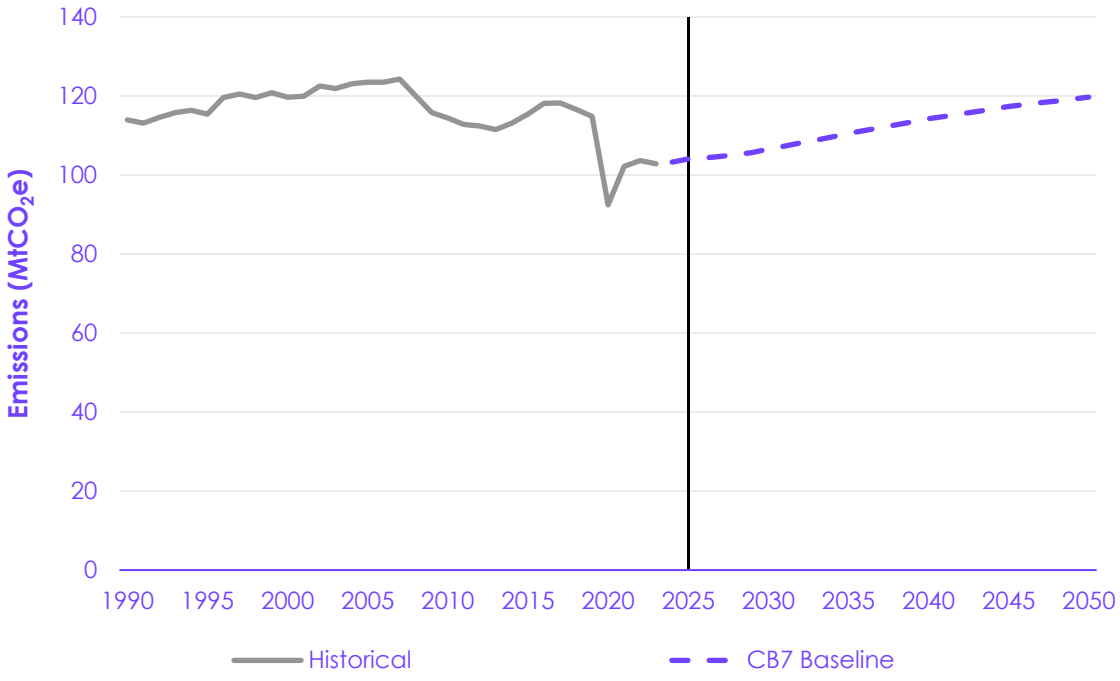
  - This approach to calculating the vehicle-km baseline could be an overestimate as DfT's NRTP assumes a higher proportion of EVs than in our baseline. As a result, it potentially includes an additional rebound effect associated with the cheaper cost of electricity relative to fossil fuels resulting in a larger number of kilometres driven by electric cars relative to ICE vehicles.

  - There is uncertainty regarding both the vehicle-km baseline projections and the scale of the rebound effect.

- There is uncertainty regarding the growth in vehicle-km in the baseline across all modes. For vans it is particularly unclear whether growth seen since 2000 will continue at its current pace. The baseline assumes that it does not, as this growth can be largely explained by a growth in online shopping for which we assume an upper limit. We explore this further in Section 6.4.

- In the baseline, we assume that passenger train numbers increase to the forecast numbers in the Rail Delivery Group's long term passenger rolling stock strategy.[15] We assume the number of freight trains in operation remain at today's levels.

Figure 6.1 Baseline emissions in surface transport



Description: Baseline emissions for surface transport rise steadily, based on growth in overall mileage in line with increases in population and GDP.
Source: Historical data from DESNZ; CCC analysis.

6.2 Pathway assumptions and modelling approach for surface transport

6.2.1 Modelling the Balanced Pathway for surface transport

Overall modelling approach

Our analysis to develop the surface transport pathway uses separate models for road transport (cars, vans, motorcycles, HGVs, and buses), rail transport (passenger and freight), and aircraft support vehicles (for example, baggage tractors and pushback tugs). The key analytical steps are outlined in Figure 6.2. See Chapter 1 for our general approach to pathway analysis.

The key elements of our modelling approach are as follows:

- The Road Transport Model (RTM) estimates energy and fuel demands, costs, and emissions for road vehicles in the Balanced Pathway based on the fleet size and composition, kilometres driven, and efficiency assumptions:
  - Fleet size in the Balanced Pathway is the same as in the baseline.
  - We calculate vehicle-kilometres (vehicle-km) in the Balanced Pathway by applying our assumptions on vehicle-km reduction measures against the baseline vehicle-km. For

cars this is based on CCC analysis to estimate the levels of modal shift away from car-kilometres (car-km) to public transport and active travel based on evidence on what has been achieved in other countries as well as regions in the UK. We then calculate a 'rebound effect' of an increase in distances driven by electric cars resulting from the cheaper cost of electricity compared to petrol and diesel. We apply an HGV kilometre (HGV-km) reduction to represent improved operating efficiencies.

  - In the Balanced Pathway, the distribution of ICE and EV/PHEV new cars and vans entering the fleet when old cars reach the end of their lives is determined by an in-house consumer choice model (Box 6.1). This considers factors such as relative purchase prices and running costs, as well as charging time, range anxiety and other consumer preferences. We model the uptake for small, medium, and large cars, and vans, separately. Motorcycle uptake is based on the pathway for small cars. The outputs of the consumer choice model are a key input into the RTM.

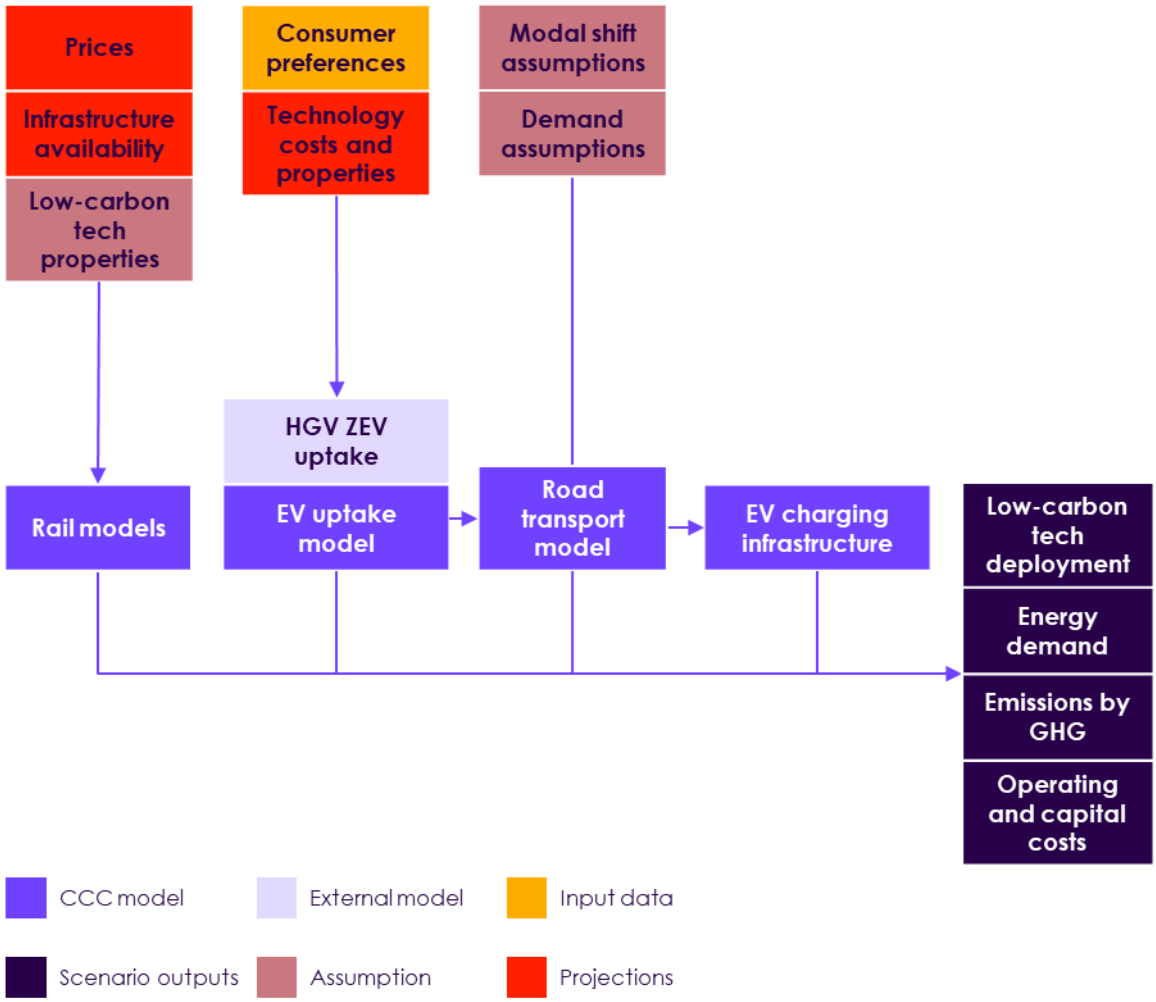
  - HGV, bus, and coach fleet composition is based on modelling that we commissioned from ERM. It is determined firstly by assessing the technical capability of different zero-emissions models technologies (EV, hydrogen-fuel cell, pantograph) and then comparing their total cost of ownership against diesels. Discounts are applied to the cheapest ZEV models at 5-year intervals to drive TCO cost effectiveness – but these are phased out by 2040. Each year, any new vehicle demand that cannot be met by a capable and cost-effective ZEV is made up by diesel vehicles. The (large) proportion of the fleet for which ZEVs are deemed technically capable reaches 100% ZEV sales by 2040 so that most diesels are replaced by 2050. Cost and roll out of charging infrastructure also influences zero-emission HGV, bus, and coach uptake.

  - Public charging infrastructure requirements are estimated by the interurban and parking models, which we commissioned from SYSTRA. These calculate the number and location of charge points and their charging speed based on energy demand assumptions from the RTM and the distribution of demand across the road network.

- The passenger and freight rail models assess the relative costs and suitability of electric, battery-electric, hydrogen, and hybrid diesel-electric trains for different routes based on CCC analysis. An increase in the proportion of the rail network that is electrified is modelled based on what was deemed feasible by the Railway Industry Association's report on delivering a Net Zero railway by 2050.[16]

- Aircraft support vehicle energy demands, costs, and emissions are based on operator data. We assume that the aircraft support vehicle fleet will transition to become fully battery electric.

Figure 6.2 Modelling schematic for surface transport



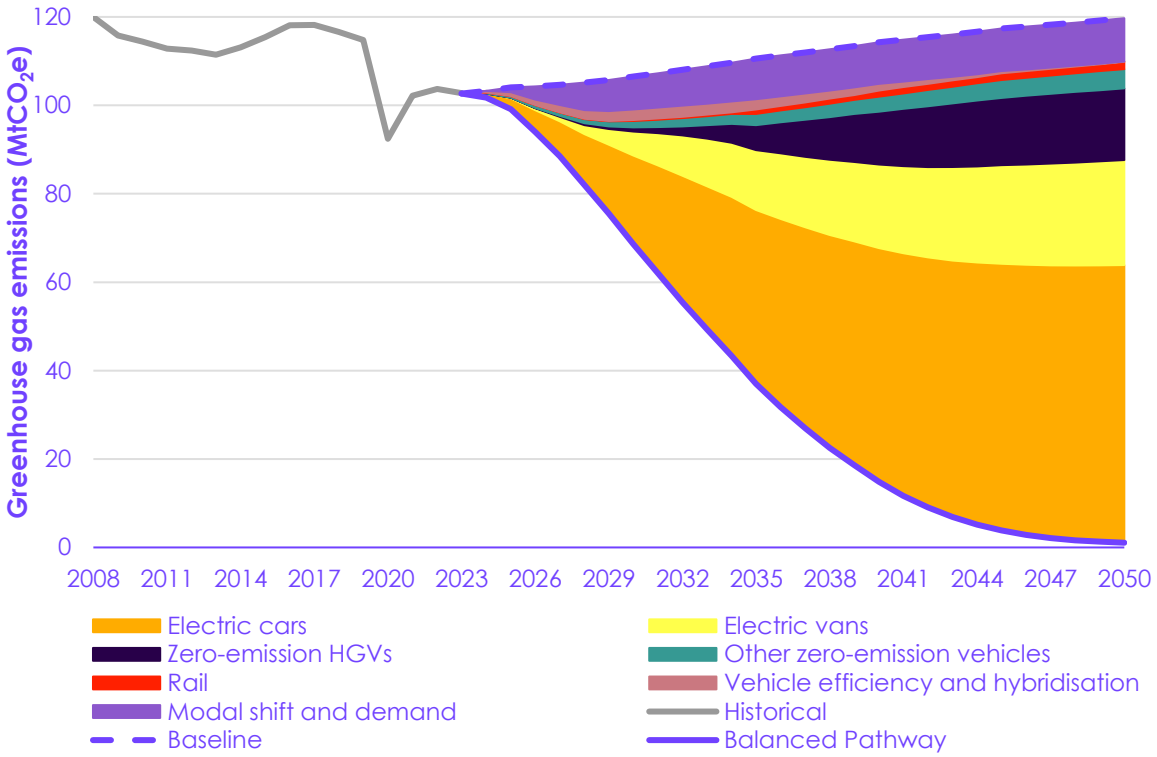
Description: Five models combine to produce our pathway outputs for surface transport.
Source: CCC analysis.
Notes: This diagram is illustrative and does not detail all model inputs and outputs.

The Balanced Pathway for surface transport

In our Balanced Pathway, surface transport emissions are projected to fall by 86% from 2023 levels, to 14.9 MtCO2e by 2040 (the middle of the Seventh Carbon Budget Period) and to 1.1 MtCO2e by 2050 (Figure 6.3).

- 88% of emissions reduction by 2040 (87 MtCO2e) in the Balanced Pathway for surface transport comes from switching from fossil-fuelled to electric cars, vans, HGVs, buses, and motorcycles.
- This is complemented by measures to reduce traffic growth, improve the efficiency of conventional vehicles, and decarbonise the rail network.

Figure 6.3 Sources of abatement in the Balanced Pathway for surface transport



Description: The largest share of emissions reduction in surface transport is from switching to electric cars and vans. Contributions also come from zero-emission HGVs, other zero-emission vehicles, rail, vehicle efficiency and hybridisation, and modal shift and demand.
Source: Department for Energy Security and Net Zero (DESNZ) (2024) Provisional UK greenhouse gas emissions national statistics 2023; DESNZ (2024) Final UK greenhouse gas emissions national statistics 1990-2022; CCC analysis.
Notes: The chart shows the measures that contribute to reducing emissions in the Balanced Pathway compared to the baseline. 'Other zero-emission vehicles' includes zero-emission buses, motorcycles, and aircraft support vehicles.

The measures in our pathway

Table 6.1 summarises the measures to reduce emissions in the surface transport sector that are considered within our modelling. It summarises what measures are selected and how they lead to emissions reductions, as well as the key factors that influence their adoption. The methodology used to develop the assumptions and analysis underpinning these is described in the rest of this section.

Table 6.1
Measures considered within our modelling for surface transport

Decarbonisation measure	How does this measure influence emissions in our modelling?	What are the key factors that affect this measure in our modelling?
Transition to zero-emission cars, vans and motorcycles	New EVs displace ICEs in the fleet as older vehicles reach the end of their lifetimes. This leads to an increasing proportion of electric vehicles on UK roads thereby reducing emissions. PHEVs make up a very small share of new car sales but are phased out by 2035. PHEVs are not an option for vans in our modelling.	EV uptake is determined largely by the relative price of an EV compared to PHEVs and ICEs, as well as other factors and consumer preferences (Box 6.1). The date of price parity is an important tipping point after which EV uptake accelerates. Charging infrastructure availability and fossil fuel and electricity prices also impact EV uptake.

		PHEVs are not modelled for vans because these are present in the market today in only very limited numbers and are expected to be less attractive than EVs in terms of cost of ownership.
Transition to zero-emission HDVs (HGVs, buses and coaches)	New ZEVs displace ICEs in the fleet as older vehicles reach the end of their lifetimes. This leads to an increasing proportion of EV HDVs on UK roads, with very few ICE HDVs remaining by 2050, thereby reducing emissions. Hydrogen technologies were considered but not selected by the model and so do not feature in our pathway. However, we recognise a greater degree of uncertainty around the potential of all BEV HDV applications, which may create a space for other technologies to play a supporting role.	ZEV HGV and bus uptake is determined by the relative total cost of ownership of ZEV technologies against ICE vehicles as well as technical capability. Discounts are applied to drive TCO cost effectiveness of ZEVs but are phased out over time. The (large) proportion of the fleet for which ZEVs are deemed technically capable reaches 100% ZEV sales by 2040 so that most diesels are replaced by 2050. EV technologies are considered to be significantly more affordable than hydrogen fuel cell vehicles on a TCO basis and this factor determines ZEV HDV uptake to a large extent. The availability of charging or refuelling infrastructure is also important.
Fuel efficiency improvements (conventional vehicle efficiency, biofuels and speed limit compliance)	Conventional efficiency improvements reduce the average emissions of new ICE vehicles in each year until they are phased out. This includes more efficient engines, aerodynamics, and halting the trend towards larger, less fuel-efficient cars. Compliance with existing speed limits reduces fuel consumption and thereby reduces emissions from ICE vehicles due to lower emissions factors at lower speeds. Increased blending of biofuels into conventional fuels reduces emissions by displacing fossil fuels with a biogenic fuel. Their use increases from today's level but then phases down. The impact of these measure on reducing emissions diminishes as EVs make up an increasing share of the fleet.	We assume that ICE vehicle efficiency incrementally increases and that the distribution of car sizes for new sales stays constant to halt the current trend towards larger cars. We apply an emissions saving based on an increase in fuel efficiency as a result of compliance with existing speed limits. The current blending of E10 into petrol is maintained throughout the pathway due to the associated emissions savings. There is increased biofuel allocated to HGVs in the early 2030s under our best-use hierarchy. Biofuel usage is phased down once EVs become widespread.
Modal shift away from cars towards public transport, walking and cycling	Potential for reductions in car use through improvements to public transport and active travel are applied relative to the baseline, thereby reducing emissions from ICE vehicles.	We assume reductions in car-kms based on examples overseas and around the UK. The distribution of rural/urban areas determine the ambition adopted in different nations of the UK.
Other car and van demand-side measures (occupancy, reduction in journeys)	Not included, however our pathway does assume that the current rate of van-km growth slows due to the saturation of online-retail.	There is a lack of evidence for policy levers that could influence car occupancy or van demand.

HDV demand-side measures (operator efficiency and freight operations)	Potential for technological improvements to existing vehicles and adoption of eco-driving delivers fuel efficiency reducing the carbon intensity per vehicle km. The impact of this measure on reducing emissions diminishes as EVs make up an increasing share of the fleet. The potential for freight operations (such as re-routing) was not explicitly modelled but is likely to play a role in delivering the required emissions reductions.	We assume progressive adoption of operator efficiency measures across the HGV fleet, achieving approximately 80% implementation by 2030. Our assumptions on operator efficiency improvements are based on measures which are cost-effective.
Rail electrification, battery electric and hydrogen trains	Increasing km of track electrified and electric trains in stock reduces emissions by replacing diesel trains. Hydrogen trains also replace diesel trains thereby reducing emissions.	Cost and availability of electrifying track is based on the Railway Industry Association report on the electrification cost challenge. Locomotive technology is determined by speed and distance requirements. Battery electric trains are chosen where range allows, and hydrogen is preferred over diesel-electric on non-electrified tracks. Diesel-electric is the option of last resort where other options aren't suitable.
Electric aircraft support vehicles	EV sales replace ICEs in the fleet when they reach the end of their lifetimes leading to a greater proportion of EVs in the fleet throughout the pathway.	Battery-electric aircraft support vehicles can carry out aircraft support functions and reach 100% of new sales by 2039.

6.2.2 Zero-emission car and van deployment

We use our consumer choice model to determine the market share of new EV, PHEV, and ICE car and van sales in the pathway. This seeks to reflect key factors such as purchase prices, running costs (fuel/energy, maintenance), charging/range requirements, and consumer preferences.

- For new cars, EVs and PHEVs compete with ICE models, but the uptake trajectory is dominated by EVs, and new PHEVs only have a small role before being phased out from new sales by 2035 (Figure 6.4). For vans, only EVs compete with ICE models because we assume no significant market for PHEV vans as these are present in the market today in only very limited numbers and are expected to be less attractive than EVs in terms of cost of ownership. We do not consider hydrogen fuel cell vehicles as EVs are the established dominant and more cost-effective low-carbon technology today.

- Unlike other sectors, our trajectory for EV car and van uptake is driven by the costs faced by vehicle purchasers, rather than the 'social cost effectiveness' of low-carbon options compared to Government's carbon values. Purchase price is the biggest factor in the consumer choice model, but other preferences including running costs are important.

  - Our consumer choice model (originally developed by Element Energy updated in structure and with the latest available data for this advice) converts a range of financial and non-financial factors that play into consumer and business choices into a utility value. For each group of consumers, an overall utility is calculated for each type of vehicle available based on a range of factors, including purchase prices, running costs, and the preferences of different consumer groups, and then these utilities are converted into purchase probabilities (Box 6.1).

- The largest contribution to utility comes from the upfront cost of buying a new vehicle. This includes our assumptions on the price of the vehicle (Box 6.2) as well as that of installing a home/depot charger for vehicle purchasers who have a feasible location for one and all taxes and incentives that drive differences (or have historically) in prices for different vehicle types. For consumers who lease or finance purchases (currently over three-quarters of the market), this cost is split into an upfront payment and an annual lease cost.

- Running costs have a smaller weight in calculating utility. These include costs for fuel, vehicle maintenance, and insurance. For the fuel costs faced by consumers, we use energy retail prices for fuel and electricity costs. For electricity, this is based on CCC modelling (see Chapters 1 and 10), while petrol and diesel prices are based on retail prices from the DfT's transport appraisal guidance.[17] We use long-run variable costs rather than retail prices when calculating the whole-economy cost impact of our pathway.

- The model segments the market for new vehicles into private and business purchasers, and the private car market is then further subdivided into five attitudinal groups. For each group, we calculate an inherent bias (positive or negative) for each powertrain which is added to the overall utility. We calculate these bias values empirically based on actual sales over the period 2020-2023.

  – When we instead tested the use of carbon values to determine 'social-cost-optimal' EV uptake trajectories, we found that these were much faster than our Balanced Pathway – reaching almost 100% by 2026 for cars, because EVs are cost-effective for many purchasers from today on that basis (Figure 6.5).

- The 2025 uptake of EV cars and vans was set to the ZEV mandate target levels of 28% and 16% respectively.[18] From 2026 onwards, EV uptake is driven by the consumer choice model, exceeding the ZEV mandate once price parity has been met. The uptake of electric vehicles in our Balanced Pathway falls within projections from a range of other sources (see Figure 7.1.3 in our Seventh Carbon Budget advice report).[19]

  – We assume that purchase prices for EVs continue to decrease while those for ICEs increase based on observed market data (Figure 6.6). Prices converge to reach parity between 2026-2028 depending on vehicle size, after which point the upfront purchase price of an EV is cheaper than an ICE equivalent (Box 6.2).

  – As a result of the different assumptions described above, EV uptake rates in our modelling vary by vehicle size, private versus business keepership, access to home charging, and consumer attitude segment (Figure 6.7).

- We use two in-house models (one for local public charging and one for public charging along major roads and motorways) to estimate the charging requirements from the EV transition.[20;21] The charging requirement is informed by the electricity demand from EVs, and the outputs are used to estimate the capital costs from installing chargers.

  – These are spatial models that model journeys of different distances between different geographies to estimate required electricity demand and then locate chargers in relevant locations to meet that demand.

  – Charging requirements affect the total cost of delivering the pathway and consumer preference regarding charging availability. We use an initial estimate of the charging requirement based on our Sixth Carbon Budget EV uptake trajectory and then feed the outputs back into our updated consumer choice model to create our updated EV uptake trajectory and cost estimates.

Vehicle uptake rates feed into the CCC Road Transport Model to estimate emissions based on overall vehicle sales, fleet makeup, and pathway vehicle-km. As the proportion of the fleet that is made up of EVs increases, the total fleet emissions decreases.

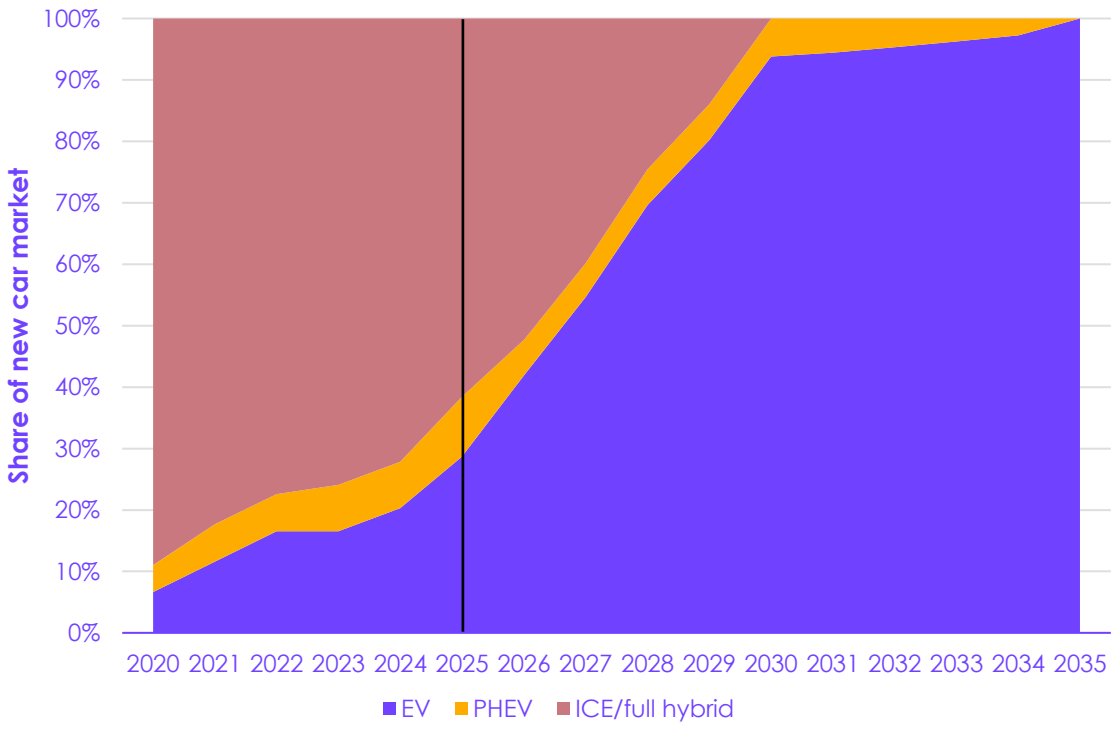
- For Scotland, Wales, and Northern Ireland, EV uptake is adjusted based on current EV sales shares and vehicle age data from DfT. Scotland (10%), Wales (8%), and Northern Ireland (11%) had lower electric car sales shares compared to the UK average in 2023 (16%).[22] This is reflected in slower EV uptake until the date of price parity. After price parity, the difference in new EV sales proportions between each nation and the UK as a whole reduces linearly to 2035.

- We also model sensitivities to assess the impact of slower EV uptake based on lower sales (see Section 6.4).

- We do not model any ICE vehicles being scrapped before the end of their normal lifetime in the Balanced Pathway. However, we have modelled this as a contingency action (see Section 6.5). We also do not directly model the used-vehicle market as this is implied by the aging of vehicles flowing through the fleet, and it is this turnover of the overall fleet which reduces emissions.

  - We expect the upfront cost savings seen in the new market to be passed on to second-hand markets. Preliminary data show that many used EVs are already price-competitive with ICE equivalents.[23]

Figure 6.4 Electric car uptake in the UK Seventh Carbon Budget Balanced Pathway



Description: From 2023 to 2030 the proportion of new car sales that are EVs increases to over 90%. During this time, the proportion of PHEVs remains relatively constant, while ICEs and hybrids decrease. From 2030, new ICEs and hybrids are fully phased out, and only EVs and PHEVs are sold until 2035, at which point 100% of new cars are electric.
Source: CCC analysis.
Notes: The EV uptake rates of the UK, Scotland, Wales, and Northern Ireland, are modelled based on their starting points which takes into account the proportion of new sales that are electric vehicles and the unique vehicle age distribution of each nation.

Box 6.1
Factors considered in our EV uptake consumer choice model

Modelling approach: our EV Uptake Model is a decision model that simulates likely consumer and business behaviour when buying a new vehicle. It assesses purchase probabilities for three choices of powertrain – EV, PHEV (for cars only), and ICE – by converting a range of financial and non-financial costs into utility values across four market segments – small, medium, and large cars, and vans. The overall price elasticities used in the model are calibrated to ensure that modelled sales for 2020-2025 align with actual historical vehicle sales over the period 2020-2023 plus projected sales to meet the ZEV mandate during 2024-2025, based on DfT and SMMT data on new vehicles sold in each segment.[24;25] We calibrate separately for private and business purchasers, reflecting the fact that these groups may have different responses to price signals.

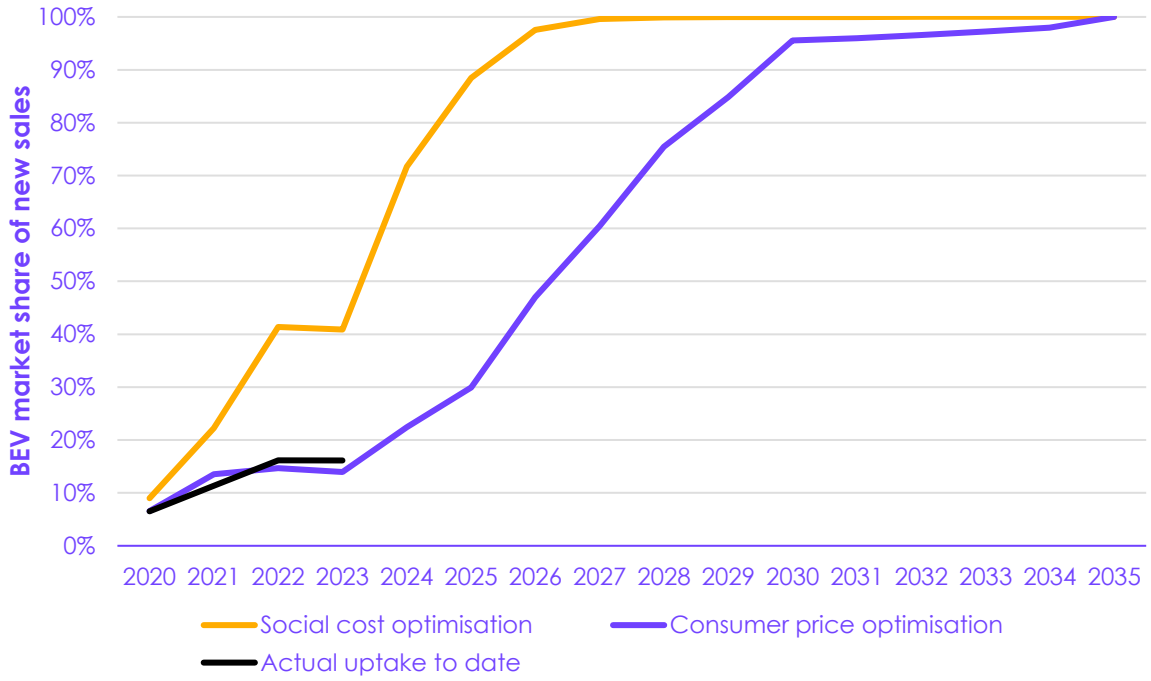
Financial costs: the model considers the price signals seen by consumers and businesses buying vehicles, which is what is relevant in informing their decision-making. Annual costs are discounted using a private discount rate ranging from 10% for enthusiasts to around 50% for sceptics, meaning that upfront costs receive proportionally more weight in the overall utility calculation than the cost that is spread over time.

- **Purchase prices:** the largest contribution to upfront costs comes from our vehicle price assumptions (see Box 6.2). We consider separately lease/finance purchases and those entirely paid upfront.
- **Taxes and incentives:** we include all taxes and incentives that apply, including preferential benefit in kind taxation rates that have an effect in boosting EV uptake among company car drivers. These are included in line with current plans, which have rates for ICE vehicles of up to 37% depending on test-cycle emissions and lower rates starting at 2% and rising by one percentage point per year for BEVs.[26] Vehicle excise duty and the expensive car supplement are also included, including the changes implemented in April 2025.
- **Running costs:** the cost of charging an EV is generally considerably lower than that of fuelling a petrol or diesel car (assuming the same distance driven), due to the greater efficiency of EVs.
  - We assume higher costs for public charging than home charging, and still higher costs for rapid charging along major roads. These are based on current charging prices (see Figure 4.7 in our Progress in reducing emissions – 2023 report to Parliament) extrapolated forward. This means that the savings from running an EV are lower for those without the ability to install a home charger.
  - In addition, EVs are expected to incur lower maintenance costs, due to the fact that they have fewer moving parts. We assume an annual saving of around one-third compared to the maintenance costs for a typical ICE. This is supported by evidence from vehicle servicing bookings. We also assume a small premium (around 1%) for the cost of insuring an EV compared to ICE. Insurance costs are assumed to be higher for larger vehicles.

Non-financial costs: people's perceptions around access to charging and the supply of vehicles are also considered within the modelling.

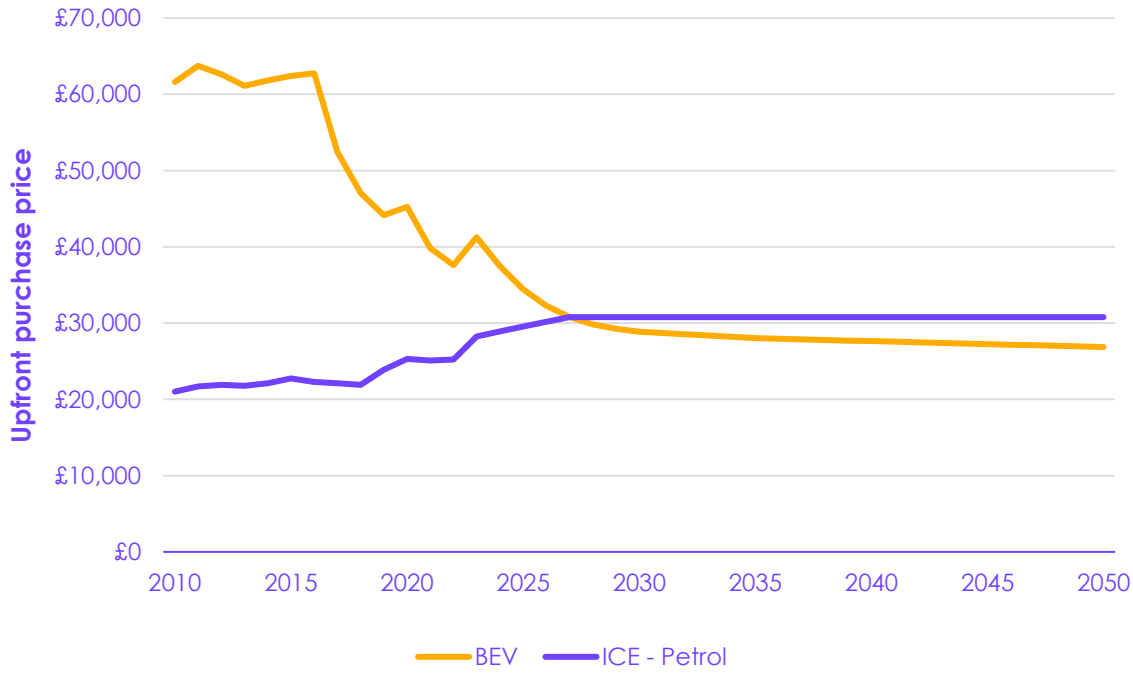
- **Charging:** around 30% of homes have no access to off-street parking.[27] We assume that the share of households able to install a home charger is higher for large cars and lower for small cars. Around two-thirds of vans are also assumed to install a depot (or home) charger. Purchasers without a private charger are assumed to face higher charging costs (see above) and incur a hassle disutility. We assume that the public charging network grows sufficiently fast so as not to pose a further barrier.
- **Vehicle supply:** where there are fewer models of a particular powertrain available than for rival powertrains, a disutility is applied to reflect supply and choice limitations. This is currently the case for EVs, but that market is growing and we assume that the number of models available increases in line with the ZEV mandate. We assume that ICEs are phased out of new sales from 2030 and PHEVs are phased out of new sales from 2035. Therefore, no supply is available and the disutility is infinite.
- **Consumer attitudes:** we divide private car buyers into five attitudinal groups using reported attitudes towards EVs from EY's Mobility Consumer Index - enthusiast, considerer, persuadable, reluctant, and sceptic.[28] For each, we determine an inherent bias (positive or negative) for each powertrain by calibrating the model to match the estimated share of sales within each group (based on actual sales data and relative responses to questions about actual vehicle ownership and purchase intentions in the EY research) between 2020 and 2023. For car purchasers, these bias values are assumed to persist until EVs exceed 50% of all new car sales, after which point negative values decline linearly to zero by the time 100% of sales are EVs or PHEVs, to reflect shifting societal attitudes. For the sceptic group, we assume that this decline never occurs. For PHEVs and vans, we assume a reduction in biases at half the rate for cars.
- **Business purchases:** business purchasers are divided into fleet vehicles and company cars used by employees. The incentives available to, and driving behaviours of each, differ according to available data. Again, bias values for each group are calibrated to past sales data.

Figure 6.5 EV uptake optimisation options for cars



Description: Electric vehicle (EV) uptake would be much faster than our Balanced Pathway on a social-cost-optimal basis.
Source: CCC analysis.
Notes: (1) The consumer price optimisation is the uptake trajectory used in our Balanced Pathway. It is determined based on the prices and conditions facing consumers at the point of purchase. (2) The social cost optimisation is determined by comparing the cost of deploying the measure compared to the Government's carbon values in a given year. (3) The social optimisation doesn't increase in 2023 due to increases in upfront prices across all vehicle types in that year.

Figure 6.6 Upfront purchase price of electric and petrol cars



Description: This chart shows the upfront purchase price of a new medium electric (BEV) and petrol car. These cost assumptions are the same across the Balanced Pathway and the baseline.
Source: CCC analysis.
Notes: Values up to 2023 are based on historical data. Values from 2024 onwards are our pathway projections, based on past trends.

Box 6.2
ICE and EV price parity assumptions

Our ICE and EV purchase price assumptions (Figure 6.6) are based on observed trends in historical market data in combination with a literature review of projected EV and battery costs.

ICE price projections

- We base our starting point for ICE costs on segmented price data from LeaseFetcher for 2023 and time series data from 2013-2023 from NimbleFins.[29;30] The trend in increasing price of ICEs is extrapolated using a logistic function to plot an S-curve through the historical observed ICE price data until price parity with EVs. After that point, we assume no further increase in ICE prices.

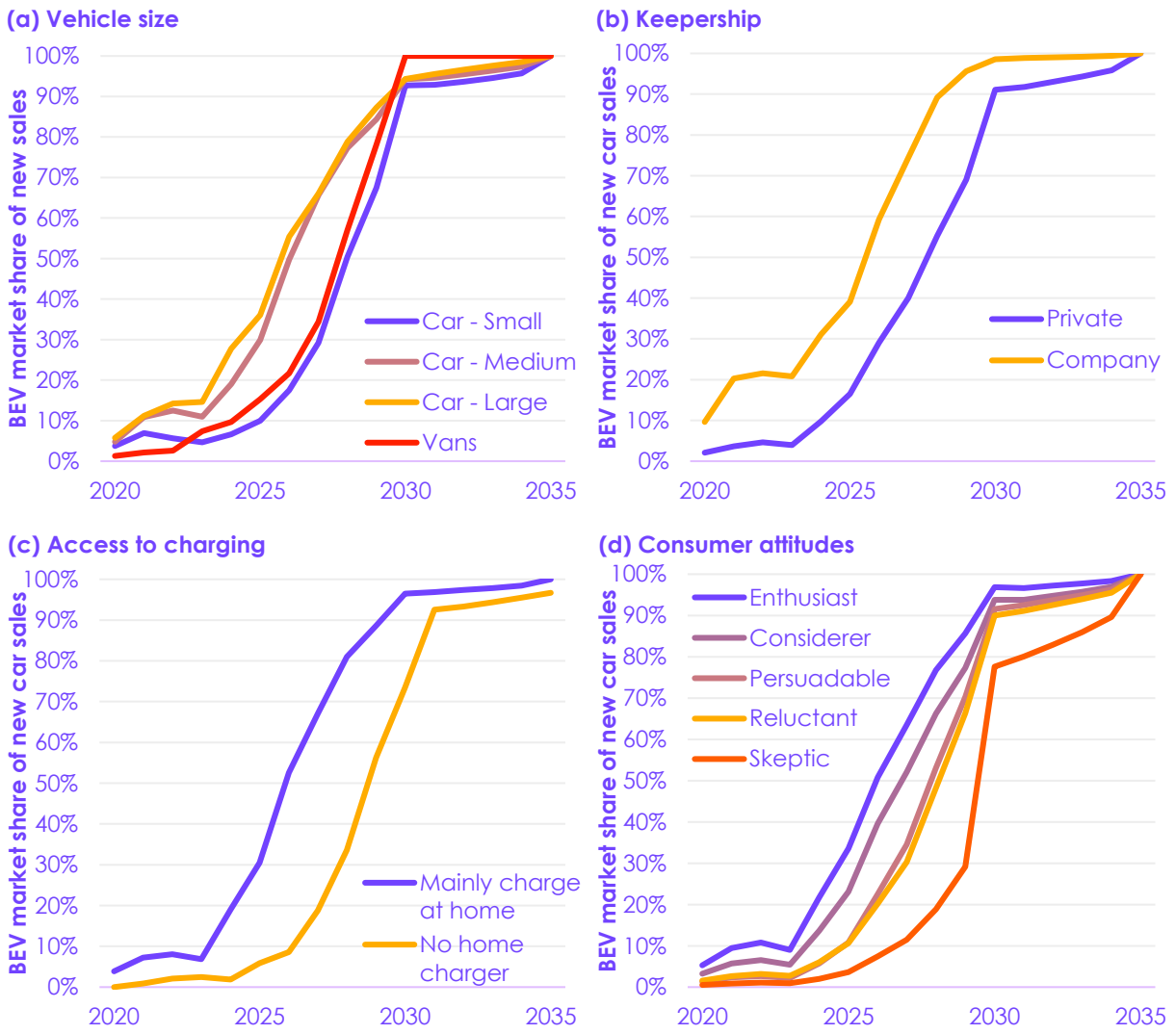
EV price projections

- **Observed trends:** our starting point for EV prices is based on historical UK new vehicle market data:
  - Prices for a typical EV from 2020 to 2023 are uplifted from average ICE prices in those years by the EV price surplus reported for new vehicles by Autotrader.[31] We disaggregated these prices across vehicle segments using the prices for representative example vehicles in each segment as listed on EV-database and compared these to the ICE prices calculated above to determine how this uplift can be expected to differ across different car sizes.[32]
  - To develop a time series further back than 2020, we then applied the trend seen in historic Nissan Leaf price data to the 2020 estimated prices by segment.
- **Price parity:** we then consider the date of price parity between an ICE and an equivalent EV:
  - We assume that this will be in 2026 for large, 2027 for medium, and 2028 for small cars. This is based on Bloomberg New Energy Finance's (BNEF) 2023 EV Outlook scenario for the European car market assuming a 16% learning rate in global battery prices.[33] We assume electric vans reach price parity with diesel equivalents in 2026 – aligned to large cars.[34]
  - BNEF's price parity assumptions are based on analysis of the underlying cost components of equivalent EVs and ICE cars, with an assumed profit margin added. They then assess future cost reductions of EVs based on observed learning rates of global average lithium-ion battery pack prices.
  - At the respective dates of price parity, we model that a small electric car will cost approximately £24,400, £30,800 for a medium car, £47,700 for a large car, and £41,700 for a van. We recognise the inherent uncertainty in price projections and consider the impact of price parity being delayed as part of our sensitivity tests (see Section 6.4).
- **Modelling price reductions to reach price parity**: we then model a learning curve:
  - We fitted a logistic function, which is typically used to model learning curves. This passes through the latest historical EV prices and the modelled ICE price for the year in which price parity is assumed to be reached for the given vehicle size segment. This is used to determine our assumed EV prices for the years from 2024 to 2030. See Section 1.7.3 for further discussion of learning curves.
- **Further EV cost reductions beyond 2030** are driven by projected reductions in battery prices:
  - We assume a 3% year-on-year reduction from 2030 to 2035 which is applied to 20% of the total manufacturing cost in line with the International Council on Clean Transport's (ICCT) modelling of the cost breakdown for a medium car with 250 miles of range.[35] We assume this cost reduction is translated to reduced purchase price.
  - There is some uncertainty regarding long-term decreases in battery costs (see Section 6.4). We model cost reductions from 2035 to 2050 by taking the mid-point between the highest cost saving seen in the literature, which is a 43% decrease between 2035 and 2050, and a scenario in which there are no further savings.[36] We assume no change to battery sizes in respective EV segments out to 2050.

PHEV price projections

- We used Office for National Statistics (ONS) data to infer that the price surplus for PHEVs compared to equivalent ICEs was around 24% of that for EVs compared to equivalent ICEs in 2021. We then modelled PHEV prices as evolving based on a weighted average between the EV and ICE prices described above.

Figure 6.7 Differences in modelled EV uptake rates



Description: Our modelling produces different electric vehicle (EV) uptake rates for different segments of the market. Uptake is faster for larger cars than for smaller ones and vans, for vehicles purchased by businesses than private purchases, among drivers who can mainly charge at home, and among more enthusiastic consumer groups.
Source: CCC analysis.
Notes: (1) Historical data on these charts is based on actual sales data by vehicle size, keepership (that is, whether the vehicle is owned by a private consumer or is part of a company fleet), and powertrain. (2) Modelled uptake is slower to ramp up among smaller cars and vans due to the fact that EV sales to date among these segments have been lower. (3) Divisions by charging access and consumer attitudes have been estimated based on outputs from our modelling and reported purchase intention data.

Box 6.3
Embodied and lifecycle emissions of vehicles

During operation, ICE vehicles generate greenhouse gas emissions directly at the tailpipe by burning fuel while EVs generate emissions indirectly via the electricity used to charge them, if this is not zero-carbon. Both ICE vehicles and EVs also generate emissions indirectly during their production – referred to as 'embodied emissions'. 'Lifecycle emissions' includes emissions from both a vehicles production and operation throughout its life.

Where these emissions are generated in the UK, they are included in our Balanced Pathway in the relevant sector (e.g. tailpipe emissions in surface transport, electricity generation emissions in electricity supply, and manufacturing emissions in industry). For vehicles imported to the UK from overseas, the 'embodied' emissions from their production are not accounted for in our Balanced Pathway, because the Climate Change Act (2008) requires carbon budgets to be set based on territorial emissions only.

However, in considering their suitability as a measure to reduce emissions in our pathway, we have reviewed evidence associated with the lifecycle emissions footprint of EVs.

Implications of the shift to EVs on vehicle lifecycle emissions

Embodied emissions depend on technology type and production location. Batteries are currently more emissions-intensive to produce than internal combustion engines, while production which uses electricity in China is more emissions-intensive than production using electricity in the UK or EU.

- More than 90% of cars registered in the UK in the first half of 2023 were manufactured abroad. In 2022, over 70% of imported cars came from the EU, 9% from China and 6% from South Korea.[37]

Research suggests that while EVs typically carry an embodied emissions premium relative to ICE vehicles, this is significantly outweighed on a lifecycle basis due to the emissions savings during operation.[38] This is the case today, even for EVs produced in countries with relatively high emissions intensity of electricity (such as China).

- For example, an average medium-sized EV built in China in 2021 has lifecycle emissions approximately one-third below that of an equivalent petrol vehicle in Europe.[39] This holds even when accounting for China's higher emissions intensity of electricity in 2021.

In practice, many of the EVs purchased in the UK will have lower embodied emissions than this example, while the operational emissions from charging an EV in the UK will continue to decrease as we decarbonise the electricity system.

6.2.3 Zero-emission HGV and bus deployment

The CCC commissioned ERM to model ZEV uptake for heavy-duty vehicles (HDVs).[*];[40] This modelling considers several zero-emission HGV and bus technologies that are currently in different stages of development and deployment. Technology choice is determined by an assessment of the Total Cost of Ownership (TCO) as well technical feasibility in different use cases and infrastructure availability.

- The modelling approach used to determine our HDV uptake trajectories is based on the approach taken by Element Energy for the Sixth Carbon Budget advice, updated to capture recent developments in zero-emission HDV technologies.[41];[42]

- Options considered to replace primarily diesel HDVs include battery-electric, hydrogen fuel cell, catenary/pantograph technology, and electrified under-road systems that allow for wireless charging via infrastructure beneath the tarmac.

[*] HDVs comprise heavy goods vehicles (HGVs) as well as coaches and buses.

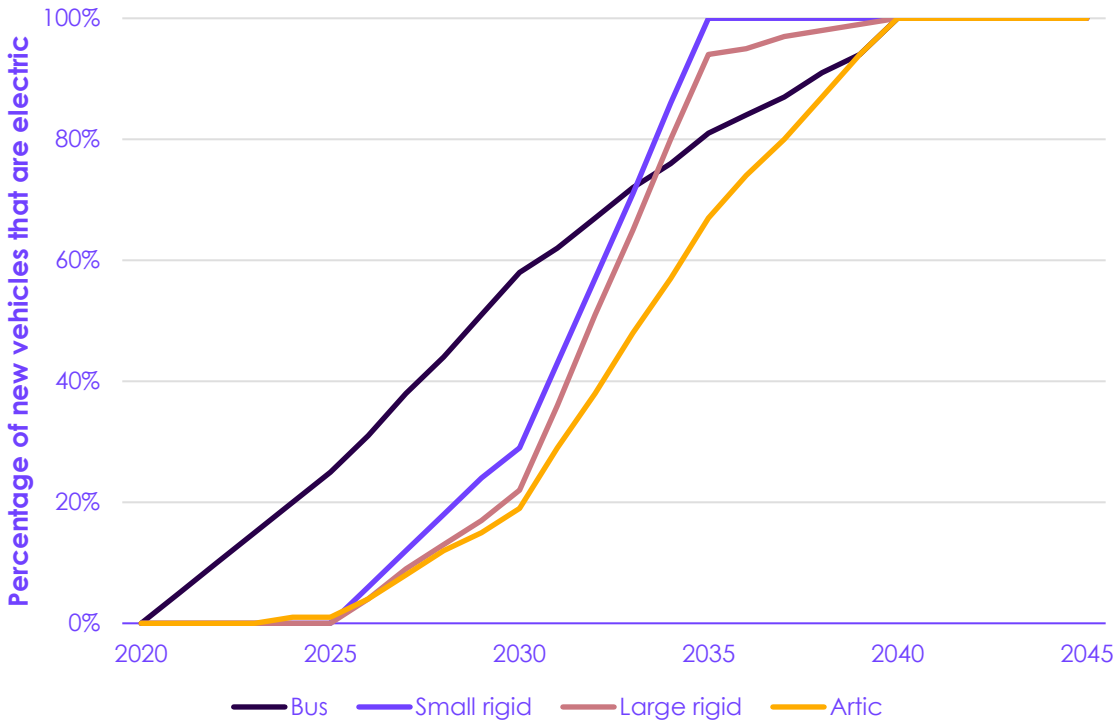
- The uptake trajectory is determined based on an assessment of the technical capability and 'Total Cost of Ownership' (TCO) of different ZEV technologies – including the upfront, fuelling and maintenance costs.
  - The model assesses vehicle technical capability, infrastructure availability and TCO within five-year periods out to 2050. Once the volume of zero-emission models capable of meeting operational requirements has been calculated, the model then assesses the relative TCO of the different technology options, with the cheapest zero-emission models purchased first. Any new vehicle demand that cannot be met by a capable and cost-effective ZEV is made up by diesel vehicles.
  - ZEV HGVs do not reach upfront price parity with ICEs at any point in our pathway, however, operational costs for electric HGVs are lower than ICEs throughout the pathway due to the greater efficiency of their electric drivetrains and lower maintenance costs. The model applies discounts to the cheapest zero-emission models to drive TCO cost effectiveness in earlier years, and these are phased out by 2040. By this point, the (large) proportion of the fleet for which ZEVs are deemed technically capable reaches 100% ZEV sales so that most diesels are replaced by 2050.
    - The capital costs of different technology options are based on ERM research. Battery-electric HDV costs are based on cost projections of battery technologies, which make up a significant proportion of the total vehicle costs. Bloomberg New Energy Finance (BNEF) battery price data suggests battery prices for HDVs are typically around five years behind batteries for cars and vans.[43]
- Due to significantly lower capital costs of lithium-batteries compared to fuel-cell technologies, the model selected EVs as the dominant zero-emission technology. However, we acknowledge uncertainty around the exact makeup of the fleet.
  - The model chose a cost-effective zero-emission HGV fleet split that was almost entirely battery electric with less than 1% of zero-emission HGVs being hydrogen in the 2030s, falling to 0% by 2040. It was decided that such a small proportion of hydrogen uptake was likely not cost-optimal when considering associated refuelling and infrastructure costs, and the importance of alignment with the EU where battery-electric technologies have made more progress than hydrogen.[44;45;46]
  - Impacts on operators and payloads have not been modelled but we recognise that for the largest, heaviest vehicles, maximum cargo weights may need to be decreased or there may need to be an increase in the number of journeys to transport the same freight where possible. This should not affect the majority of HGVs, including those in the small-rigid class. For larger, heavier vehicles, cargo impacts could be minimised by increasing maximum weight allowances on certain routes. In a small number of cases this may present additional costs which we have not modelled.
- The market for ZEV buses is more advanced than for HGVs due to proactive action from many local authorities and aims to reduce air pollution in urban areas. The starting point of ZEV uptake is therefore higher for buses than for HGVs and continues to be up to 2033.
  - The proportion of diesel bus sales is higher than for HGVs in the mid to late 2030s due to challenges associated with the transition for coaches which include long-distances and less predictable routes.
- The costs of depot and ultra-rapid charging infrastructure is modelled separately, based on analysis undertaken by Ricardo for the CCC for our advice on the Sixth Carbon Budget. We have uprated these costs based our Seventh Carbon Budget HGV energy demands and inflation. We have also added the cost of electricity grid connections for depot and ultra-rapid chargers.

Zero-emission HDV sales are input into the CCC Road Transport Model which models the impact of these on the makeup of the fleet. Combined with assumptions on the distances driven by vehicles based on their different types and ages, this then estimates the emissions associated with these vehicle fleets.

- Zero-emission HGV uptake values are shown in Figure 6.8. We assume electric HGV and bus uptake in Scotland, Wales, and Northern Ireland is the same as UK-wide. The proportion of the fleet that was battery electric at the end of 2023 was 0.2% for England, 0.1% for Scotland, 0.1% for Wales, and 0.01% for Northern Ireland.[47]

- We do not assume any early scrappage in the Balanced Pathway and as a result some ICE HDVs remain in the fleet in 2050.

Figure 6.8 Zero-emission heavy duty vehicle uptake



Description: The market for zero-emission HGVs begins to increase during the rest of this decade, before growing rapidly during the 2030s in our pathway.
Source: ERM (2025) *ZEV HDV uptake trajectories*.

6.2.4 Demand-side measures for passenger transport

In our Balanced Pathway, we assume improvements to make public transport and active travel more attractive, affordable, and accessible allow 7% of car-km to be switched to these modes by 2035, compared to the baseline.

- The role of modal shift away from cars is primarily focused on what can be achieved before 2035 when new sales of non-zero-emission cars are fully phased out – after which point the emissions benefits from reducing car travel diminish due to an increasing number of EVs on UK roads.

- We also consider a potential 'rebound effect' which captures an expected increase in car-km resulting from the lower cost of driving electric vehicles compared to ICE vehicles.

To inform our expectations of modal shift we conducted a meta-analysis based on evidence of the observed impact of modal shift interventions in several towns in the UK (including London, Bristol, and York) and comparable countries (e.g. Netherlands, Germany).[48;49;50;51;52;53;54;55;56;57;58;59]

- We assume increases in modal share (in terms of passenger-km) for bus, rail, walking, and cycling based on what has been observed in the literature across different geography types (urban conurbation; urban city and town; rural town and fringe; and rural village, hamlet and isolated dwelling).

- The evidence reviewed largely focussed on interventions to improve bus travel and walking and cycling. We do not expect any significant modal shift to rail before 2035 due to the timescales involved in delivering major rail improvements.

- By identifying the minimum and maximum modal shifts reported in successful case studies, we select the midpoint as our Balanced Pathway assumption. These modal share increases are projected across UK geographies by 2035, with greater changes assumed for more urban geographies and smaller for more rural ones. The total increase in bus, rail, walking, and cycling passenger-km is translated to an equivalent reduction in car passenger-km. Table 6.2 shows the current and 2035 car modal share for the different geography types and Table 6.3 shows the reduction in car-km in 2035 compared to the baseline for the UK and each nation.

  - We use pre-pandemic 2019 data for England as a starting point to determine the mode share in terms of passenger-km by different geography types to avoid COVID-19 effects.[60]

  - We estimate mode-share for Scotland, Wales, and Northern Ireland by applying England's mode-share data for each geography type to the specific geography type distributions of these nations. This also gives us the mode-share by passenger-km for the UK.

  - We apply the reduction in car-km in our Road Transport Model before modelling EV uptake and any potential rebound effect.

  - For our contingency option which goes further in modal shift, we applied the same method but used the maximum, rather than average, mode-share for public transport and active travel achieved in the literature (See Section 6.5).

Table 6.2
Car modal share by geography type based on annual passenger-km

Geography type	Current – 2019	Balanced Pathway – 2035	Contingency – 2035
Urban conurbation	67%	60%	57%
Urban city and town	79%	72%	69%
Rural town and village	86%	81%	79%
Rural village, hamlet, and isolated dwelling	87%	85%	83%

Source: Department for Transport (2019) *National Travel Survey: 2019;* CCC analysis.
Notes: Mode share analysis across geographic regions used 2019 data as a proxy for current travel patterns, as this was the latest data unaffected by COVID-19 disruptions.

Table 6.3
Modal shift away from car-km by 2035 in each nation compared to the baseline

Nation	Balanced Pathway – 2035	Contingency – 2035
United Kingdom	7%	9%
England	7%	10%
Scotland	6%	8%
Wales	7%	9%
Northern Ireland	5%	7%

Source: CCC analysis.
Notes: The higher level of modal shift in England and Wales reflects the higher proportion of urban traffic share compared to Northern Ireland and Scotland.

- We did not consider measures related to increased working from home or higher car occupancy in our pathway, as there is limited evidence that these present meaningful opportunities for further emissions reduction.
  - **Working from home**. These behaviours have already been embedded since the pandemic, leading to a sustained reduction in car-km compared to pre-pandemic levels and reducing emissions in our baseline compared to our Sixth Carbon Budget advice. It is not clear, however, what extent of further home working would be feasible and whether this would be desirable from an emissions perspective, as it can result in higher emissions from buildings (from heating homes) and higher emissions from freight (from more home deliveries).
  - **Car occupancy**. While there are some policy levers to drive this change, they are limited and may not be widely applicable to the UK context (e.g. car pool lanes). There is also no strong evidence of interventions that have led to increases in car occupancy much beyond the levels seen in the UK.
- After considering the potential for demand reduction from modal shift, we model a rebound in electric car-km due to the cheaper relative cost of driving an EV over an ICE. We apply a 19% price elasticity of demand based on research on the rebound effect for personal car travel in Great Britain.[61] The rebound does not impact surface transport emissions, however it does increase the electricity demand from EVs in our analysis and could increase congestion.

6.2.5 Conventional vehicle efficiency and fuel-efficient driving

We have considered the following options to reduce vehicle emissions, including changes to vehicles and driving behaviour.

- **Stabilising vehicle sizes.** We assume an end in the trend towards larger vehicles, with distribution of vehicle sizes staying at today's levels, so that future efficiency improvements deliver emissions reductions.
- **New vehicle emission standards.** We assume a 2% improvement in the efficiencies of new ICE cars and vans each year, identified as achievable in the DfT's consultation on future CO_2 emissions regulations.[62] We also assume that these efficiency improvements will be extended to HGVs and can be achieved through measures such as light-weighting and increasing hybridisation.

- **Compliance with speed limits.** We estimate that better compliance with 70 mph speed limits could reduce fuel consumption from cars, vans, and motorcycles by 2%. This is based on DfT statistics on the levels of speeding, vehicle traffic by road type, and emissions factors at various speeds.[63;64;65]

- **Biofuels.** The current blending of E10 into petrol is maintained throughout the pathway due to the associated emissions savings. Blending of biodiesel, predominantly used in HGVs and vans, progressively increases as Fischer-Tropsch process production capacity expands throughout the 2030s and is allocated under our best use hierarchy. Emission savings from biofuels gradually decrease as the vehicle fleet transitions to electric and total fuel demand decreases, whilst blending remains high.

6.2.6 Demand-side and efficiency measures for freight

Our scenario projects a progressive adoption of operator efficiency measures across the HGV fleet, with approximately 80% implementation across all HGVs by 2030. These measures deliver fuel efficiency improvements ranging from 13% for a small rigid HGV up to 22% for an articulated HGV. This is based on a study by the Centre for Sustainable Road Freight conducted for our advice on the Fifth Carbon Budget.[66]

- **Technological improvements to existing vehicles.** This includes enhancing fuel efficiency through advanced aerodynamic designs (e.g. tear-drop trailers, retrofitted fairings for HGVs), performance-optimising components (e.g. low rolling resistance tyres), and other vehicle modification technologies.

- **Eco-driving**. Eco-driving includes measures such as selective use of gears, utilisation of engine-breaking, use of cruise control, and compliance with speed limits.[67] Driver training in and use of eco-driving is possible in the HGV sector and helps to reduce the carbon intensity per HGV-km.

In total, our demand-side and efficiency assumptions in road freight deliver emissions reductions that are roughly consistent with the annual pace of improvement required during the 2020s by the voluntary industry-supported Government commitment to reduce HGV emissions by 15% by 2025, compared to 2015 levels.[68]

- We have not included any costs associated with these measures, but some may involve moderate costs.

- Emissions savings from optimising logistical operations have not been modelled explicitly although are likely to play an important role in contributing to delivering the required emissions reductions. Improvements to logistics operations include measures such as improved routing, use of consolidation and distribution centres, higher lading factors, a reduction in empty running, and use of computerised technologies. These measures reduce emissions by reducing overall distance driven by HGVs.

- We have not included any modal shift from road to rail for freight demand as zero-emission HGVs are expected to become available across the road haulage sector sooner than it will be possible to remove diesel from rail freight.

6.2.7 Zero-emission rail deployment

Our rail analysis first considers the potential for electrification of the rail network given this solution is already common today. We then consider the potential for other low-emission technologies to supplement track electrification.

- We phase-out diesel trains from the railway by 2040 in line with the previous Government's stated ambition.[69]

- Our analysis is conducted at a UK-wide level and then scaled by the proportion of track-kilometres in Northern Ireland, Scotland, and Wales. No freight rail is assumed in Northern Ireland as no goods are currently transported by rail.

- Our pathway assumes growing demand for passenger and freight rail. This reflects overall growth in demand rather than modal shifts from road or air to rail.

  - In both the baseline and the Balanced Pathway, passenger rail traffic is projected to grow linearly to 46% above today's levels by 2050, based on projections by the Rail Delivery Group.[70;71]

  - In our baseline scenario, total rail freight demand is expected to remain at today's levels, whereas in our Balanced Pathway this is expected to increase by 75% in line with the UK Government's rail freight growth target.[72]

  - In our Balanced Pathway, we assume that emissions from diesel trains decrease by 9 gCO_2e/kWh each year due to improvements in diesel efficiency.[73]

- In the Balanced Pathway we project UK rail network electrification to increase from 39% of route-kilometres today to 55% by 2040 and 66% by 2050, compared to the baseline scenario's 46% and 51%, respectively. [*];[74];[75]

  - This target aligns with the Railway Industry Association's assessment that one third of Great Britain's network does not need to be electrified and can be decarbonised with battery trains.[76] We have extended this approach to the entire UK rail network, with adjustments made for Northern Ireland based on its current proportion of track-kilometres.

- We assume a combination of battery-electric, hydrogen, and diesel-electric technologies across routes that cover the remaining 34% of the rail network which is not electrified.

  - By 2040, diesel passenger and freight train operations will be phased out. Most diesel passenger trains are replaced at end-of-life, with some requiring early retirement between 2030-2040. For freight, 55 diesel trains are replaced annually until 2040.

  - In 2040, most new passenger trains are electric (92%) or battery-electric (6%), with smaller roles for diesel-electric and hydrogen. In the same year, 56% of new freight trains are diesel-electric and the rest are purely electric. See Table 6.4 for the distribution of train stock by drivetrain technology.

- The distribution of these trains between powertrain options is based on an assessment undertaken for our Sixth Carbon Budget advice of the speed and distance requirements of rail operations on each track section that is assumed to not be fully electrified by 2050.

  - For passenger rail, battery-electric options are preferred on arcs that are partially electrified with distance off the electrified segments shorter than the assumed 60-mile battery range, while hydrogen is preferred on arcs that are completely non-electrified. Diesel-electric is the option of last resort in our modelling, where other options are not suitable.

  - The high energy requirements of freight trains mean that hydrogen and battery-electric 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.

[*] We have applied the increase in proportion of route-kilometres to be electrified to total track-kilometres as a proxy to calculate track electrification costs.

Table 6.4
Train stock by drivetrain technology

Drivetrain technology	Passenger rail		Freight rail	
	Current – 2024	Balanced Pathway – 2040	Current – 2024	Balanced Pathway - 2040
Diesel	22%	0%	87%	0%
Electric	71%	84%	10%	26%
Hydrogen	0%	1%	N/A	N/A
Battery-electric	0%	6%	N/A	N/A
Diesel-electric	7%	8%	3%	74%

Source: Office of Rail and Road (2024) *Rail infrastructure and assets;* National Infrastructure Commission (2019) *Better Delivery: The Challenge for Freight*; CCC analysis.
Notes: (1) Numbers may not sum to 100% due to rounding. (2) 'Locomotive hauled' trains are included in the diesel drivetrain technology category. (3) The period for current passenger rail drivetrain technology split is April 2023 to March 2024. (4) 2019 data is used as a proxy for the current drivetrain technology split for freight trains.

- Our cost assumptions for rail are based on a range of external evidence:
  - Train capital costs were sourced from the Rail Safety and Standards Board and updated for inflation.[77]
  - Maintenance costs are calculated from the acquisition cost based on the assumption that capital and maintenance costs are 31% and 44% of a train's lifetime costs, respectively.[78]
  - An electrification cost of £2.5 million per single track kilometres is sourced from the Railway Industry Association and has been updated for inflation as well as applying a 44% optimism bias as recommended as the upper bound for capital expenditure on Standard Civil Engineering projects.[*;79;80]
  - Hydrogen infrastructure costs assume a cost of £3.9 million per 800 kg/day capacity, adjusted for inflation, and a hydrogen energy density of 33 kWh/kg.[†;81;82]
  - Fuel prices are sourced from our central energy cost analysis (see Chapter 1).

6.3 Changes since our Sixth Carbon Budget advice

6.3.1 Comparison with our Sixth Carbon Budget pathway

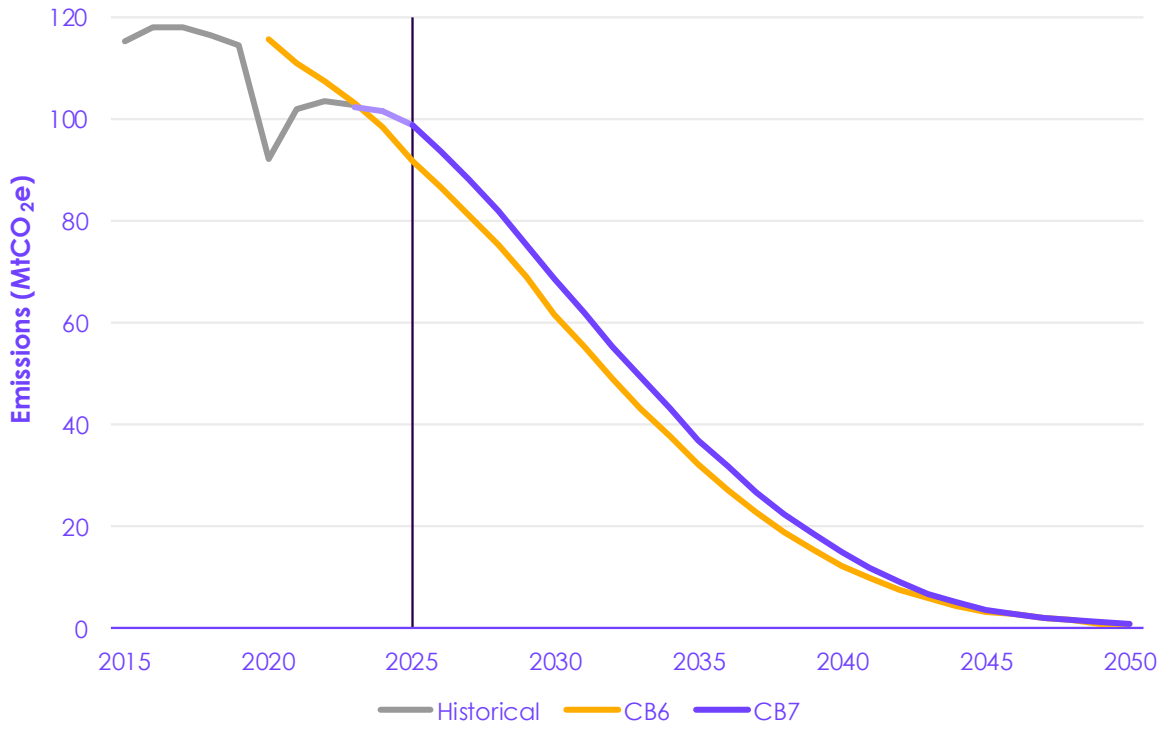
The latest historical emissions data is on track compared to the Balanced Net Zero Pathway in our Sixth Carbon Budget advice, in large part due to an embedded reduction in demand since the

[*] £1.5 million per single track kilometre has been adjusted for inflation from 2019 to 2023.

[†] Hydrogen infrastructure costs of £3.4 million have been adjusted for inflation from 2019 to 2023.

pandemic.* However, the year-to-year trend is falling less quickly than projected, due to new EV sales growing slightly slower than in our previous analysis and the car market having been smaller since the pandemic, with people keeping older cars for longer. Our Seventh Carbon Budget emissions pathway therefore begins slightly higher than the Sixth Carbon Budget pathway, although this gap closes gradually over time (Figure 6.9).

Figure 6.9 The Balanced Pathway for surface transport compared to our Sixth Carbon Budget advice



Description: Our Seventh Carbon Budget (CB7) Balanced Pathway for surface transport starts slightly higher than the Balanced Net Zero Pathway presented in our Sixth Carbon Budget (CB6) advice but follows a similar pace of decarbonisation.
Source: DESNZ (2024) *Provisional UK greenhouse gas emissions national statistics* 2023; CCC analysis.
Notes: The Sixth Carbon Budget advice pathway is shown as published in our 2020 advice. These have not been adjusted to account for changes in emissions accounting since that publication.

6.3.2 Emissions changes since our Sixth Carbon Budget advice

A structural reduction in car-kms mean emissions are lower today than we estimated in 2020, when we advised on the Sixth Carbon Budget. Although the most recent data for electric car uptake is promising, both electric car and van uptake are behind the Sixth Carbon Budget pathway.

- Total car-km decreased by 25% from 2019 to 2020 due to the pandemic.[83] They stabilised in 2023 to a level 4% lower than pre-pandemic levels (Figure 7.1.4e in our Seventh Carbon Budget advice report shows per capita car-km were 7% lower than pre-pandemic levels).† This car-km for 2023 figure, which is uplifted for Northern Ireland and used as the starting

* All comparisons in this section compare the Balanced Pathway in this advice with the Balanced Net Zero Pathway in our Sixth Carbon Budget. Our Sixth Carbon Budget advice also included four other exploratory pathways, which are not discussed here. Data for those pathways can be found in our Sixth Carbon Budget advice.

† This represents a change from the CCC's 2024 Progress Report to Parliament, which indicated that total car-km were 6% below pre-pandemic levels in 2023. The difference arises because the 2024 Progress Report used provisional data for Q1-Q3 2023 and uplifted figures for Q4 whereas we used final 2023 data in our Seventh Carbon Budget Balanced Pathway. The difference between the change in total and per capita car-km between 2019-2023 is due to a 2% population increase.

point for our updated Balanced Pathway, is 4% lower than what was assumed in the Balanced Pathway of our Sixth Carbon Budget advice.

- The new car market was smaller than expected in 2020-2022 due to supply chain disruptions caused by the pandemic (particularly for semiconductors) and the impact of an increased cost of living.[84] These factors mean that, although at points the EV market share was greater than assumed in our Sixth Carbon Budget advice, the total market volume for 2020-2022 was smaller than assumed. Therefore, the pace of turnover from ICEs to EVs has been slightly slower than modelled in our Sixth Carbon Budget pathway due people keeping older cars for longer.

- There was a slowdown in the turnover of EVs into the fleet due to a smaller EV market share in 2023-2024 compared to what we assumed in our advice on the Sixth Carbon Budget, however the latest data show that EV sales volumes are growing.[85]

6.3.3 Key pathway differences compared to our Sixth Carbon Budget advice

There are several key areas in which the deployment rates, measures included, or underlying assumptions in our updated Balanced Pathway have been revised since publication of our Sixth Carbon Budget advice in 2020. These include:

- **Electric cars.** The market share of electric cars is slightly lower than in our Sixth Carbon Budget pathway. This is primarily due to the starting point being lower than we had previously assumed, although sales accelerate quickly and almost catch up by 2030. This is driven by our assumed price parity between 2026 and 2028, which is earlier than the 2030 price parity date assumed in our Sixth Carbon Budget modelling (Figure 6.10a).

- **Electric vans.** Our updated trajectory for electric van sales is considerably lower than assumed in our Sixth Carbon Budget advice, as the electric van market has been slower to scale up than the electric car market. But again, sales grow quickly, with price parity assumed to take place earlier than assumed in our Sixth Carbon Budget advice (Figure 6.10b).

- **Zero-emission HGVs.** Sales are similar to those in our Sixth Carbon Budget pathway from 2030, although there is more of an early market in the 2020s than in our previous assessment. This reflects the commitments being made by some large fleets in recent years (Figure 6.10c).

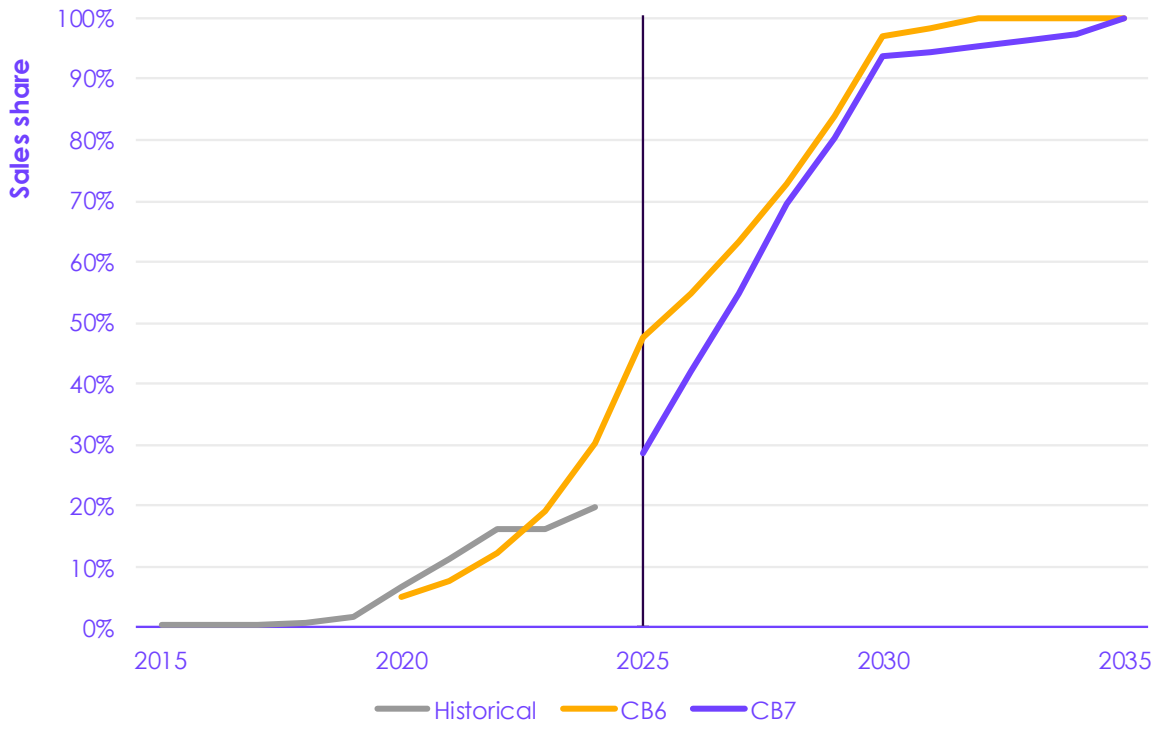
  - Hydrogen no longer has a significant role in our pathway for road transport. In our Sixth Carbon Budget advice, we anticipated that hydrogen fuel cell vehicles could play a substantive role in the HGV technology mix. However, in the last five years battery prices have fallen at significantly faster rates than hydrogen fuel cell prices and as a result are the most cost-effective option. Hydrogen HGVs were not selected by the model at sufficient levels to play a role in our pathway, but we note there is still some uncertainty regarding the exact make-up of technologies in the fleet that will meet requirements for specific long-distance journeys or for particularly heavy cargoes.[86]

- **Modal shift and demand reduction.** In our Sixth Carbon Budget advice Balanced Pathway, we assumed an 8% reduction in total car-km by 2035 compared to the baseline due to societal and behavioural change, and technology, progressing to a 12% reduction by 2050. Many of these changes are now embedded in our baseline.

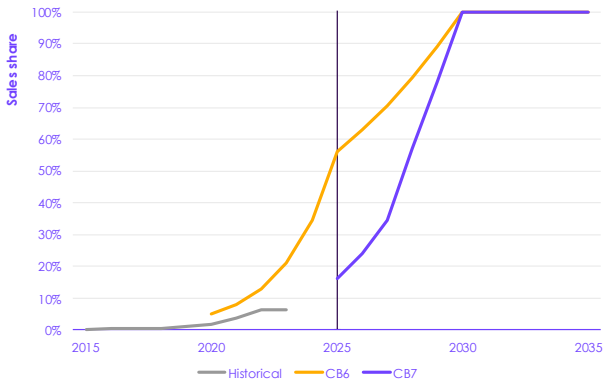
  - We do not include further home working as an additional measure to reduce travel in our Balanced Pathway and instead focus on modal shift to reduce car-km against the baseline. Our assumed level of modal shift is slightly lower than in our Sixth Carbon Budget pathway but is more clearly linked to evidence of shifts that have actually been delivered elsewhere.

Figure 6.10 Key differences in deployment trajectories in the Balanced Pathway for surface transport compared to our Sixth Carbon Budget advice

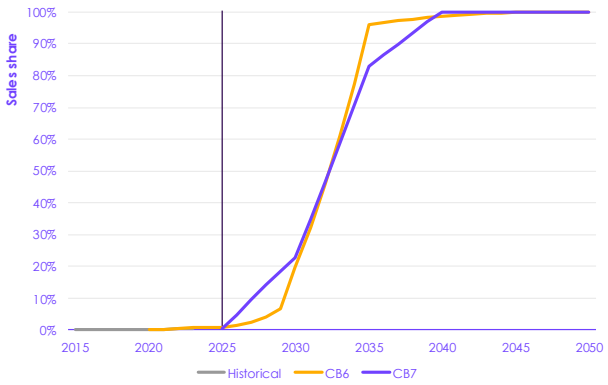
(a) Electric car share of new car sales



(b) Electric van share of new van sales



(c) Zero-emission HGV share of new HGV sales



Description: The key differences in the rate of deployment of electric cars, vans and HGVs in our Seventh Carbon Budget (CB7) pathway compared to our Sixth Carbon Budget (CB6) pathway are that the new market share of electric cars is slightly lower and for electric vans is considerably lower, whilst HGV sales are similar to CB6 from 2030, although there is a stronger early market in the 2020s.
Source: DfT (2024) *Vehicle licensing statistics;* CCC analysis.
Notes: The car and van charts are shown only to 2035, as from this point all new car and van sales are assumed to be electric vehicles in both our Balanced Pathway and our Sixth Carbon Budget pathway. The HGV chart is shown out to 2050.

6.4 Uncertainties and sensitivity analysis

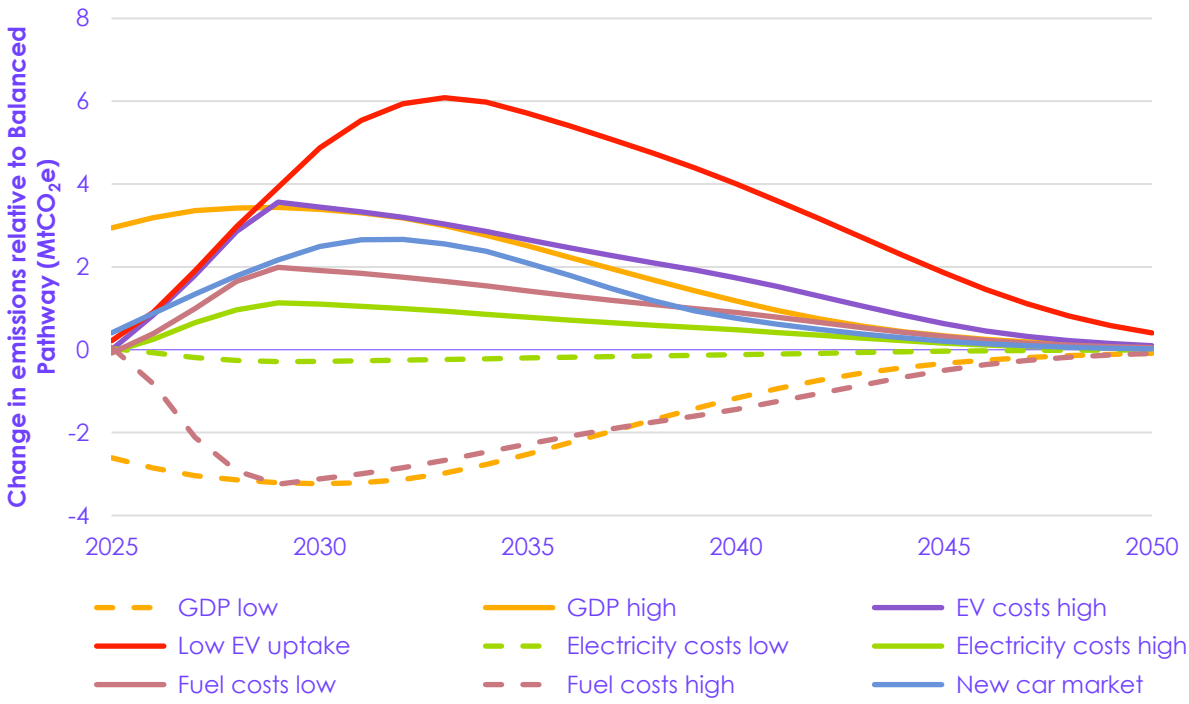
There are inevitably uncertainties around how the drivers of our pathway will develop over the next 25 years. We have undertaken sensitivity tests to explore the effect of some of the main uncertainties which influence emissions and costs associated with our pathway, namely: new car

market size, EV upfront costs, fossil fuel and electricity costs, GDP, and the rebound effect. The approach to and results of each of these sensitivity tests are described in this section, including Table 6.5 and Figure 6.11. See Chapter 5 for our general approach to uncertainty, including descriptions of the methodology behind sensitivity tests that apply across multiple sectors.

Table 6.5
Key sensitivity tests for surface transport

Sensitivity test	Description	Impact on emissions in 2040		
		$MtCO_2e$	% of sector emissions	% of total emissions
Low EV uptake	Assume EV sales only meet minimum ZEV mandate requirements	+4.0	+27%	+4%
New car market	Assume car market grows in line with GDP rather than returning to pre-pandemic levels	+0.8	+5%	+1%
EV costs	Assumed later price parity between upfront EV and ICE costs between 2029 and 2031, rather than 2026 and 2028	+1.7	+12%	+2%
	Assumed battery costs decline more rapidly after 2035	0	0%	0%
Fossil fuel costs	Assumed higher petrol and diesel costs	-1.4	-10%	-1%
	Assumed lower petrol and diesel costs	+0.9	+6%	+1%
Electricity costs	Assumed higher electricity costs	+0.5	+3%	+0%
	Assumed lower electricity costs	-0.1	-1%	-0%
GDP	Assume increased vehicle-kilometres due to higher GDP	+1.2	+8%	+1%
	Assume reduced vehicle-kilometres due to lower GDP	-1.2	-8%	-1%
EV rebound effect	Assume no rebound effect in vehicle-kilometres, compared to 19% in Balanced Pathway	0	0%	0%

Figure 6.11 Emissions impact of key sensitivity tests for surface transport



Description: Low EV uptake has the largest impact on additional emissions compared to the Balanced Pathway. High and low GDP scenarios create symmetrical deviations from the Balanced Pathway and have the largest near-term variations. The high electricity cost scenario leads to the second highest emissions increase across the pathway. While absolute uncertainty decreases over time, relative uncertainty grows as overall emissions decline.
Source: CCC analysis.
Notes: The EV rebound effect is not included in this chart as this sensitivity test has no impact on pathway emissions.

6.4.1 Low EV uptake

This sensitivity test examines a scenario where electric car and van uptake only meets the minimum ZEV sales targets set by the ZEV mandate (Table 6.6).

- Our Balanced Pathway projects EV uptake to exceed these requirements from 2026, largely due to expected upfront price parity being reached between 2026 and 2028. This scenario explores the emissions and cost implications if various factors (such as delayed price parity or consumer hesitancy) result in slower adoption rates and assumes that uptake matches the minimum ZEV mandate requirements in each year up to 2030 and increases linearly from 2030 to reach 100% by 2035.

- If EV adoption only meets ZEV mandate requirements, this would increase emissions by 5 Mt in 2030.

Table 6.6
ZEV mandate sales targets

Year	New car sales (zero-emission)	New van sales (zero-emission)
2025	28%	16%
2026	33%	24%
2027	38%	34%
2028	52%	46%
2029	66%	58%
2030	80%	70%
2035	100%	100%

Source: Department for Transport (2023) *Zero emission vehicle (ZEV) mandate consultation: summary of responses and joint government response.*

6.4.2 New car market

This sensitivity test examines uncertainty in the new car market, accounting for suppressed growth rates observed since the COVID-19 pandemic.

- For this sensitivity test, we have aligned car and motorbike market projections with our central GDP growth assumptions, resulting in a new vehicle market that remains smaller than the Balanced Pathway until the late 2030s. Total fleet size remains below the Balanced Pathway until the early 2040s, averaging 5% lower throughout the 2030s.

- This market dynamic leads to slower electric vehicle adoption and extends the average car fleet age from eight years and 10 months in 2025 to nine and a half years in 2050 as car owners retain vehicles longer, contributing to higher emissions through to 2050 compared to the Balanced Pathway.

6.4.3 Electric vehicle costs

This sensitivity explores the uncertainty in the date at which upfront price parity will be reached between EVs and ICEs. We model different rates of EV cost reduction, primarily driven by the decline in battery costs, and assess the impact on EV uptake rates.

- In our Balanced Pathway, EVs are assumed to reach price parity with ICE vehicles between 2026 and 2028, depending on vehicle size.[87] This is driven by decreases in battery costs, which we model to fall further beyond 2035.

- The upfront price of an electric car, based on average prices across all car sizes, was 37% higher than a petrol car in 2023. By the start of 2025, the average retail price of a new EV had fallen to 24% higher than the equivalent ICE model.[88] Many analysts forecast that upfront price parity will be reached by the period between 2026 and 2028, with price parity already being met for some models.[89;90] However, some car manufacturers suggest that price parity will not be achieved until 2030 or later.[91]

- To assess the impact of slower reduction in upfront EV costs, a delayed price parity is modelled to occur three years later for each vehicle type than in the Balanced Pathway.

This results in price parity occurring for large cars and vans in 2029, medium cars in 2030, and small cars in 2031.

- In the delayed price parity scenario, electric car uptake is slower than in the Balanced Pathway but still exceeds the ZEV mandate requirements until the 2035 ICE vehicle phase-out. Electric van uptake however falls behind the ZEV mandate until 2030.

- To assess the potential for further reductions in EV costs beyond 2035, we have also modelled a 'low EV cost' scenario, where the date of price parity is aligned with the Balanced Pathway but there are greater reductions in price post 2035. This is based on the most significant decrease in battery costs that could be found in the literature by 2050.[92] The low EV cost scenario does not affect emissions as costs only differ from the Balanced Pathway from 2035, by which time 100% of new vehicles are EVs.

6.4.4 Fossil fuel and electricity costs

The relative costs of vehicle fossil fuels (petrol and diesel) and electricity play a crucial role in shaping the EV market. Lower electricity compared to fossil fuel prices make EVs more attractive to consumers, driving adoption. These cost differentials also determine operational cost savings, with lower relative electricity costs yielding greater long-term economic benefits. The high and low scenarios for fossil fuel and electricity costs are based on central assumptions (see Chapter 5).

- In the high fossil fuel cost scenario, EV uptake exceeds the Balanced Pathway until 2035, leading to the most significant reduction in emissions among the surface transport sensitivity tests. Conversely, low fossil fuel costs slow EV uptake until 2035, resulting in higher emissions compared to the Balanced Pathway.

- It is important to note that lower electricity costs create a stronger rebound effect in vehicle-km driven. While reduced electricity cost reduces total cost compared to the Balanced Pathway, increased driving partially offsets these savings. In our zero-rebound scenario analysis (see Section 6.4.6), price changes would not affect vehicle-km travelled, resulting in greater cost savings when electricity costs are low.

6.4.5 GDP and impact on traffic growth

This sensitivity test is designed to consider GDP uncertainty, given that economic growth typically increases the vehicle-km travelled, consequently influencing emissions when ICE vehicles are still on the road. GDP sensitivity assumptions are based on central assumptions (see Chapter 5).

- GDP variations significantly impact vehicle travel, with the high-GDP scenario increasing car, van and HGV kilometres by 4%, 11% and 19% respectively and the low-GDP scenario decreasing them by 4%, 14% and 19% respectively, by 2050 compared to the Balanced Pathway.*

- A higher GDP leads to an increase in average vehicle-km travelled and causes the largest near-term emissions increase (2025-2028), while a lower GDP leads to the largest emissions reduction throughout 2025 to 2050 of all surface transport sensitivity scenarios (see Figure 6.11).

6.4.6 Rebound effect

The lower cost of driving for electric cars is assumed to lead to an increase in vehicle-km in our analysis, which more than offsets the overall reduction in car-km resulting from modal shift to public

* Note these figures represent the change in vehicle-km compared to the Balanced Pathway before modal shift and a rebound effect is modelled (i.e. represent changes in baseline vehicle-km demand).

transport and active travel (see Section 6.2.4). We have chosen a level of rebound towards the high end of what is seen in the literature to account for the increase in energy demand that this would incur. As there is uncertainty surrounding this, and we have picked a scenario towards the top end of estimates, we have also modelled a zero-rebound scenario.

- Since the increased vehicle usage from the rebound effect involves only zero-emission vehicles in the Balanced Pathway, this scenario produces no direct impact on emissions.

- The zero-rebound scenario does however reduce electricity demand and result in a decrease in total costs compared to the Balanced Pathway. There are also increased co-benefits with a zero rebound effect (see Chapter 3).

6.4.7 Other sources of uncertainty

We have not addressed every area of uncertainty in this sensitivity analysis:

- The sensitivities set out above mostly explore the impact of changes to core assumptions on results for cars and vans, which make up the majority of emissions. Changing assumptions on energy costs and HGV and bus technology costs could shift the balance away from battery-electric being the dominant option, although we have not modelled this.

6.5 Contingencies in surface transport

The contingencies that we have modelled in the surface transport sector are shown in Table 6.7. See Chapter 5 for our general approach to contingency analysis.

Table 6.7
Contingency options in surface transport

Contingency	Description	Potential average annual emissions savings ($MtCO_2e$, % of sector emissions)			
		2030	CB6	CB7	2050
Incentives for EV cars and vans	Bonus-malus scheme for new electric car and van purchases	4.7 7%	3.5 9%	2.2 15%	
Scrappage of older cars and vans	Scrappage scheme to incentivise replacing older ICE vehicles with EVs	0.8 1%	2.6 7%	1.9 12%	
Increased measures to enable modal shift	Increased measures to incentivise active travel and public transport over driving	0.6 1%	0.6 2%		

Source: CCC analysis.
Notes: (1) We have blanked out cells where the contingency measure in question is estimated to deliver less than 0.3 MtCO2e in potential emissions savings, to focus on high-yield options.

6.5.1 Fiscal incentives for electric cars and vans

Introducing fiscal incentives, for example in the form of taxes or subsidies, can influence consumer choices by improving the cost of EVs relative to ICE vehicles and in doing so increase the rate of EV uptake. Furthermore, for cars, much of the recent improvement in vehicle efficiency has been

offset by the shift towards larger vehicles. Implementing incentives to reverse the recent vehicle size trends would help reduce energy demand and the embodied emissions of vehicle production, while making the transition cheaper at a societal level due to the lower cost of smaller vehicles.

- For this contingency option, the consumer choice model (see Box 6.1) has been updated to include a £1,750 subsidy for small electric vehicles and apply a £1,750 penalty to ICE cars of all sizes, making electric cars more attractive than their ICE counterparts and increasing the appeal of small electric cars compared to medium or large electric cars. It is assumed that this allows the trend towards larger vehicle purchases to be reversed to match 2010 levels by 2035. A £3,200 subsidy is also applied to electric vans. These incentives and penalties are implemented halfway through 2026 and expire in 2030, as new ICE sales will be mostly phased out by this point under the ZEV mandate.

- Implementing fiscal incentives for electric cars and vans could have a significant impact on emissions reduction in the late-2020s and across the 2030s, with the greatest annual emissions reduction of 4.8 $MtCO_2e$ compared to the Balanced Pathway occurring in 2029.

- Fiscal incentives are not considered in the Balanced Pathway as price parity is expected very soon (2026-2028), so incentives may not be required for consumers to make the switch.

- This contingency option provides some cover in the case that price parity is reached later than expected, or if levels of consumer uptake are lower than we have modelled. This contingency also offers the possibility of going further in surface transport if other sectors fall behind the Balanced Pathway.

6.5.2 Scrappage scheme for cars

A targeted scrappage scheme can accelerate the turnover of ICE cars from the fleet. In the Balanced Pathway, with a 15-year average vehicle lifetime, ICE vehicles (excluding PHEVs) are projected to still make up 17% of the fleet in 2040. If decarbonisation falls behind schedule – whether from slower EV adoption or insufficient progress in other sectors – a scrappage scheme could serve as an effective policy lever to realign with emissions targets.

- For this contingency option, we assume a scrappage scheme runs between 2030 and 2040, offering owners of ICE cars over 10 years old incentives to replace these with new cars. The scheme targets approximately 500,000 cars each year, across vehicle sizes distributed proportionally to the fleet's average composition during this period.

- Our modelling approach assumes each scrapped car is replaced by a new car entering the fleet in the corresponding scrappage year. This approach recognises the cascade effect within the vehicle marketplace, whereby while individual participants may purchase used vehicles with their scrappage incentives, this increased demand for used vehicles will encourage those vehicle owners to sell sooner and purchase new vehicles themselves. At the fleet level, this results in new vehicle sales corresponding to scrapped vehicles, regardless of whether the initial replacement transaction involves a new or used vehicle.

- Overall, this scheme accelerates fleet turnover and reduces the average lifetime of ICE vehicles in the fleet, leading to significant additional emissions reductions across the 2030s and 2040s compared to the Balanced Pathway.

- A scrappage scheme is not included in the Balanced Pathway due to the potential cost to the Exchequer and because decarbonisation in the surface transport sector can be achieved without it due to the rapid market-led uptake of electric vehicles.

- We have not modelled the impacts of a scrappage scheme for vans or HGVs, although this could also have significant impact on reducing emissions.

6.5.3 Increased modal shift

Modal shift concerns the total vehicle-km travelled and is already considered in the Balanced Pathway (see Section 6.2.4). However, the Government may wish to go further on modal shift for reasons beyond emission reductions, such as reducing congestion and energy demand.

- In the Balanced Pathway, we assume improvements to make buses and active travel more attractive, affordable, and accessible allow 7% of car demand to be switched to public transport and active travel by 2035, compared to the baseline. The contingency scenario builds upon this foundation, projecting a further 3% of car demand to be switched to public transport or active travel by 2035, compared to the baseline.

- This further modal shift is underpinned by evidence on interventions in leading countries, such as Germany and the Netherlands and parts of the UK.[93;94;95] For this scenario, we considered the maximum shift to public transport and active travel observed across this literature, whereas in the Balanced Pathway we considered the average.

- Increased modal shift has the smallest impact on emissions of the contingency options considered in the surface transport sector, peaking at 0.6 $MtCO_2e$ additional emission reduction in the early 2030s, compared to the Balanced Pathway.* However, higher levels of modal shift could also offer a range of co-benefits, including less congestion and healthier lifestyles.

* The additional 0.6 $MtCO_2e$ figure appears relatively smaller than the original 4.4 $MtCO_2e$ modal shift reduction because it represents additional modal shift applied after vehicle electrification is already modelled. The initial 7% modal shift abatement calculation was performed before accounting for fleet electrification, effectively accounting the emissions reductions that modal shift would deliver on the basis of the current vehicle fleet.

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Chapter 7: Residential buildings

Introduction

The residential buildings sector modelling is split into three broad areas of energy use and emissions: heat in existing homes, heat in new homes, and other home energy use. Other home energy use is further divided into lighting and electrical appliances, fossil fuel cooking, and fossil fuel machinery. The dominant source of emissions and energy use is heat in existing homes, accounting for 87% of baseline emissions in 2040.

To develop baselines and pathways we use differing approaches to analysis for different areas of energy use and emissions:

- **Heat in existing homes** is modelled using a set of detailed archetypes representing the existing housing stock. We use an in-house model which selects the cost optimal combination of measures for each archetype, then generates deployment pathways for the measures based on abatement costs and supply/demand constraints.

- **Heat in new homes** is modelled using a top-down approach, using assumptions about build-rates of new homes and their expected fabric performance. The pathway assumes that all new homes are constructed with air source heat pumps, compared to gas boilers in the baseline, from 2025.

- **Other home energy use** is modelled using a top-down approach, using assumptions about aggregate energy use of different categories of appliances. The pathway assumes that fossil fuel appliances are substituted with electric technologies from 2035 in line with their expected natural turnover.

To model heat in existing homes, we developed a new in-house model and input data.

- We commissioned Kamma Climate to develop an archetype dataset, which provides a detailed representation of the UK housing stock.

- We commissioned PwC to produce up-to-date assumptions on the cost and performance of retrofit decarbonisation measures.

To model heat in new homes and other home energy use we used separate models, drawing on analysis prepared for our advice on the Sixth Carbon Budget.

7.1 Baseline emissions in residential buildings

7.1.1 The baseline for residential buildings

This baseline represents a scenario in which there is no further decarbonisation action by either the Government or the market in the residential buildings sector. The addition of new homes increases emissions over time, with the increase slightly offset by a reduction in space heating demand over time, due to a warming climate. See Chapter 1 for our general approach to baselines.

In this baseline scenario, emissions would rise by 24% from 2023 levels by 2040 (the middle of the Seventh Carbon Budget period) and by 28% by 2050 (Figure 7.1).

Our baseline for the residential buildings sector is based on differing sets of assumptions for different areas of energy use and emissions:

Heat in existing homes

- Baseline emissions and fuel consumption are derived from the aggregated energy demand of the stock of each archetype in the archetype dataset (the use of the archetype dataset in our analysis is discussed in further detail in Section 7.2).
  - The fuel consumption and emissions for each archetype are based on the delivered energy required to meet space heating and hot water demand, using their existing heating system.
  - The useful energy demand (the energy actually required for its intended purpose) for space heating and hot water in each archetype is calculated using EPC data.
  - The useful energy demand for space heating and hot water for each archetype is then calibrated so that aggregate consumption of each fuel is aligned to estimates in 'Energy consumption in the UK' statistics (ECUK)[1]. The useful energy demand is recalibrated by the model to ensure that the aggregate emissions of archetypes within England, Scotland, Wales, and Northern Ireland align with the GHG inventory.
    - In aggregate the calibration to ECUK reduces the energy demand of archetypes by about 1%.
    - The calibration to the GHG inventory reduces the energy demand of archetypes on average across the UK by a further 1.8%.
  - We used emissions from 2019 as the starting point for the baseline as this was an average temperature year and was prior to the COVID-19 pandemic and the energy crisis (the long-term impacts of which are uncertain).
  - The archetype energy demand and emissions for historic years since 2019 are adjusted so that aggregated figures align with emissions inventory data. Baseline energy consumption and emissions for future years are assumed to revert to 2019 levels, with space heating demand adjusted to allow for a reduction in demand due to a warming climate.
    - We adjust space heating demand using projections of future winter heating degree days from the Government's Energy and Emissions Projections.[2]
- In our baseline we assume that the characteristics of existing homes remain unchanged over time. We do not consider the potential impacts of changing fuel prices, GDP, or earnings growth on home heating demand. This is reflected in the baseline emissions, energy use, capex, and opex.
  - Heating systems in the baseline remain the same throughout the model period. Heating system performance is assumed to remain at the current average levels for each heating system type.
  - Baseline opex for each archetype is calculated from baseline fuel use and LRVCs, plus estimated maintenance costs for the heating system type.
  - Baseline capex is based on the prices, size, and lifetimes of existing heating systems. We assume existing heating systems are replaced with similar systems when they reach the end of life.

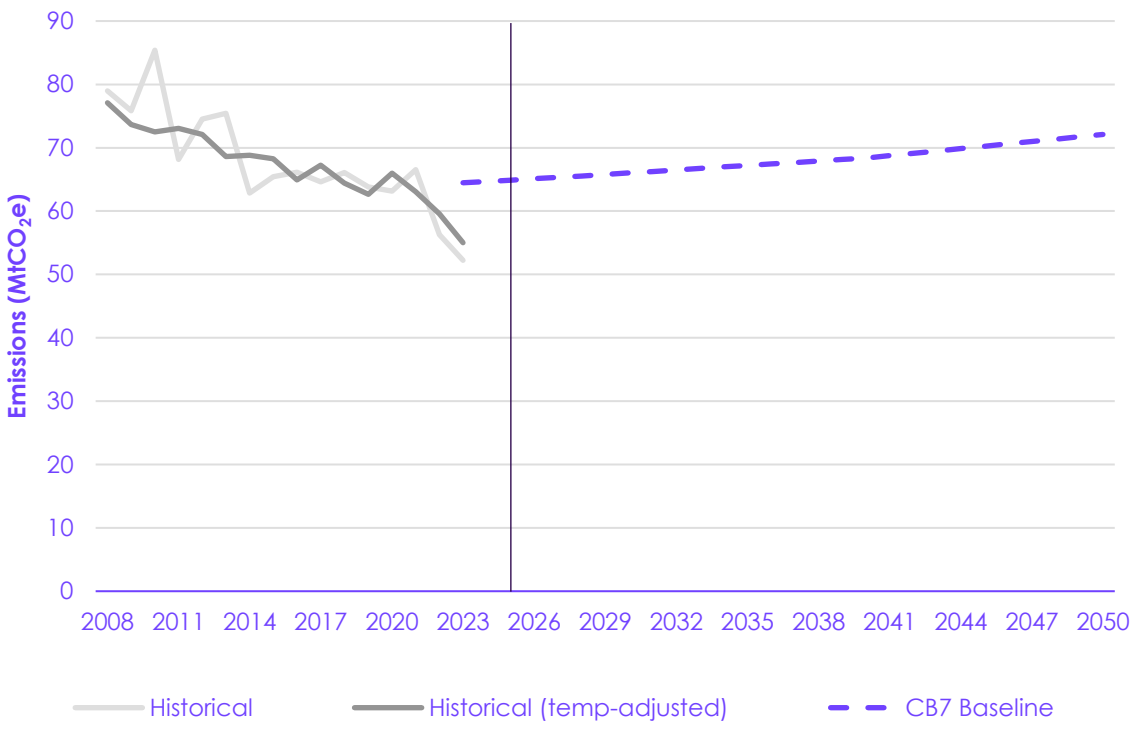
Heat in new homes

- Baseline emissions and fuel consumption are derived from assumptions about the average fuel consumption of new homes.
  - The fuel consumption and emissions for new homes are based on the delivered energy required to meet space heating and hot water demand to a new home, built with a gas boiler to the current requirements of Part L of the Building Regulations.
  - Assumptions on fuel consumption and emissions in new homes were taken from the Future Homes Standard Impact Assessment.[3]
  - The number of new homes modelled is based on assumed new build completions in England used in the Future Homes Standard consultation-stage impact assessment (2023)[4], scaled to the UK. The impact assessment provides a series to 2035, and rates are assumed to flatline thereafter.
- In our baseline we represent new homes as two archetypes, which capture the characteristics of an average new build flat and new build house. These archetypes are used to calculate the baseline emissions, energy use, capex, and opex for new homes.
  - Baseline opex for new homes is calculated from assumed average fuel consumption and LRVCs, plus estimated maintenance costs for the heating system type.

Other home energy use

- Baseline emissions and fuel consumption associated with the use of fossil fuels for cooking and garden machinery, and the use of electricity for lighting and appliances, are assumed to grow from current levels in proportion to the construction of new homes.
  - The fuel consumption and emissions are based on the energy required to meet petroleum, gas and electricity demand for cooking, garden machinery, and lighting and appliances, using households' existing appliances.
  - The energy demand for cooking, garden machinery, and lighting and appliances are derived from ECUK.
  - We assume that the technology mix between fossil fuel and electric equipment in new homes is the same as the existing stock and grows accordingly.
  - We assume that as the climate warms, there will be increased demand for electricity for active cooling. Baseline electricity consumption increases over time to account for this cooling demand, totalling 6TWh of additional electricity demand by 2050.
- Baseline opex and capex for other home energy use are not calculated. Instead, any differences in these costs are included in pathway costs.

Figure 7.1 Baseline emissions in residential buildings



Description: The baseline for residential buildings increases gradually out to 2050, due to the addition of new homes increasing emissions. This is slightly offset by a warming climate.
Source: CCC analysis.

7.2 Pathway assumptions and modelling for residential buildings

7.2.1 Modelling the Balanced Pathway for residential buildings

Overall modelling approach

Our modelling approach considers heat in existing homes, heat in new builds, and other home energy use. See Chapter 1 for our general approach to pathway analysis.

Modelling heat in existing homes

The key inputs into our model are: input data defining the performance, costs, and deployment constraints for energy efficiency and low-carbon heating measures; and an archetype dataset, representing the UK housing stock.

- The input data consists of properties of energy efficiency measures and low-carbon heating systems.
  - The properties include suitability constraints, lifetimes, energy savings, efficiencies, load factors, capex costs, and maintenance costs.

  - Capex costs for low-carbon heating systems include core installation costs and ancillary costs which may only be incurred in particular instances or have differing lifetimes.

- The archetype dataset consists of 11,657 archetypes, providing a detailed representation of the UK housing stock.[5] Each archetype represents a stock of homes with similar characteristics, located in a particular region of the UK.

  - The variables included in the archetype dataset enable our model to choose which measure options can be applied to each archetype, and to calculate the energy use, emissions and cost impacts of measures based on a range of factors.

  - The variables include: energy demand; region; typology; size; heating system; tenure; and levels of roof, wall, and floor insulation. A full list of variables is given in Table 7.1.

Box 7.1
Archetype dataset methodology

We commissioned Kamma Climate to produce the archetype dataset which forms a key input into our model for decarbonising heat in existing residential buildings.

The dataset was derived from the national EPC databases and other government datasets.

- Kamma used their proprietary system to predict the characteristics of homes without an EPC and fill gaps in coverage.
- Government housing surveys for each of the UK nations and other government datasets were used to enhance the integrity of the EPC data and to add variables which are not included in the EPC dataset.
- Kamma undertook a process of refining and transforming data at the level of individual homes, then grouping homes with shared characteristics to form archetypes. For each home the delivered energy demand for space heating and hot water was calculated from EPC energy cost data, by applying the appropriate energy price for the year of the EPC assessment. The useful energy demand was calculated by applying the appropriate efficiency for the heating system in each home.
- The useful energy demand for each archetype was calibrated so that aggregate consumption of each fuel is aligned to estimates in ECUK.
- Insulation levels in different fabric elements were categorised according to the thickness of insulation present.
- The 135 different heating system attributes in the EPC data were merged into 14 heating system types, reducing unnecessary differentiation while capturing important variations in fuel and efficiency.

A hierarchical clustering process was used to merge similar archetypes, so that archetypes typically have a stock of greater than 500, limiting the dataset to a manageable size. A process was used to ensure that important but relatively uncommon attributes were not lost, including reducing the threshold stock level for archetypes with particular attributes. This ensured that the dataset remained representative across a range of variables and less common heating systems were adequately represented.The dataset contains 11,657 archetypes. The average stock of an archetype is 2,515 homes. The distribution of stock sizes in the dataset is positively skewed, with a large number of archetypes having a stock size less than the mean, to capture the heterogeneity of the housing stock.

The characteristics captured include the region in which the archetype is located. The regions are based on the climatic regions in SAP (the tool used to calculate home energy use for EPC assessments). This allows the model to capture the differing energy demand of similar homes in different parts of the UK.

Further details of the methodology used to produce the archetype dataset are provided in the report: Residential Archetypes Dataset Methodology (Kamma Climate).

The model consists of two main steps: an optimisation step selects the measures to be deployed in each archetype; and a pathway step calculates the deployment pathways for the selected measures.

Optimisation step

The optimisation step analyses all the combinations of energy efficiency measures and low-carbon heating system which could be applied to each archetype. For each archetype it selects the combination with the lowest lifetime cost.

- For each combination of measures which can be applied to an archetype, the model calculates the 2030 NPV of the annualised additional capex and opex (compared to the baseline) of all the measures in the combination over the period 2030 to 2050. This includes the costs of renewals of measures (such as renewing heating systems which reach end of life within the time period).

- For each archetype the model selects the combination of measures with the lowest lifetime cost.

The optimal choice of measures is uncertain and sensitive to assumptions about the costs and performance assumed for each measure. Real-world conditions and incentives inevitably mean that actual measure deployment will differ from our pathway. Our model suggests feasible, cost-effective measure choices and estimates of the costs of delivering them. This is discussed in further detail in Section 4 of this chapter.

Pathways step

The pathways step compares the total stock eligible to receive each measure type in a given year to the supply constraints for each measure in that year. Measures are deployed up to the limits imposed by either the eligible stock or the supply constraints.

- The maximum stock eligible for energy efficiency measures is the aggregate of all eligible archetypes due to receive the measure, less the stock where it has already been deployed.

- The maximum stock eligible for deployment of low-carbon heating is the aggregate of the annual replacement rate of existing heating systems in each archetype that is due to receive the measure. The annual replacement rate is calculated by dividing the stock of the archetype by the lifetime of the existing heating system.

- In each year, the abatement costs of measures selected in the optimisation stage are compared to the carbon price. If the abatement cost is less than the carbon price, then the archetype is eligible for deployment of the selected measures. This gives a pool of eligible stock that is cost effective to deploy for each year of the pathway.

- In each year, the eligible stock is compared to the supply constraints for the measure. Measures are deployed up to the limits imposed by supply constraints. Remaining stock eligible for energy efficiency measures is carried over to the following year. Remaining stock eligible for low-carbon heating measures is assumed to receive a new baseline heating system and becomes eligible again when that system reaches end of life.

For each year of deployment of each measure in each archetype the model calculates the abatement cost, and the streams of annual abatement, net fuel demand, capex, and opex (from deployment to 2050). Archetypes are finally grouped and measures aggregated by type to give individual pathways for measure types, split by characteristics including tenure, fuel poverty status, and baseline heating system.

Table 7.1
Archetype dataset variables

Variable	Attributes
Property type	Detached, Semi-detached, Terrace, End terrace, Bungalow, Flat, High rise flat
Age band	Pre 1930, 1930 to mid-1970s, Mid-1970s to mid-1990s, Mid-1990s to present
Wall type	Solid uninsulated, Solid insulated, Cavity uninsulated, Cavity uninsulated hard to treat (HTT), Cavity insulated
Roof type	Insulated, Uninsulated, Underinsulated, Underinsulated HTT, No roof
Floor type	Solid uninsulated, Solid insulated, Suspended uninsulated, Suspended insulated, No ground floor
Glazing type	Single glazed, Double glazed
Size	S, M, L
Space constrained	Yes, No
Region	Central Scotland/Orkney/Shetland, Midlands/Northern England, North England, North Scotland, Northern Ireland, Scottish Borders/Western Isles, South England, South West England, Wales*
Country	England, Scotland, Wales, Northern Ireland
Heating system	Air source heat pump (ASHP), Biofuel boiler, Communal gas, Communal low carbon, Electric boiler, Electric resistive, Electric storage, Gas boiler, Gas boiler (electric hot water), Gas other, Gas other (electric hot water), Ground source heat pump (GSHP), Oil boiler, Solid fuel boiler
Location type	Urban, Rural
Solar PV	Yes, No

Modelling heat in new homes

- Our modelling for the decarbonisation of heat and energy efficiency measures in new homes assumes that, from 2025, no new homes are connected to the gas grid and instead are built with high energy efficiency standards and are heated using heat pumps.
- The model assumes that new builds are constructed at the rate set out by government in the Future Homes Standard consultation, which also provides other key inputs for energy demand and cost. These are split between new build flats and new build houses.
- To calculate the pathway for new builds, the model takes weighted average energy demand and costs and multiplies these by the number of new builds expected each year. The weighted average is based on a 20-year average of the split between new build flats (30%) and new build houses (70%).

* SAP regions were merged to reduce the size of the archetype dataset. The methodology used for merging regions is described in Kamma's supporting methodology report for the archetype dataset: Residential Archetypes Dataset Methodology.

Modelling other home energy use

- The model uses ECUK data to calculate current energy use and emissions.
- For lighting and appliances, the model assumes that these are replaced with more efficient equivalents as they are naturally replaced. This assumes that product standards continue to improve the energy performance of energy-using products.
- For fossil fuel appliances and machinery, the model assumes that from 2035, these will be phased out. All fossil fuel using appliances are replaced with electric equivalents. This is in line with the expected date that gas boilers will have to be phased out, given an average boiler lifetime of 15 years and the target of Net Zero by 2050. From 2035, these appliances and machinery are phased out as they are naturally replaced.

The diagram below illustrates the models used to generate the Balanced Pathway, the key steps within the models, and the inputs into them.

Figure 7.2 Modelling schematic for residential buildings

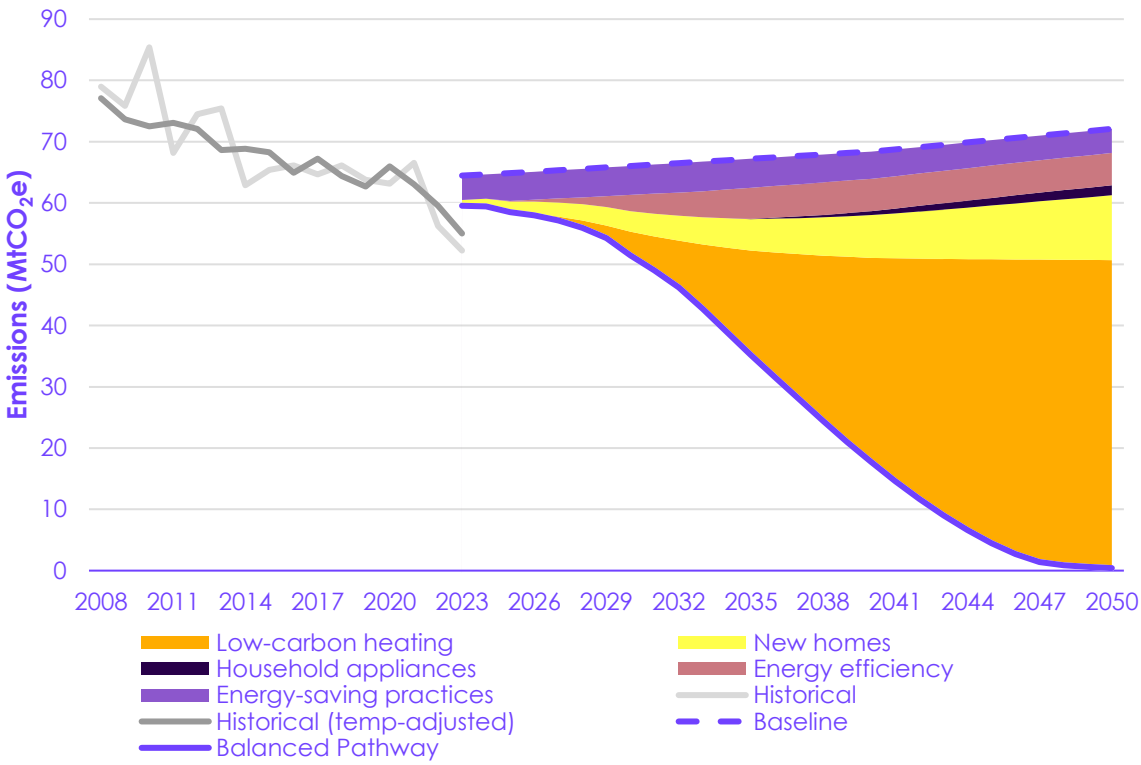
Description: Our modelling for residential buildings considers heat in existing homes, heat in new homes, and other home energy use. Models for these three areas produce our pathway outputs.
Notes: This diagram is illustrative and does not detail all model inputs and outputs.
Source: CCC analysis.

The Balanced Pathway for residential buildings

In our Balanced Pathway, emissions from residential buildings are projected to fall by 66% to 17.7 $MtCO_2e$ by 2040 (the middle of the Seventh Carbon Budget Period) and to 0.4 $MtCO_2e$ by 2050 (Figure 7.3). Our analysis uses heating emissions in 2019 as a starting point for calculating the baseline. This was an average temperature year and was prior to COVID-19 and the energy crisis (the long-term impacts of which are uncertain).

Residential buildings are fully decarbonised by 2050. Replacing fossil fuel heating systems with low-carbon, electric heating technologies is central to eliminating emissions from homes. Most homes also receive small energy efficiency improvements (such as draught-proofing), while big energy efficiency improvements are installed in 17% of homes.

Figure 7.3 Sources of abatement in the Balanced Pathway for residential buildings



Description: The largest share of emissions reduction in residential buildings is from the electrification of heat, in both existing and new homes. Energy efficiency improvements and the continuation of some energy-saving practices also play an important role.
Source: DESNZ (2024) *Provisional UK greenhouse gas emissions national statistics 2023*; DESNZ (2024) *Final UK greenhouse gas emissions national statistics 1990-2022*; CCC analysis.
Notes: (1) We generally account for emissions reductions due to measures to reduce demand for high-carbon activities (including low-carbon choices and efficiencies) first, before the impact of low-carbon technologies. (2) There was a significant drop in emissions from residential buildings between 2021 and 2023 due to warmer-than-average winters and record high energy prices. Our pathway assumes that some of this reduction was a direct response to the weather and prices and will therefore only be short-term. It is assumed that the rest of this reduction is due to energy-saving practices that will be maintained into the future, such as reducing boiler flow temperatures, adjusting thermostats, and other measures to reduce energy bills.

The measures in our pathway

Table 7.2 summarises the measure categories for reducing emissions in the residential buildings sector that are considered within our modelling, how these lead to emissions reductions in our modelling, and the key factors that influence their uptake. The methodology used to develop the assumptions and analysis underpinning these is described in the rest of this section.

Table 7.2
Measures considered within our modelling for residential buildings

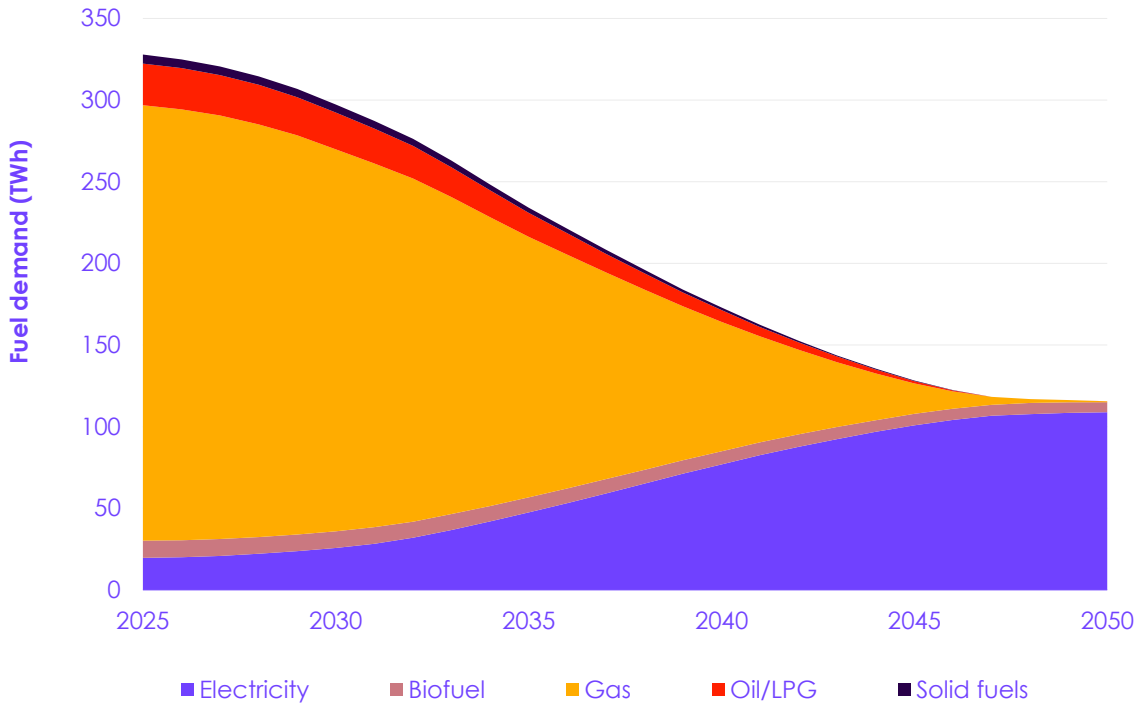
Decarbonisation measure	How does this measure influence emissions in our modelling?	What are the key factors that affect uptake in our modelling?
Heat in existing homes		
Energy-saving practices	Some of the reduction in energy use and emissions between 2019 and 2023 is assumed to be maintained.	All homes are assumed to reduce energy use by 6.5% compared to baseline.
Energy efficiency	Improving the fabric efficiency of homes reduces energy use and therefore emissions.	Homes receive fabric efficiency measures if they are suitable and contribute to reducing the costs of decarbonisation.
Low-carbon heating	Replacing fossil fuel heating systems with low-carbon heating eliminates direct emissions from heating existing homes.	All homes receive a suitable type of low-carbon heating. For each archetype the low-carbon heating system with the lowest lifetime costs is selected. Deployment depends on cost-effectiveness of the total package of measures.
Heat in new homes		
Energy efficiency	Improving the fabric efficiency of homes reduces energy use and therefore emissions.	No improvements to baseline energy efficiency standards for new homes are assumed in the pathway.
Low-carbon heating	Building new homes with low-carbon heating instead of fossil fuel heating systems eliminates direct emissions.	All new homes assumed to be built with low-carbon heating. The deployment trajectory for new homes is taken from the Future Homes Standard impact assessment.
Other home energy use		
Electrical appliance efficiency	The electricity demand for homes is lower and therefore the indirect emissions are reduced.	Electrical appliances are assumed to be replaced with more efficient alternatives when they reach the end of their life.
Cooking decarbonisation	Replacing fossil fuel cooking systems with low-carbon alternatives eliminates direct emissions from cooking in existing homes.	From 2035, all fossil fuel cooking systems are phased out at the end of their lives.
Garden machinery decarbonisation	Replacing fossil fuel garden machinery with low-carbon alternatives eliminates direct emissions from garden machinery in existing homes.	From 2035, all fossil fuel garden machinery is phased out at the end of their lives.

7.2.2 Heat in existing homes

All homes are fully decarbonised by 2050. Space heating and hot water in existing homes are decarbonised through a combination of maintaining a proportion of current energy-saving practices, energy efficiency, and low-carbon heating measures.

The combination of energy efficiency measures and the efficiency of heat pumps dramatically reduces the fuel demand for space heating and hot water in existing homes (Figure 7.4).

Figure 7.4 Changing fuel demand for heat in existing residential buildings



Description: The use of gas for home heating decreases to zero by 2050 in our pathway.
Source: CCC analysis.

Energy-saving practices

We assume that some of the reductions in energy use and emissions which occurred between 2021 and 2023 are maintained in the future.

- These reductions occurred in response to high energy prices. These are likely to have been achieved through behaviours such as reducing boiler flow temperatures, adjusting thermostats, and reducing hot water use.

- After temperature adjustment, direct emissions fell by 13% from 2021 to 2023.* We assume that half of this reduction is maintained and that energy-saving practices deliver 6.5% reductions in energy use and emissions in our pathway. Provisional emissions data for 2024 shows that, after temperature adjustment, emissions increased by 4% from 2023 to 2024, but are still ~9 $MtCO_2e$ lower than 2021 levels. Energy prices remain high, and energy use is likely to rebound as prices recover.

Energy efficiency measures

Our model considers a range of energy efficiency measures which can be retrofitted to existing homes to reduce space heating and hot water demand. By reducing energy demand, energy efficiency measures can deliver immediate opex and emissions savings.

* Calculated using provisional 2023 emissions figures.

- Where the value of the cost savings over the measure lifetime exceeds the capex costs, energy efficiency measures help to reduce the cost of decarbonising existing homes.
  - Energy efficiency opex savings are based on the reduction in fuel costs for the baseline heating system. A measure may be selected because it delivers further cost savings with a low-carbon heating system (for example by enabling lower radiator flow temperatures, or reducing heat system size), even if it is not cost effective on its own.
  - Energy efficiency measures also deliver co-benefits, such as improved comfort and air quality, and reduction in cold-related health risks. These are not quantified in the residential buildings modelling and do not influence uptake, but are quantified in the co-benefits modelling in Chapter 8 of the Seventh Carbon Budget advice report.
- Improvements to energy efficiency complement the installation of low-carbon heating systems, however they are not necessarily a requirement.

Table 7.3 lists the energy efficiency options which are included in our model and their associated properties.

Table 7.3
Energy efficiency measure options in the residential model

Measure type	Measure	Suitability	Lifetime (years)	Energy savings (% of space heating or hot water demand)	2025 capex (range, £)	2035 capex (range, £)
Basic	Small measures such as draught proofing and heating controls	All homes	25	1.7 to 9.8% of space heating	£120 to £450	£110 to £390
Wall	Cavity wall insulation	Homes with uninsulated cavity walls	40	5.0 to 18.3% of space heating	£1,100 to £7,200	£1,000 to £6,500
	Cavity wall insulation (hard to treat)	Homes with uninsulated cavity walls that have complex cavities e.g. particularly narrow space within cavity	40	5.0 to 18.3% of space heating	£1,800 to £11,000	£1,500 to £9,700
	Internal wall insulation	Homes with uninsulated solid walls	40	6.8 to 18.9% of space heating	£4,000 to £25,000	£35,00 to £22,000
	External wall insulation	Homes with uninsulated solid walls	30	9.0 to 23.0% of space heating	£7,800 to £49,000	£6,700 to £42,000
Roof	Loft insulation	Homes with uninsulated lofts	40	2.1 to 21.1% of space heating	£270 to £1,100	£240 to £930
	Loft insulation (hard to treat)	Homes with uninsulated or under-insulated	40	3.0 to 10.8% of space heating	£290 to £1,100	£250 to £980

		lofts requiring special measures				
	Loft top up	Homes with insulated lofts with less than 200mm of insulation	40	3.0 to 10.8% of space heating	£200 to £760	£170 to £670
Floor	Suspended floor insulation	Homes with uninsulated suspended floors	42	1.8 to 7.5% of space heating	£4,900 to £19,000	£4,400 to £17,000
	Solid floor insulation	Homes with uninsulated solid floors	42	1.5 to 10.6% of space heating	£5,400 to £21,000	£4,900 to £19,000
Hot water	Hot water tank insulation	Homes with a hot water tank	15	17.0 to 37.2% of hot water	£33	£27

Measure options

- Energy efficiency measures consist of basic measures, fabric measures, and hot water measures. Fabric measures are applicable to a particular fabric element and are split into roof, wall, and floor measures.
  - Basic measures include measures such as draughtproofing, improved heating controls, and thermostatic radiator valves. For each property type and size, we assume a certain saving in space heating demand can be achieved through a flat rate of investment that would deliver some combination of these measures.
  - Our model includes several measure options for each fabric element. For each fabric element in an archetype there will typically be only one, or sometimes two, suitable measure options. Each fabric element can only receive one measure at a time.
- Our model does not include the option of window measures. Window replacements are expensive and deliver relatively low energy savings, so are not cost-effective. Households will continue to install replacement windows in homes for reasons other than saving energy (such as sound-insulation and replacing end-of-life units), and these may contribute to reductions in energy demand and emissions above those in the Balanced Pathway.

Measure suitability

- The energy efficiency measures which can be applied to an archetype depend on its existing characteristics.
  - The primary constraint on the fabric measure options which are suited to an archetype are the construction type and the existing levels of insulation to the relevant fabric element.
  - Some measures may be unsuited to homes with certain attributes, such as having a heritage designation or limited internal space. Our model limits the application of some measures in these archetypes.
- Cost-effectiveness can be marginal and is sensitive to assumptions about capex. In the case of easy-to-treat cavity wall insulation and loft insulation, we apply measures to all eligible homes regardless of the result of the cost-effectiveness calculation.

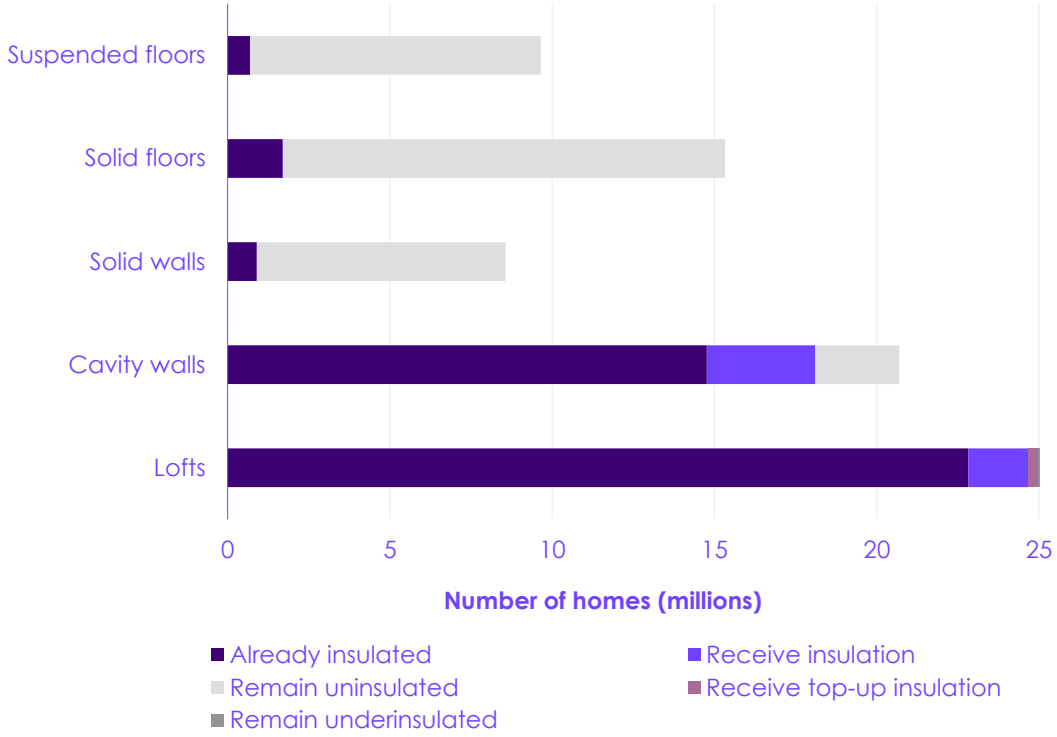
Measure properties

- For each energy efficiency measure, the model inputs include data on the estimated energy savings, capex, and lifetime of the measure.
  - Capex and energy savings of a measure vary according to the characteristics of the home they are installed in. We use differing values for capex and percentage energy savings, for different property types and sizes. The calculated energy savings are used to calculate changes in opex and emissions.
  - Measure lifetimes impact on the cost-effectiveness of measures and the total pathway capex. When calculating cost-effectiveness of measures, we annualise the capex according to the measure lifetime. Within the timescale of the Balanced Pathway most energy efficiency measures are one-off investments as their lifetimes extend beyond 2050.
  - Measure prices vary by location within the UK. We adjust capex rates according to the region in which an archetype is located.
- Data on energy savings, measure suitability, capex, and lifetimes for energy efficiency measures were produced for the CCC by PwC. PwC's research included: a literature review; modelling (using PwC's 'Green.House Toolkit'); and engagement with key stakeholders in the domestic retrofit market.
  - Data on energy efficiency costs was obtained from sources including Eunomia's study (commissioned by CITB) on Building Skills for Net Zero and SPON'S data on construction pricing.[6;7]
  - Energy savings were estimated using PwC's 'Green.House' toolkit. A subset of homes in the toolkit was used to calculate the average energy savings for each measure in each property type in our archetype dataset. Energy savings were calibrated to real world performance data using the Government's National Energy Efficiency Data (NEED) framework.[8]
  - Full details can be found in PwC's methodology report.[9]

Measure selection

- Measure selection occurs in the optimisation step of the model, described in Section 7.2.1. The resulting uptake of energy efficiency measures is shown in Figure 7.5.

Figure 7.5 Energy efficiency uptake by construction type

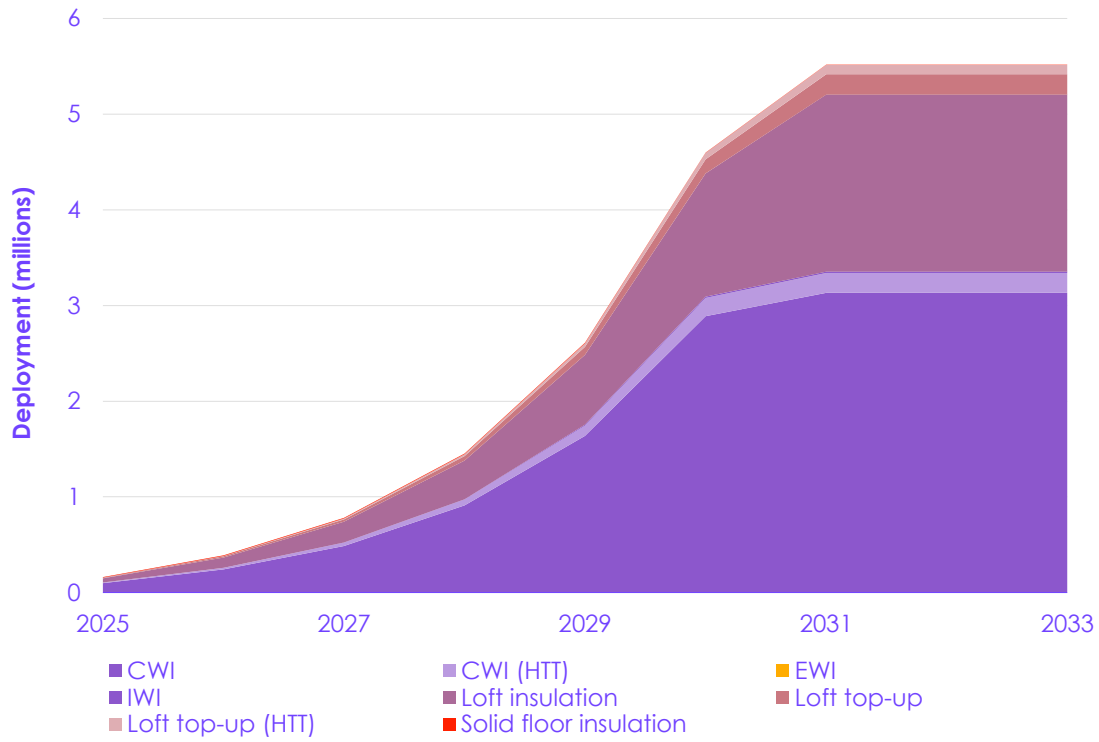


Description: Most homes with uninsulated lofts and cavity walls receive insulation for these in our pathway.
Source: CCC analysis; Kamma Climate (2024) Residential Archetypes Dataset.

Deployment constraints

- For each energy efficiency measure type we assume limits on the annual deployment which can be achieved. These constraints are based on expectations for both supply and demand.
  - Energy efficiency measures must be installed ahead of or at the same time as low-carbon heating, to ensure appropriate sizing of the heating system.
  - We estimated limits on annual deployment by taking current deployment rates for the measure group in the UK and applying a compound annual growth rate (CAGR).
    - The current deployment data was aggregated from UK Government publications on government energy efficiency schemes, including the Household Energy Efficiency, Social Housing Decarbonisation Fund, and Home Upgrade Grant statistical datasets. [10;11;12]
    - Energy efficiency installations are heavily tied to capital schemes funding. This means the historical trajectory is volatile and not suitable for estimating historic growth in the supply chain. There is limited evidence on how adaptable the supply chain is to demand.
    - The CAGR used for energy efficiency growth was taken from the international analysis of the heat pump supply chain (see below section on deployment constraints for low-carbon heating). Noting that energy efficiency is a more developed industry than low-carbon heating, the higher CAGR of 72% was applied.

Figure 7.6 Cumulative energy efficiency deployment by measure



Description: Deployment of energy efficiency measures ramps up during the late 2020s and early 2030s.
Notes: CWI stands for cavity wall insulation; EWI stands for external wall insulation; IWI stands for internal wall insulation; HTT stands for hard to treat.

Low-carbon heating

Our model considers a wide range of low-carbon heating systems to replace the existing heating systems in homes. Low-carbon heating systems eliminate direct emissions from homes by avoiding the use of fossil fuels for space heating and hot water.

- Our model requires all homes to receive a low-carbon heating measure. For each archetype, the model compares multiple options, but only one option can be selected.

Table 7.4
Low-carbon heating options in the residential buildings model

Low-carbon heating category	LCH system	Lifetime (years)	Space heating efficiency	2025 fixed capex (£)	2025 marginal capex (£/kW)	Non-fuel opex (£)
Heat pumps	ASHP	15	2.94 – 3.15, dependent on flow temperature	£4,100	£330	£200
	GSHP	15	3.00 – 3.43, dependent on flow temperature	£3,400	£550	£200
Communal heat pumps	Communal ASHP	20	2.27 – 3.29, dependent on flow temperature	£0	£790	£180
	Communal GSHP	20	3.34 – 3.99, dependent on flow temperature	£3,800	£540	£180
Heat network*	Heat network	20	1.96	£0	£790	£140
Direct electric	Electric storage	13	1.00	£0	£300	£70
	Electric resistive	13	1.00	£0	£240	£65
Hybrid heat pump	ASHP + Biofuel boiler	15	Dependent on combination of systems	£19,000	£190	£300
	ASHP + Electric resistive (point-of-use hot water)	15	Dependent on combination of systems	£7,300	£98	£300
Communal heating conversion	Communal heating conversion†	20	3.00	£0 (no data)	£0 (no data)	£180

Notes: (1) Capex for a low-carbon heating system depends on the system size. For each measure capex costs are provided as a fixed cost plus a rate per kW of installed capacity. In some cases, the fixed cost is zero, as the costs correlate closely to the installed capacity, without requiring a fixed cost. Low-carbon heating installations typically require additional investments alongside the main system: these costs are not included in this table. (2) *Assumptions for heat networks are described in further detail in Table 14.8 in Chapter 14. (3) †Communal heating conversion refers to converting existing gas and biofuel communal heating systems to use communal heat pumps. In the absence of suitable data capex costs were assumed to be the same in the baseline and pathway.

Measure options

- Low-carbon heating measures are broadly categorised into individual heat pumps, communal heat pumps, low-carbon heat networks, direct electric heating, biofuels,

hydrogen, and hybrid solutions. Each of these categories is split into specific types (such as air-source heat pumps (ASHPs) and ground-source heat pumps (GSHPs)).

- Electrified low-carbon heating types are split into further variants depending on the potential flexibility of their electricity demand for space heating and hot water. Flexibility enables lower prices for electricity to be applied. Flexibility options may require particular ancillary investments, or may only be applicable to archetypes with certain attributes or levels of fabric performance.

Table 7.5
Heating flexibility options

Energy use	Technology	Measure variant	Electricity variant	Criteria
Space heating (SH)	None	Inflexible SH	Inflexible	Fabric performance
	Pre-heating/flexible heating	Flexible SH	Flexible	Fabric performance
	Heat storage	Flexible SH / SH storage	Highly flexible	Thermal store
	Hybrid heating system (non-electric peak)		Highly flexible	Hybrid ASHP with bioLPG boiler
Hot water (HW)	Point-of-use hot water	No HW storage	Without storage	Point-of-use hot water installed
	Hot water storage	HW storage	With storage	Hot water tank installed
	Instantaneous hot water		No electricity required	Hybrid ASHP with bioLPG boiler, no hot water tank

- Hydrogen boilers and hydrogen heat pump hybrids were not included in the Balanced Pathway modelling. Hydrogen is not a viable fuel for widespread decarbonisation of home heating, and would delay direct emissions reductions and increase indirect emissions (see Box 7.2.2 in the Seventh Carbon Budget advice report).

- There is no use of fossil fuel heat pump hybrids in the Balanced Pathway. These systems are more complex than standalone heat pumps and would need to be replaced with zero emissions systems prior to 2050 (meaning they could not be installed after 2035, to avoid scrappage).

- Biofuels should have a very limited role in decarbonising buildings. The biomass used to produce biofuels is a limited resource, and its consumption should be targeted in sectors where this maximises abatement.

  – Standalone biofuel boilers were not included in our model. Biofuel heat pump hybrids were included in the Balanced Pathway modelling and were selected for a small number (<0.01%) of homes. This use offers the most cost-effective solution in some homes with very high energy demand, where a standalone heat pump is not viable.

  - Around 4.3 TWh of biofuel is used in the existing heating systems of archetypes in the model. Our model replaces these systems with alternative low-carbon heating systems, allowing this biomass to be put to other uses.

  - Government estimates suggest that a further 6.6 TWh of biomass is consumed in homes, beyond that allocated to primary heating systems in the domestic EPC data. We do not model any reduction in this use.

- Direct electric heating is an option where other low-carbon heating technologies are unsuitable.

  - Both electric storage and electric resistive heating systems were included in our analysis, as standalone systems and as part of hybrid systems with heat pumps. Direct electric heating is deployed in 14% of homes by 2050 in the Balanced Pathway, compared to 8% with direct electric heating today.

  - The use of direct electric heating in our model is limited to flats and park homes; more widespread deployment would have excessive impacts on electricity demand, and use in larger homes would be very expensive.

- Communal heat pumps are shared systems serving a single block of flats or row of terraced houses, including shared ground loops and large air source heat pumps. Communal heat pumps are an important technology for blocks of flats, where space constraints may limit the installation of individual systems.

- Heat networks refer to large, centralised systems, distributing heat to a number of buildings and often connecting to non-residential buildings to provide anchor loads. This technology is only an option for homes in locations where heat networks are likely to be viable and specific research was undertaken to make this assessment (see box 7.2 below).

  - We assume that, for homes that are within a heat network zone as defined by the Arup research described in Box 7.2, this is likely to be the most cost-effective solution.

Box 7.2
Heat network modelling

The CCC carried out a project with Arup to look at potential for heat networks in the UK to inform our advice. This project built upon work Arup had carried out with the Department for Energy Security and Net Zero (DESNZ) on the second National Comprehensive Assessment (NCA), which identified the opportunity for low-carbon heat network deployment across the UK. The NCA model is a spatial model that maps current levels of heat demand and supply across the UK. Combining this spatial data with cost data, the model identifies where heat networks could have economic potential. The model is demand-led, looking to identify demand clusters where heat networks might be suitable, rather than generating the networks based on the sources of supply. The model provides data at a building level, which enabled it to align with the archetype dataset (see box 7.1) in residential buildings and provide the required data for non-residential buildings modelling.

The NCA modelling used in our analysis provided input data on heat networks for the CCC's residential and non-residential buildings models. This modelling was specific to the requirements of our analysis, and therefore several key adjustments were made to ensure the model was fit for this purpose, which included:

- Removing a lower threshold on building size, to allow individual residential properties to be modelled.
- Constraining the geographic radius for large buildings, to manage the size of proposed heat network clusters.
- Updating the pipe cost, to reflect changes since the original NCA modelling.
- Using a weighted average linear heat density, a measure of heat load per meter of district heating pipework, to allow for more accurate estimation of the potential size of each network.

The model was run with these changes implemented, which generated a dataset of heat network potential at building-level. For residential buildings, this potential was added as a variable to the archetype dataset, highlighting properties where a heat network is likely to be an economic solution. Our modelling deploys heat networks to all homes with potential.

Source: DESNZ National Comprehensive Assessment model.[13]

Measure suitability

- The low-carbon heating measures which can be applied to an archetype depend on its existing characteristics. Our model limits the application of low-carbon heating measures to archetypes with particular attributes.
  - The primary constraint on the low-carbon heating measures which are suited to an archetype is the property type (flat, terrace, detached etc) of the archetype.
  - Some measures may be unsuited to homes with particular attributes, such as having a heritage designation or limited internal space. Some measures may only be suited to homes with particular attributes, such as whether the archetype is designated as being in areas where heat networks are viable (see Box 7.2).
  - The flexibility options which can be considered depend on the fabric performance of the archetype, the assumed threshold for allowing for pre-heating, and the availability of thermal stores.

Measure properties

- For each low-carbon heating measure, the model inputs include data on the efficiency, capex, ancillary costs, maintenance costs, demand flexibility and lifetime of the measure.
  - The efficiency of low-carbon heating measures depends on the technology used, the design and installation of the system, and how it is operated.
    - The seasonal coefficient of performance of heat pumps depends on the maximum flow temperature required for space heating. This depends on the fabric efficiency

of the home and radiator sizes. Our model calculates the maximum flow temperature required for space heating (after applying energy efficiency measures) and uses different efficiencies for different flow temperatures.

- Heat pumps should become more efficient in future. We have assumed that heat pump efficiencies will improve at a rate of 1% per year, up to a maximum derived from the top of the interquartile range for low temperature heat pumps in the Electrification of Heat Demonstrator Project[14]. Our model cannot vary heat pump efficiencies by deployment year, so we use an average of the changing efficiency over time, weighted based on expected heat pump deployment. Efficiency gains could come from improvements in performance, installation and use.

- Heat pumps require the heating system to be operated more continuously than with a gas boiler. This can increase the energy demand for space heating. An uplift of 15% has been applied to space heating energy demand for homes that install a heat pump.[15]

– The capex for a low-carbon heating system depends on the system size. For each measure, capex costs are provided as a fixed cost plus a rate per kW of installed capacity.

– The non-fuel maintenance costs for heat pumps are assumed to be in line with the non-fuel maintenance costs of a gas boiler.

– Heating system lifetimes impact on the cost-effectiveness of the technology and the total pathway capex. When calculating cost effectiveness of measures we annualise the capex according to the measure lifetime. Within the timescale of the Balanced Pathway many low-carbon heating measures will require renewal, and these renewals are included in the optimisation calculations and the costs of the pathway.

– Low-carbon heating installations typically require ancillary measures alongside the main system (Table 7.6). These may be one-off investments or have different lifetimes to the main system. For each low-carbon heating measure our model considers a list of ancillary measures which may be required, depending on the existing attributes of the archetype. The model applies the ancillary costs where necessary.

- Ancillary costs may be fixed, or dependant on the heating system size or the size of the home. For each ancillary measure costs are provided as a fixed cost and a rate per kW of installed capacity or m^2 of floorspace.

- Many ancillary measures have lifetimes of ~60 years, which means these represent a one-off cost in our Balanced Pathway. Those with shorter lifetimes create further capex when they require renewal.

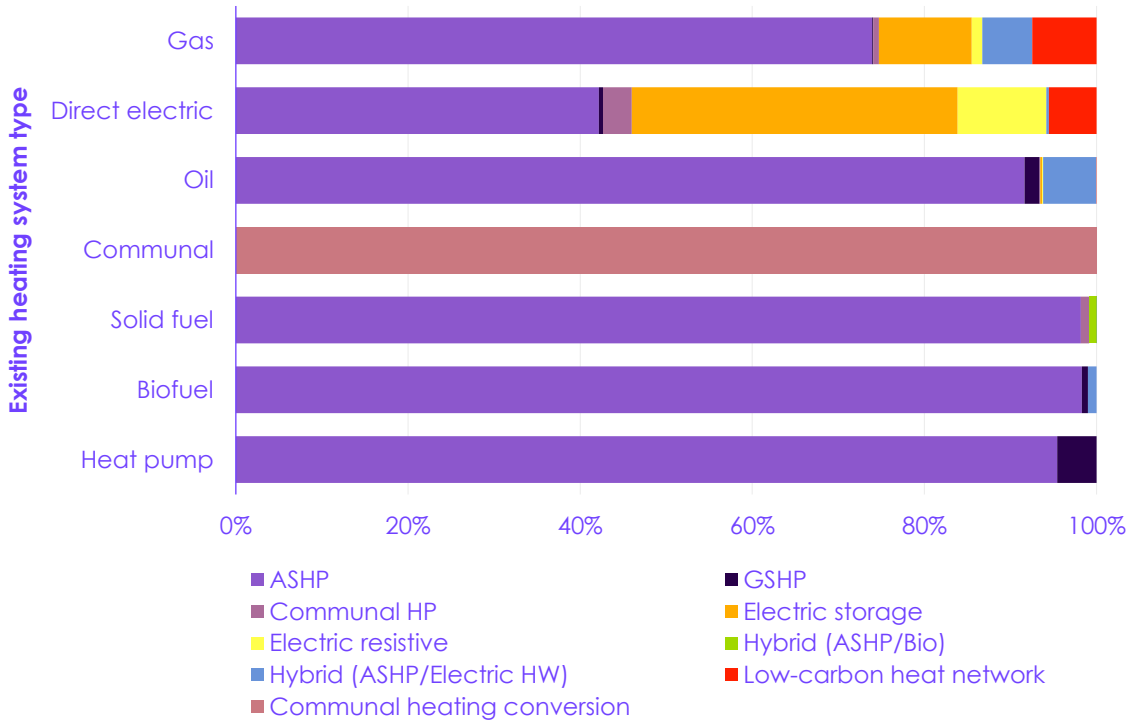
- Data on efficiencies, measure suitability, capex, and lifetimes for low-carbon heating measures were produced for the CCC by PwC.

Table 7.6
Ancillary measures for low-carbon heating

Capex requirement	Required for	Not required for	Fixed capex (£)	Variable capex	Lifetime (years)
Radiator upgrade	Heat pumps with radiator upgrade (to reduce flow temperatures)	Heat pumps with existing radiators, hybrid heat pumps		£18/m^2	30
ASHP retrofit costs	New ASHP installations	Replacement of existing ASHP	£890	£160/kW	60 (one-off)
GSHP retrofit costs	New GSHP installations	Replacement of existing GSHP	£990	£15/kW	60 (one-off)
Install wet heating system	Hydronic heating systems in homes without existing wet heating system	Homes with existing wet heating system	£1600	£21/m^2	60
Remove wet heating system	Existing wet heating system replaced by direct electric system		£310		60 (one-off)
Decommission combustion appliances	Homes with existing fossil fuel boilers		£210	£3/m^2	60 (one-off)
Communal heat pump pipework flats	New communal heat pump installations in flats	Existing communal heating conversions	£4,600		60
Communal heat pump pipework terraces	New communal heat pump installations in terraces	Existing communal heating conversions	£8,500		60
Hot water cylinder	Heating systems requiring hot water storage in homes without an existing hot water cylinder	Homes with an existing hot water cylinder		£42/m^2	30
Point-of-use hot water	Heating systems without hot water storage or instantaneous hot water capacity		£2,100		15
Additional thermal store	Heating systems with highly flexible electricity use for space heating		£1,300	£1/m^2	20
Additional wiring (electric resistive)	New electric resistive heating systems	Homes with an existing direct electric heating system	£930	£8/m^2	60
Additional wiring (electric storage)	New electric storage heating systems	Homes with an existing direct electric heating system	£930	£8/m^2	60

Heat interface unit	Heat networks		£2,600	£12/kW	30
GSHP groundworks urban (boreholes)	GSHP systems in urban areas		-£120	£970/kW	60
GSHP groundworks rural (trenches)	GSHP systems in rural areas		£400	£340/kW	60
Heat network infrastructure	Heat networks			£710/kW	60
Heat network pipes	Heat networks			£730/kW	60

Figure 7.7 Low-carbon heating uptake by existing heating system type



Description: Heat pumps are the main choice for replacing most types of existing heating system.
Source: CCC analysis.
Notes: Air Source Heat Pump (ASHP), Ground Source Heat Pump (GSHP), Heat Pump (HP), Hot water (HW)

Deployment constraints

- For each category of low-carbon heating measure, we assume limits on the annual deployment which can be achieved. These constraints are based on expectations for both supply and demand.

- We assume that boilers and other fossil fuel heating systems are replaced at the end of their life. This avoids scrappage and limits the stock eligible for replacement in a given year.

- We estimated limits on annual deployment by taking current deployment rates for the measure in the UK and applying a compound annual growth rate (CAGR).

  - The current deployment data was taken from the UK Heat Pump Association.[16]

  - Data from the European Heat Pump Association was used to analyse deployment rates for heat pumps in other comparable countries.[17] For each country we calculated the maximum CAGR over five year and three-year periods. We calculated the average of these figures for the top five and top three countries respectively. We used the five-year figure for the Balanced Pathway and the three-year figure in contingency analysis.

- We compared heat pump deployment rates to heat pump demand predictions from the Centre for Net Zero's agent-based model for England and Wales.[18]

  - We asked the Centre for Net Zero to run agent-based simulations where no supplier constraints are applied and with changes to current levels of heat pump awareness and incentives.

  - For these simulations, the Centre for Net Zero's agent-based model assumes current heat pump prices, existing grant levels (until 2028) and an increased BUS funding cap of £770 million per annum from 2027. It assumes a reduction in running costs of heat pumps by lowering policy costs on electricity relative to gas*. It also assumes an increasing level of consumer awareness of the technology over time. Two model runs test the impact of a slower and a more rapid increase in awareness over time. In the first test, awareness increases from 25% in 2024 to 50% by 2028, and then to 75% by 2034. In the second test, awareness increases from 50% in 2024 to 75% by 2028.

  - Based on these assumptions, the model predicts demand for between 260,000 (based on a slower increase of awareness) and 360,000 (based on a more rapid increase in awareness) installations annually achieved by 2028 in existing owner occupier and private rented homes in England and Wales.

  - This demand would be sufficient to meet the Balanced Pathway for heat pump installations until 2028 (200,000) assuming the lower end of the modelled range, and 2029 (280,000) if we assume the upper end of the modelled range in England and Wales.

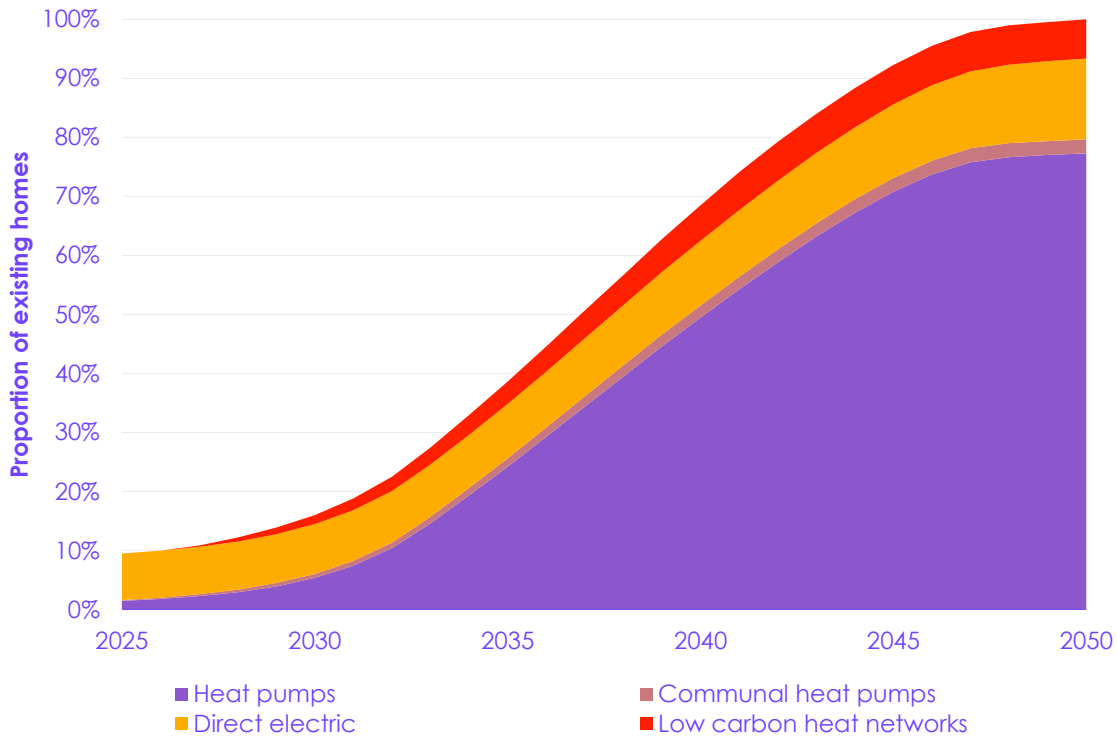
  - To create demand for meeting deployment rates beyond this level, the Centre for Net Zero's modelling implies that further improvements to incentives would be needed.

* The Centre for Net Zero's agent-based model does not forecast changes in fuel prices and instead keeps fuel prices constant throughout simulations. This assumption is distinct from fuel price assumptions we make elsewhere in our analysis.

Table 7.7
Compound annual growth rates (CAGR) in heat pump deployment, international comparisons

Scenario	Countries included	CAGR	Use in model
Average of top 10 countries, highest five-year CAGR	Poland Ireland Slovakia Belgium Germany Czech Republic Italy Netherlands Lithuania Austria	35%	N/A
Average of top 5 countries, highest five-year CAGR	Poland Ireland Slovakia Belgium Germany	42%	Balanced Pathway
Average of top 3 countries, highest three-year CAGR	Poland Ireland Slovakia	72%	Contingency (see Section 7.5)

Figure 7.8 Low-carbon heating deployment in existing homes, by system type



Description: The share of homes with low-carbon heating increases following an S-curve. Among these, the majority are heat pumps.
Source: CCC analysis.

7.2.3 Heat in new homes

Our model assumes that new homes are energy efficient and built with low carbon heating systems, compared to a baseline of being built with a gas boiler to current Building Regulations Part L standards.

- We assume there are no supply chain constraints for installing in low-carbon heating in new homes at the time they are constructed.
- For the efficiency standards of new builds, Part L of the current Building Regulations has been used to define the energy use requirements for new build properties.
- For the heating system standards, the Future Homes Standard proposes all new homes are built with a low-carbon heating system from 2025. We have used this standard in our modelling, such that all new builds are built in accordance with Part L, plus a low-carbon heating system.
- Data on the average heating demand of new build properties under this standard was provided by MHCLG.

7.2.4 Other home energy use

Our model considers all appliances, cooking (gas-powered hobs), and machinery (petrol-powered lawnmowers) in UK homes.

- Existing electrical appliances are all replaced at end of life with more efficient equivalents, reducing indirect emissions from electricity use.
- Gas cooking is phased out in line with gas boilers from 2035. We assume no new gas cookers from this point, and all existing gas cookers are replaced with electric alternatives in line with natural replacement cycles, eliminating the direct emissions associated with the use of gas.
- Petrol-powered lawnmowers are phased out in line with gas boilers from 2035. We assume no new petrol lawnmowers from this point, and all existing petrol lawnmowers are replaced with electric alternatives at end of life, eliminating the direct emissions associated with the use of petrol.
- Table 7.8 details the different appliances we account for in the pathway, and what the pathway assumes about the demand reduction achieved by using more efficient appliances.

Table 7.8
Appliances, cooking, and household machinery measures

Baseline appliance	Pathway appliance	Energy savings between baseline and pathway appliances (kWh saved per appliance per year)
Halogen lightbulbs	LED lightbulbs	18
Chest freezer	Efficient chest freezer	169
Fridge freezer	Efficient fridge freezer	251
Refrigerator	Efficient refrigerator	110
Upright freezer	Efficient upright freezer	172
Washing machine	Efficient washing machine	70
Tumble dryer	Efficient tumble dryer	85
Dishwasher	Efficient dishwasher	66
Electric oven	Efficient electric ovens	62
TV	Efficient TV	207
Gas hob	Electric hob	88
Gas oven	Electric oven	74
Petrol lawnmower	Electric lawnmower	48 / hectare of lawn

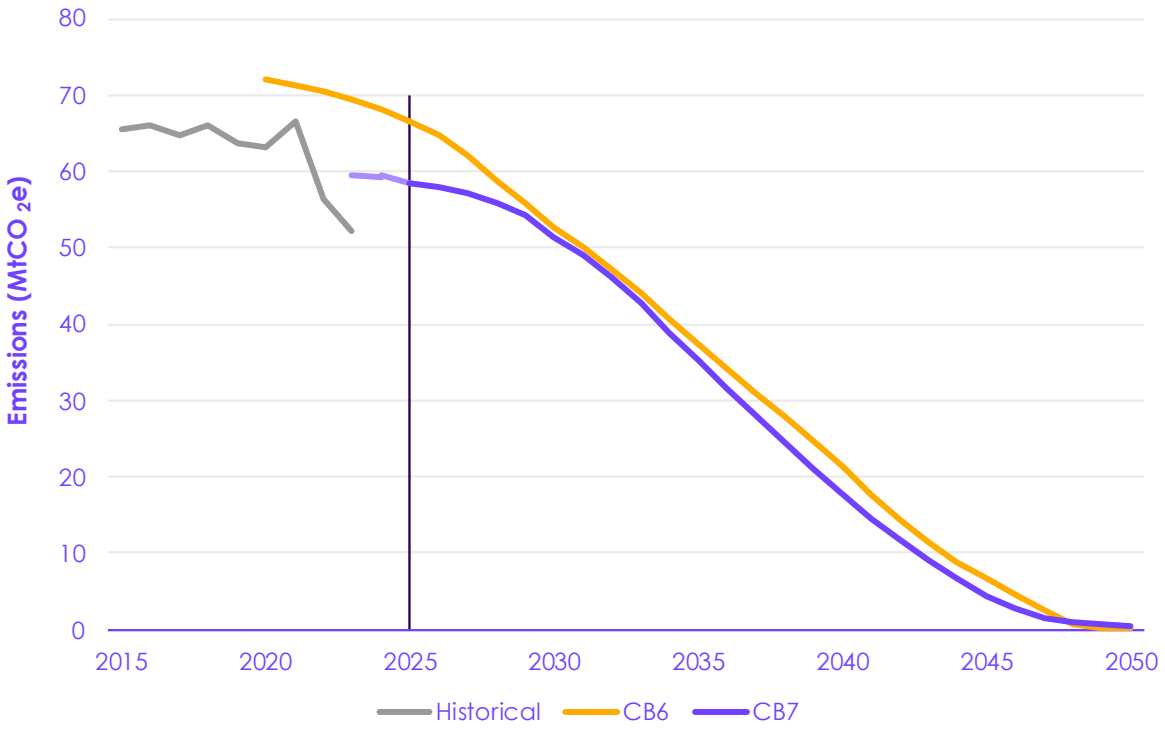
7.3 Changes since our Sixth Carbon Budget advice

7.3.1 Comparison with our Sixth Carbon Budget pathway

There has been a sharp fall in emissions since 2021, resulting in emissions now being considerably below our Sixth Carbon Budget pathway.* An update to our baseline methodology to better reflect the effect of rising average temperatures has also played a role in reducing the starting point of our updated Balanced Pathway. Uptake of heat pumps is expected to grow more steadily than in our Sixth Carbon Budget trajectory, which means that emissions fall more slowly than in the previous analysis, closing the gap between the pathways by the early 2030s. By this point, the heat pump market needs to be operating at scale to allow emissions to fall quickly (Figure 7.9).

* All comparisons in this section compare the Balanced Pathway in this advice with the Balanced Net Zero Pathway in our Sixth Carbon Budget. Our Sixth Carbon Budget advice also included four other exploratory pathways, which are not discussed here. Data for those pathways can be found in our Sixth Carbon Budget advice.

Figure 7.9 The Balanced Pathway for residential buildings compared to our Sixth Carbon Budget advice



Description: Emissions in our Seventh Carbon Budget (CB7) Balanced Pathway begin below those in our Sixth Carbon Budget (CB6) pathway. Emissions fall more slowly in the early years, as uptake of heat pumps grows more steadily than in our CB6 pathway.
Source: CCC analysis.

7.3.2 Emissions changes since our Sixth Carbon Budget advice

There has been a sharp fall in emissions since 2021, which is mostly due to behavioural response rather than action to mitigate the impacts of climate change.

- The emissions reductions since 2021 have been driven by mild winters and behavioural responses to very high gas prices. We assume that some of these behavioural responses rebound when energy prices normalise.

- Uptake of heat pumps and other low-carbon heating technologies is still low, with around 60,000 heat pump installations in 2023. Significant scale up is still required in order for heat pumps to be deployed at scale.

7.3.3 Key pathway differences compared to our Sixth Carbon Budget advice

There are several key areas in which the deployment rates, measures included, or underlying assumptions in our updated Balanced Pathway have been revised since publication of our Sixth Carbon Budget advice in 2020. These include:

- **Heat pumps.** For our Seventh Carbon Budget pathway, we have modelled an S-curve roll-out for heat pumps, starting from today's installation rates and growing based on the rate at which sales have ramped up in other comparable countries. This results in lower sales in the 2020s than in our Sixth Carbon Budget pathway, although the market needs to grow quickly during this period and beyond (Figure 7.10).

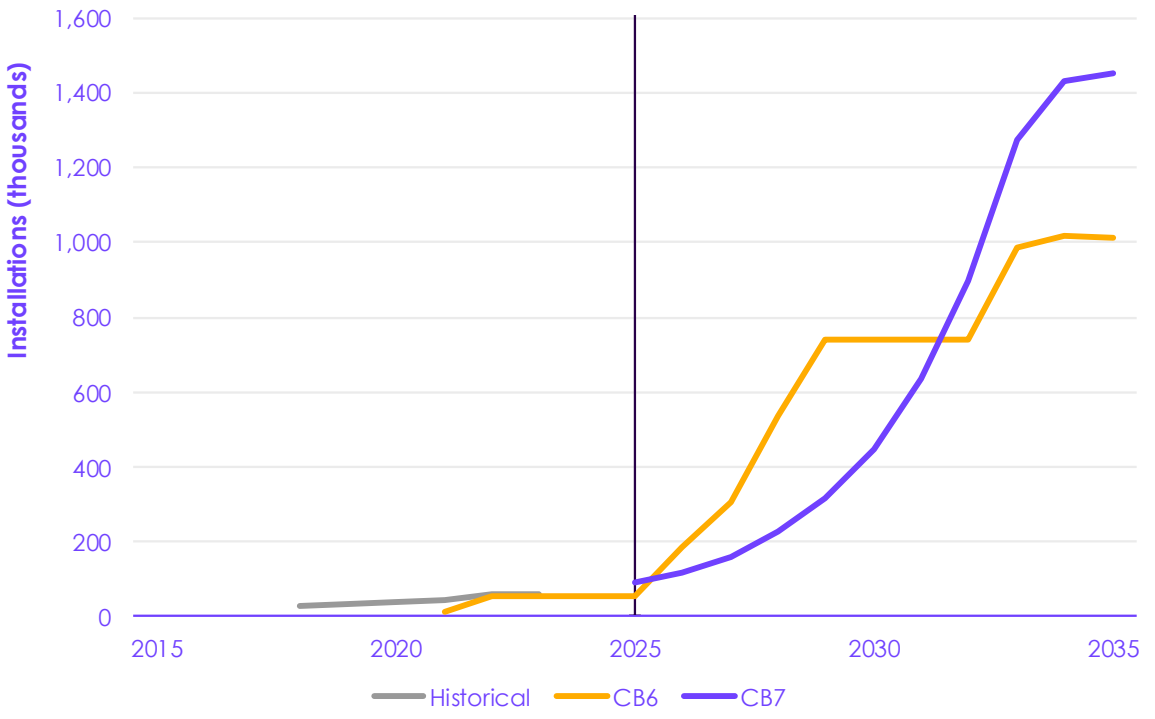
- We assume in our Seventh Carbon Budget advice that all new builds are built with low-carbon heating – any that are not will require retrofitting at additional cost.

- In our Sixth Carbon Budget advice, the Committee projected that annual heat pump installations in both new and existing homes would reach over a million by 2030. In the Seventh Carbon Budget, annual heat pump installations in new and existing homes reach around 750,000 by 2030. Reaching 750,000 installations by 2030 requires rapid scale up of the supply chain for heat pumps.

- A smaller share of homes are connected to heat networks in our Balanced Pathway than in our Sixth Carbon Budget analysis, while our Balanced Pathway now focusses entirely on electrified heating technologies – there is no role for hydrogen in home heating.

- **Energy efficiency measures.** While we do not have a directly comparable indicator, it is likely the case that our pathway now has less big energy efficiency, such as wall and floor insulation, being installed in the 2020s and early 2030s, in part due to the latest evidence suggesting that a 'fabric first' approach to heat pump installation is no longer required for all homes. Our modelling suggests most homes could benefit from smaller energy efficiency measures, such as draught proofing and hot water tank insulation. In our modelling, energy efficiency measures are all frontloaded into the period before the early 2030s, due to less restrictive assumed constraints on their deployment and because they can support the roll-out of low-carbon heating by ensuring that heat pumps can be more properly sized for the fabric efficiency of the property.

Figure 7.10 Key differences in deployment trajectories in the Balanced Pathway for residential buildings compared to our Sixth Carbon Budget advice



Description: Heat pump installations scale up following an S-curve profile, meaning that these grow more steadily in the early years of our pathway than in our previous advice.
Source: CCC analysis.
Notes: The chart is shown only to 2035, as this is the point in our Balanced Pathway at which low-carbon heating is assumed to reach the full market for new heating installations.

7.4 Uncertainties and sensitivity analysis

The mix of technologies, rate of measure deployment, and pace of decarbonisation in our pathway are influenced by a range of factors. The outputs of our model depend on the values of inputs which are inherently uncertain, such as capex costs and fuel prices. The results also depend on assumptions about the priority given to policy concerns such as affordability and fuel poverty. We undertook sensitivity analysis to investigate the impacts on the pathway of variations in a number of inputs and assumptions. See Chapter 5 for our general approach to uncertainty, including descriptions of the methodology behind sensitivity tests that apply across multiple sectors.

- A lack of robust data on the influence of lifetime measure costs on supply chains, and limitations imposed by our approach to modelling measure deployment pathways, mean that the impacts of variations in fuel prices on the pathway could not be assessed. This could be addressed in future, with better data and modifications to the model design.

- Choices about energy efficiency and low-carbon heating deployment impact on affordability and fuel poverty. We undertook a sensitivity analysis to assess the impacts of requiring additional energy efficiency measures (beyond those which are cost-effective) for households in fuel poverty.

The measures in our pathway provide an indication of the scale of deployment of the technologies required. The actual choice of technologies will depend on a range of factors including: how actual costs and performance differ from our assumptions; and the incentives faced by homeowners in the real world.

7.4.1 Energy efficiency to address fuel poverty

Fuel poverty is defined as a household that has an income below the poverty line after fuel costs and has an EPC rating of D or below. Energy efficiency measures improve the energy performance of homes and thus reduce fuel poverty. Additional energy efficiency installations, compared to the Balanced Pathway, may be required to meet Government fuel poverty objectives. We have modelled a scenario to look at the impact of additional energy efficiency measures for fuel poor homes specifically.

- In this sensitivity, non-fuel poor homes are treated as described for the Balanced Pathway. For homes in fuel poverty, measures are deployed based on the overall energy savings of packages of measures over their lifetime, regardless of cost. This means that fuel poor homes receive all suitable energy efficiency measures, a notable increase compared to the Balanced Pathway.

- All measures additional to the Balanced Pathway are installed in fuel poor homes. This equates to 1.5 million solid wall insulation installations, 600,000 cavity wall insulation installations (including hard to treat) and 3.4 million floor insulation installations.

- Increasing the deployment of energy efficiency measures presents additional upfront costs of roughly £2.4bn annually.

- Increasing the level of energy efficiency brings forward demand reduction in the Balanced Pathway, meaning that abatement is achieved earlier – equivalent to emissions being 20% lower than the Balanced Pathway in 2040.

7.5 Contingencies in residential buildings

Contingency options are action plans that can be implemented to deliver additional emissions reductions to make up for shortfalls in the pathway. The contingencies that we have modelled in the residential buildings sector are shown in Table 7.9. See Chapter 5 for our general approach to contingency analysis.

Table 7.9
Contingency options in residential buildings

Contingency	Description	Potential average annual emissions savings ($MtCO_2e$, % of sector emissions)			
		2030	CB6	CB7	2050
Earlier action to scale up residential heat pump markets	Using a higher compound annual growth rate in the low-carbon heating supply chain (the average growth rate in the top 3 comparator countries – see Table 7.7)	2.2 4%	4.8 14%	4.7 26%	
Scrappage of older residential gas boilers	Reducing the lifetime of existing heating systems in all owner-occupied homes to 10 years, regardless of existing heating system, to proxy early replacement of heating systems (see Table 7.5 for details of lifetime by heating system)	0.3 1%	2.4 7%	4.4 25%	

Source: CCC analysis.
Notes: We have blanked out cells where the contingency measure in question is estimated to deliver less than 0.3 $MtCO_2e$ in potential emissions savings, to focus on high-yield options.

7.5.1 Earlier action to scale up residential heat pump markets

The supply chain for heat pumps needs to rapidly develop to facilitate the installations required to meet Net Zero targets. As described in Section 7.2, our assessment of how quickly the supply chain can grow is based on analysis of heat pump roll outs in other countries in Europe. This contingency action assumes a higher rate of growth in the supply chain for heat pumps compared to the Balanced Pathway, and only affects the deployment of heat pumps.

- The contingency action assumes a compound annual growth rate of 72%. This is scaled up from the current rate of 18% over 2 years. This comes from the same analysis as our central assumption (42%).
- To achieve this, the supply chain would need to scale up at a rapid speed, requiring significant investment into jobs and skills.
- If the supply chain is scaled up more quickly, then the natural replacement rate for current heating systems can be reached earlier, allowing for earlier deployment of heat pumps. This would yield earlier abatement in the pathway, with 4.8 $MtCO_2e$ of additional emissions reduction by 2040.

7.5.2 Scrappage of older residential gas boilers

In the Balanced Pathway, it is assumed that heating systems are only replaced at the end of their life. In this contingency action, all homeowners (excluding landlords) replace their heating system before the end of its life. This affects the deployment of low-carbon heating only.

- In this contingency, the baseline heating system lifetime is reduced to 10 years for all owner-occupied homes. This is based on the frequency at which mortgaged homeowners have moved in the last 10 years.
- To achieve this, there would need to be significant incentives in place to encourage homeowners to switch to a low-carbon heating system ahead of their current system reaching the end of its life.
- This contingency action would bring forward abatement in the pathway, with 2.4 $MtCO_2e$ additional emissions reduction by 2035.

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Chapter 8: Industry

Introduction

The industry sector includes all manufacturing (except fuels, which are covered in our fuel supply sector) as well as non-road mobile machinery.

We developed the Balanced Pathway for industry by assessing the extent, pace and cost of deploying various low-carbon measures, against a counterfactual baseline in which these measures are not adopted. This is done using models that select options with the lowest total system cost out to 2050. For the manufacturing sector options are compared at the level of individual sites.

We used two separate approaches and models to develop the industry pathway:

- The approach for the manufacturing sector, which includes all industrial subsectors except non-road mobile machinery. We modelled this sector using NZIP2 (Net Zero Industry Pathways model) – a least cost optimisation model developed by the Department for Energy Security and Net Zero (DESNZ). We worked with DESNZ to develop NZIP2, ensuring the model is able to meet our specific requirements.

- The approach for the non-road mobile machinery sector (NRMM), which includes a wide range of machinery used in the mining, construction, ports and waste sectors. We developed our pathway for the decarbonisation of this sector using a least-cost optimisation model commissioned by DESNZ in 2023.

- For both NZIP2 and the NRMM model we used our own assumptions for many inputs, such as those relating to technologies, infrastructure and costs. We also included assumptions about the emissions reductions that can be achieved through efficiency savings.

8.1 Baseline emissions in industry

Our baseline for industry represents a scenario in which there is no further decarbonisation action by either the Government or the market in the industry sector. In this scenario, emissions would fall by 2% from 2023 levels by 2040 (the middle of the Seventh Carbon Budget period) and rise by 8% by 2050 (Figure 8.1), driven largely by changes in industrial output. See Chapter 1 for our general approach to baselines.

Our baseline for industry is based on the following assumptions:

- The emissions baseline starts aligned to historical emissions for 2023, based on the National Atmospheric Emissions Inventory (NAEI).[1] Energy starting points are calibrated to the NAEI Energy Background Dataset, which underpins the UK's GHG inventory.[2]

- The baseline is based on the UK Government's Energy and Emissions Projections (EEP) reference scenario, as published in October 2023.[3]

  - The EEP reference scenario assumes that overall industrial output and emissions fall slightly until 2031 and then rise slightly to 2040 (the last year of the EEP). Our baseline extrapolates this rise in the 2030s out to 2050.

  - The industry baseline is a bespoke scenario for the CCC which follows the trend of the EEP reference scenario, but with the effect of efficiencies and climate policies removed. This aligns with our cross-economy baseline approach where low-carbon technologies generally remain at today's stock levels.

  - Total emissions in 2023 for each industry subsector is based on the UK's GHG inventory and data from the UK ETS.

  - Fuel use in 2023 in each industry subsector is based on the UK Government's *Energy consumption in the UK* statistics.[4]

- For our modelling we estimated a figure for iron and steel emissions in 2023 (9.8 $MtCO_2e$) using UK ETS reporting for 2023.[5] Our estimated value was higher than the figure in the UK Government's provisional emissions estimates for 2023 (8.1 $MtCO_2e$) and closer to the final figure of 12.5 $MtCO_2e$ (released after publication of our Seventh Carbon Budget advice report).[6]

- The UK's future industrial output, and therefore industrial emissions in a baseline scenario, are uncertain. The UK has seen a long-term trend of falling output of emissions-intensive industrial goods. In the baseline this trend slows and then reverses.

  - The Government published a revised EEP reference scenario in December 2024, after we had finalised our modelling.

- The industry baseline assumes that industry continues to deploy the same range of production technologies that are available today. The baseline also:

  - Assumes that Port Talbot blast furnaces are still operating so we can account for the planned installation of an electric arc furnace.

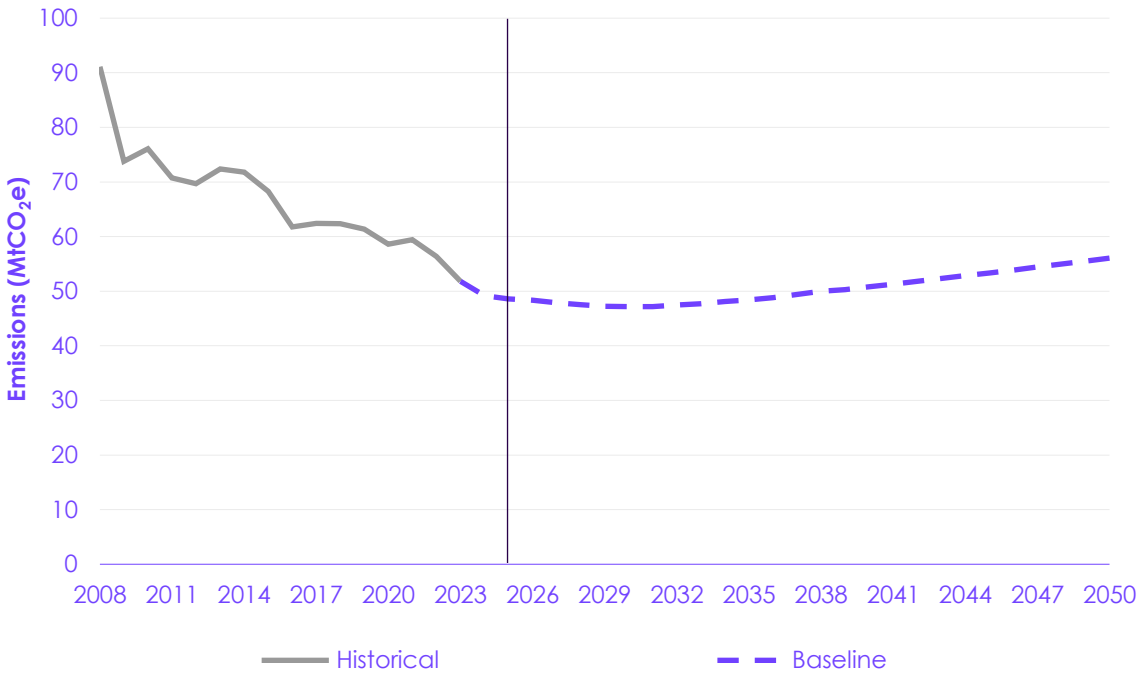
  - Includes no CCS, hydrogen or newer electric heating technologies, such as heat pumps.

  - Assumes no specific energy efficiency measures, but includes some energy efficiency improvements as end-of-life equipment is replaced with newer, more efficient kit.

  - Assumes no abatement from resource efficiency.

  - Includes estimates of the current efficiencies and capital costs of new and replacement high-carbon industrial equipment, fixed operating costs, and our standard baseline energy costs. These estimates are taken from the UK TIMES model, which is underpinned primarily by UKERC's useable energy database.[7;8]

Figure 8.1 Baseline emissions in industry



Description: Baseline emissions for industry fall slightly and then rise out to 2050, driven largely by changes in industrial output.
Source: CCC analysis.

8.2 Pathway assumptions and modelling for industry

8.2.1 Modelling the Balanced Pathway for manufacturing

Overall modelling approach

The manufacturing sector (which represents all of industry except NRMM) is modelled using NZIP2 – a least cost optimisation model developed by DESNZ (Figure 8.2). See Chapter 1 for our general approach to pathway analysis.

- NZIP2 splits manufacturing into 15 subsectors.* For each subsector it includes assumptions about incumbent technologies, emissions, energy and non-energy inputs and annual production outputs. For our modelling outputs we condensed the number of manufacturing subsectors to nine (Table 8.1).

- For each industrial site in the UK, the model selects sufficient technological capacity to allow it to produce a certain level of output (e.g. tonnes of cement). NZIP2 includes over 400 high- and low-carbon industrial technologies, each representing a type of machinery or method of production for a specific subsector. These low-carbon technologies involve

* In total the model includes 17 subsectors but we excluded two that are in our fuel supply sector: refineries and hydrogen production.

either low-carbon energy (electricity, hydrogen or bioenergy) or CCS capture. Assumptions about technologies include operating and capital costs, fuel efficiency, load factor, lifetime and first year of availability.

- All types of industrial output can be produced using a range of both fossil fuel and low-carbon alternatives. Output quantities for all subsectors are the same as in the baseline.

- The model selects technologies that minimise the total system cost over the 2021 to 2050 period (Box 8.1). The calculation of total system cost takes account of:

  - Carbon value of abated emissions.

  - Capital costs of equipment.

  - Energy costs and other operating costs.*

  - Capital and operating costs of CCS and hydrogen infrastructure.

- As NZIP2 accepts only a single value for the capital and fixed operating costs of equipment, we were not able to model potential reductions in these costs over time. Such reductions, which often occur with developing technologies, would lower the capital costs of industrial decarbonisation and speed up deployment.

- As the carbon value increases year-on-year, the likelihood of switching to low-carbon technologies grows. We use supply chain and technology constraints to guide a feasible pace of deployment. As far as possible, these are based on relevant historical examples.

- All equipment is assumed to be reinstalled at the end of its lifetime (if this happens by 2050). Early scrappage of high-carbon equipment is allowed, where cost-effective versus the carbon values.

- NZIP2 outputs include emissions, energy demands, capital and operating costs, CO_2 transport volumes, and the start and end points of hydrogen and CO_2 pipelines. It provides these outputs at site, cluster and subsector levels.

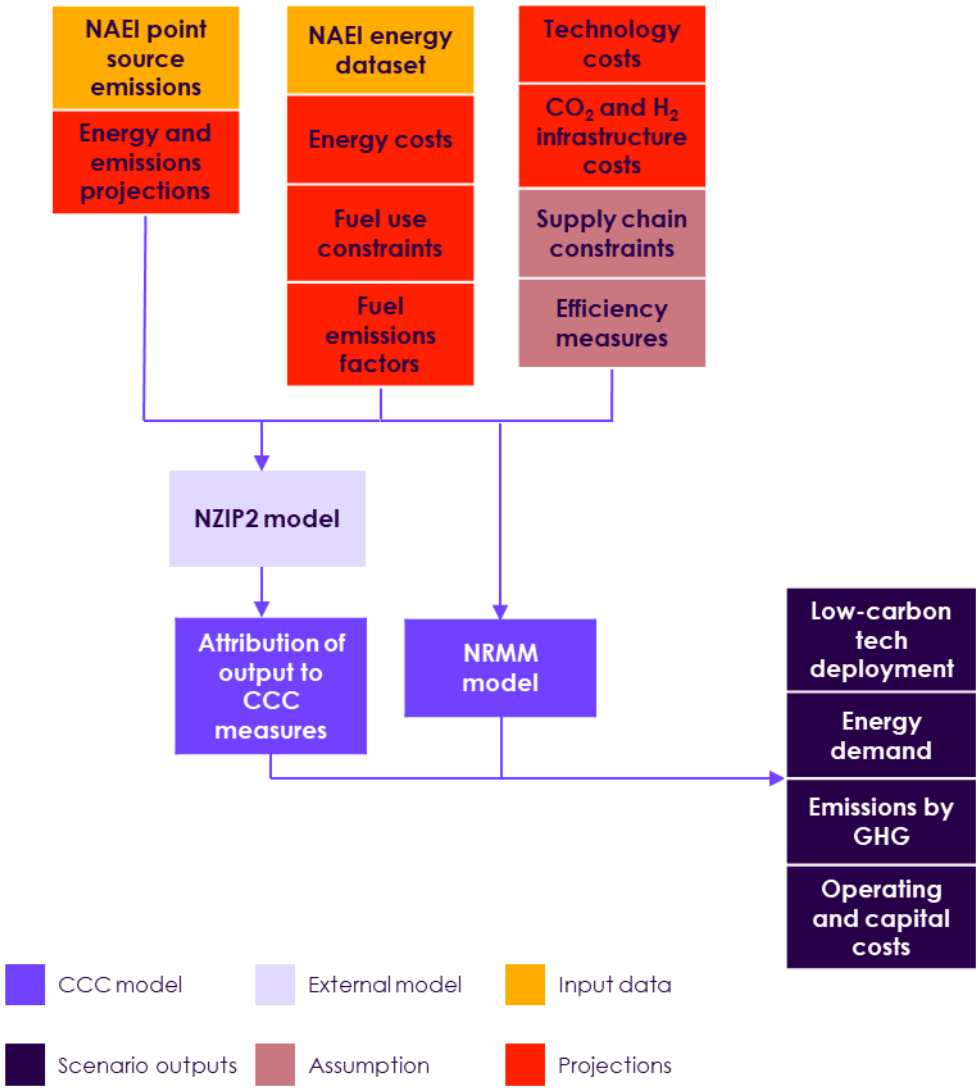
- The main assumptions for the over 400 technologies are based on those in UK TIMES model, which are underpinned primarily by UKERC's useable energy database.[9;10]

- The CCC refined some assumptions used by NZIP2. Our assumptions for carbon values and energy costs are set out in Section 1.7, emissions factors for different fuels in Section 1.8, discount rate and optimism bias in Section 2.1, and bioenergy consumption constraints in Chapter 12. Further CCC assumptions about technologies including CCS and hydrogen are outlined below.

- Emissions reductions from resource efficiency and energy efficiency are included in NZIP2 as inputs. The model adjusts energy and emissions baselines to account for these efficiency measures. All other alternative technologies are deployed subsequent to this baseline adjustment. We describe our approach to developing energy efficiency and resource efficiency assumptions below.

* Energy costs are based on long-run variable costs – see Section 1.7.

Figure 8.2 Modelling schematic for industry



Source: CCC analysis.
Description: Our industry pathway outputs are based on modelling using NZIP2, plus an in-house NRMM model.
Notes: Inputs are grouped, from left to right, by emissions, energy, and technology. Certain inputs flow into NZIP2 only. NAEI = National Atmospheric Emissions Inventory; EEP = Energy and Emissions projections. This diagram is illustrative and does not detail all model inputs and outputs.

Table 8.1
Manufacturing subsectors in NZIP2

9 subsectors in final outputs	15 subsectors in NZIP2 model
Iron and steel	Iron and steel
Cement and lime	Cement Lime
Chemicals	Chemicals
Glass and other minerals	Glass Ceramics
Food and drink	Food and drink
Paper	Paper
Other industry	Construction Electrical engineering Mechanical engineering Other industry Textiles
Non-ferrous metals	Non-ferrous metals
Vehicles	Vehicles

Box 8.1
Net present value calculations in NZIP2

The NZIP2 model maximises national net present value to 2050 while meeting industrial demand. It does this by selecting the technology options with the lowest total cost. To identify these lowest cost options, the model calculates the present value at each site, summed to 2050. The present value (PV) is the sum of eight cost components:

$$PV(t) = PV_{\text{technology capex}}(t) + PV_{\text{fixed opex}}(t) + PV_{\text{fuel costs}}(t) + PV_{\text{carbon cost}}(t) + PV_{\text{site H2 T\&S}}(t) + PV_{\text{site CO2 T\&S}}(t) + PV_{national\ CO2\ T\&S}(t)$$

Where:

- t: cumulative over 2021-2050 period
- $PV_{\text{technology capex}}$: the cost of buying a unit of new technology
- $PV_{\text{fixed opex}}$: operating cost of a unit of technological capacity
- $PV_{\text{fuel costs}}$: cost of fuel needed to run a unit of technological capacity
- $PV_{\text{carbon cost}}$: amount of emissions emitted at each site multiplied by in-year carbon value
- $PV_{\text{site H2 T\&S}}$: combined capex and opex cost of hydrogen pipeline between a site and cluster
- $PV_{\text{site CO2 T\&S}}$: combined capex and opex cost of a CO_2 pipeline between a site and a cluster
- $PV_{\text{national CO2 T\&S}}$: cost of shipping a unit of CO_2 from a cluster to a storage site

The first six PV components are site-level; the last is system-wide, summed across all CO_2 pipelines

Industrial sites

NZIP2 includes over 800 named industrial sites (called 'point sources'), which account for about 65% of modelled emissions in 2023.* Industrial sites' name, sector, location and annual emissions are sourced from the NAEI data (2021). Every site is allocated to its nearest industrial cluster (Box 8.2), based on cluster centre points. Sites outside a 30 km cluster radius are designated as 'dispersed' sites.

- The remaining approximately 35% of industrial emissions recorded in the UK's GHG inventory are from 'non-point sources' – smaller industrial sites not listed in the NAEI site data. NZIP2 assigns these non-point source emissions to 12 UK regions, weighted by the number of businesses of each subsector type in each region, as reported by the Office for National Statistics.[11] For each subsector and region the model creates one artificial site inside a cluster and another outside the cluster, and allocates regional non-point source emissions to these artificial sites. Each of the artificial modelled sites can represent multiple sites in the real world.

- The model apportions a level of production output to each site based on its emissions. For the artificial sites these emissions are estimated based on current subsector emissions data.

The Balanced Pathway for industry

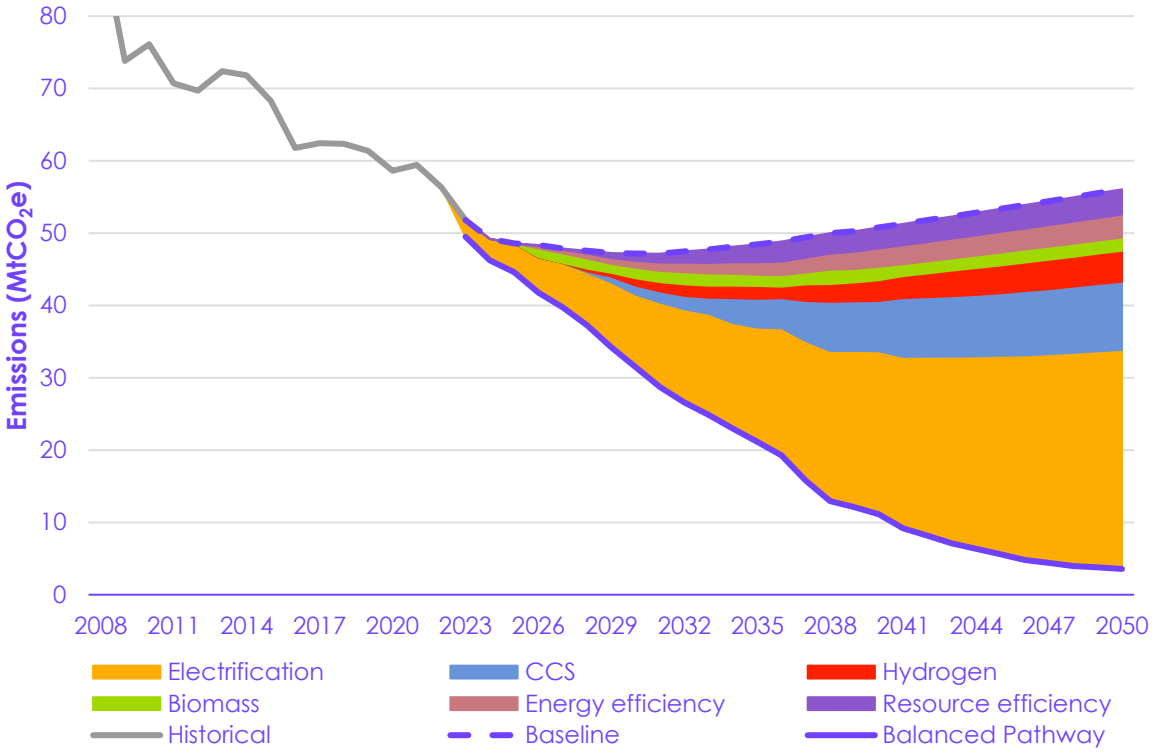
The largest share of emissions reduction in the Balanced Pathway for industry is from the electrification of heat processes. This is complemented by fuel switching to hydrogen and bioenergy (Figure 8.3).

- CCS is important for dealing with industrial process emissions that cannot be avoided by fuel switching.

- Resource efficiency and energy efficiency reduce industrial emissions by reducing demand for materials and energy respectively.

* Most of these 800 sites are participants in the UK ETS and submit emissions data as part of that scheme.

Figure 8.3 Sources of abatement in the Balanced Pathway for industry



Description: The largest share of emissions reduction in industry is from electrification. Contributions also come from CCS, hydrogen, resource efficiency, energy efficiency, and biomass.
Source: CCC analysis.
Notes: The industry baseline is based on the UK Government's Energy and Emissions Projections, with an adjustment to remove the effect of efficiency and climate policy. The decline in baseline emissions to 2032 reflects recent trends and the subsequent rise to 2050 reflects Government assumptions about a future increase in industrial output. Industry also achieves emissions reductions through BECCS (0.8 $MtCO_2e$ in 2050), but we account for this in our removals pathway, rather than the industry pathway.

The measures in our pathway

Table 8.2 summarises the measures considered in our modelling, how these lead to emissions reductions in our industry pathway, and the key factors influencing their uptake. The methodology used to develop the assumptions and underpinning analysis is described in the rest of this section.

Table 8.2
Measures considered within our modelling for industry

Decarbonisation measure	How does this measure influence emissions in our modelling?	What are the key factors that affect uptake in our modelling?
Electrification	Electric technologies are used in our modelling to replace fossil fuel-based heating processes in industry, as well as petrol/diesel-powered non-road mobile machinery. Electrification removes direct emissions from combustion.	Electrical alternatives are the dominant option selected (particularly heat pumps), despite supply chain constraints which slow their rate of deployment. In many cases they are most cost-effective option, with the higher cost of electricity compared to fossil fuels largely offset by the greater energy efficiency of many electric alternatives. We model the UK's remaining integrated steelworks electrifying, in-line with their owners' plans. Where electrical technologies were not selected it was either because there was no available electrical

		option (e.g. in cement) or because we applied a deployment constraint to the electrical option(s).
Carbon capture and storage (CCS)	CCS captures and permanently stores combustion and process emissions from industry. When combined with bioenergy it delivers carbon removals.	CCS is selected in sectors with significant process emissions which have few viable alternative decarbonisation options. It becomes available as an option to sites in the year their nearest cluster starts storing CO_2. CCS is important for abatement in the chemicals and cement and lime sectors.
Low-carbon hydrogen	Low-carbon hydrogen reduces emissions by replacing fossil fuels in industrial combustion processes.	Hydrogen is typically selected where alternative options are limited. It becomes available as an option to sites in the year their nearest cluster starts producing hydrogen, after which it can be delivered by pipeline or trucking. Both the high cost of hydrogen fuel and its limited geographic availability restricted the selection of hydrogen options. It is mostly selected in the chemicals, ceramics, glass and non-road mobile machinery sectors.
Bioenergy	Bioenergy reduces emissions where it replaces fossil fuels in industrial combustion processes.	Bioenergy has wide potential as a replacement for fossil fuels with low capital and fuel cost requirements. However, it plays a minor role in the industry pathway as sustainable supply is limited and we constrained its use, prioritising it for subsectors that deploy CCS, as well as non-road mobile machinery. See Section 12 for discussion of optimal biomass use. In the cement sector it combines with CCS to deliver carbon removals (BECCS).
Resource efficiency	Resource efficiency means reducing the amount of, or emissions-intensity of, materials required for an economic activity. This can be done by material switching, reducing consumption or producing goods with less material input.	We assumed annual rates of abatement from resource efficiency for each subsector. These rates were based on CCC analysis to interpret, refine and apply research commissioned by DESNZ. Resource efficiency starts at a low level in 2025 and ramps up until 2035, after which its effect on emissions reduction remains flat to 2050. In our pathway resource efficiency has most impact in the cement subsector, but provides some abatement in all subsectors, except non-road mobile machinery.
Energy efficiency	Using energy more efficiently reduces operating costs while cutting emissions.	We assumed annual rates of abatement from energy efficiency for each subsector, based on research commissioned by DESNZ. We selected a plausible level of energy efficiency in between business-as-usual and maximum technical potential. Energy efficiency plays a small but important role in all subsectors but is more significant in non-road mobile machinery. It starts at a low level in 2025 and in most subsectors continues increasing until 2050.

8.2.2 Electrification of heat

There is a broad range of electric alternatives to industrial heating systems run on fossil fuels. We included electrical heating options that are readily available today, as well as those that we consider will become commercially available by or before 2030.

The CCC updated the NZIP2 assumptions for electrical technologies that we considered likely to be important. For example, we used our own assumptions for industrial heat pumps, electric boilers, glass furnaces, electric steam crackers and electric arc furnaces.

- The assumptions we focussed on reviewing and updating were capital cost, first year of availability, fuel efficiency and lifetime (Table 8.3).

- To develop these assumptions, we engaged with industry trade associations such as British Glass and UK Steel, as well as companies with experience of designing industrial energy systems. We also carried out a review of relevant sources such as academic research, unpublished government research, and research by overseas governments.[12;13]

- The model includes specific electrical heating technology options for all industrial subsectors except cement and lime. The assumed heat output of electrical options ranges across the full temperature range required by industrial processes. Most subsectors also have options for an electric boiler and a high-temperature electric option. High-temperature processes are those above about 200°C, low-temperature processes are 200°C and below.

- Some electrical options for industry are not widely available today but are expected to become so in the near future. For these technologies we found evidence for their initial year of commercial availability, after which they can play a role in our pathway (Table 8.3).

- Operational costs are based on fixed operating costs and fuel costs, with the latter being far more significant. Fuel costs for each technology are calculated according to its efficiency and the energy costs as set out in Section 1.7.

- A limitation of NZIP2 is that it is unable to take account of the time required to deliver any required network connection upgrades to accommodate electrification. In general, the model deploys technologies as soon as they become available and cost effective, so we use supply chain constraints to simulate connection timelines and other delays (see section on supply chain and deployment constraints below).

Table 8.3
Assumptions for key electric heating options

Electric technology	Capital cost	Efficiency	First year of availability	Lifetime (years)
Boiler	£22 (per MWh capacity)	90%	2020	25
Heat pump	£86 (per MWh capacity)	255%	2028	20
Higher-temp heat pump	£86 (per MWh capacity)	*	2030	20
Electric furnace - glass	£164 (per tonne output)	85%	2028	8
Electric steam cracker - chemicals	£800 (per tonne output)	N/A	2029	20
Electric arc furnace - steel	£250 (per tonne output)	60%	2020	25

Source: Danish Energy Agency; AMP Energy; British Glass; UK Steel.
Notes: (1) Heat pump data estimated using data Danish Energy Agency and other sources. (2) Glass furnace estimated using data from British Glass. (3) Electric arc furnace data based on various sources and corroborated by UK Steel. (4) *Higher-temperature heat pumps replace combined heat and power plants. But as they replace only the heat output of those plants, not the electricity generation, their comparative efficiency is not a straightforward percentage.

There were also a range of electric technologies that we excluded as options for the model after considering their current readiness and costs, but these technologies could become viable options in the future subject to further innovation and development.

- Electric calciners have the potential to reduce combustion emissions from the manufacture of lime and cement. This technology was not included as the model has difficulty combining technologies that reduce combustion emissions with CCS (the dominant option for cement and lime), which abates both combustion emissions and process emissions. In reality, electric calciners could be an option worth exploring as they improve the concentration of CO_2 in flue gases.

- Electric heat batteries, an emerging technology that converts electrical energy into stored heat which can be discharged on demand. This was not selected as its business case relies heavily on the ability to use electricity when it is cheap. A limitation of NZIP2 is that it is assumes a static electricity cost in any given year, so is unable to factor in the benefits of flexible use.

- Electric technologies with low technological readiness (below TRL 6) were excluded, for example, electric cement and brick kilns, microwave-assisted brick kilns and electrolytic methods of steel production.

8.2.3 Carbon capture and storage (CCS)

In principle, CCS could be used to tackle emissions from any industrial process. In practice, its use is likely to be restricted to industrial subsectors with significant process emissions or where switching from fossil fuels is not practical or cost-effective.

We worked with DESNZ to identify the following industrial subsectors where CCS is available as an option: cement, lime, chemicals, and iron and steel. For cement and lime, it is the only site-based decarbonisation option available. Section 1.7.2 sets out our general CCS assumptions that we also applied in industry, such as capture technologies, transport, storage costs and start dates.

- In the UK the future deployment of industrial CCS is reliant on the development of CCS infrastructure and a wider CCS industry, primarily at industrial clusters (Box 8.2). We have assumed CO_2 injection starts to become available in the most advanced clusters from 2028 (see Section 1.7.2). We have assumed the earliest feasible start dates for all industrial clusters.

- In our pathway CCS is only available as an option for industrial sites with process emissions but is assumed to capture both combustion emissions and process emissions. Process emissions comprise 75% of the captured emissions in the industry pathway. We have assumed that CCS technologies capture 90% of emissions until 2040, and 95% from 2041 onwards (see Section 1.7.2).

- NZIP2 calculates the capital and operating costs of CO_2 pipelines, according to their capacity and distance between the site and nearest cluster, based on a report by Element Energy.[14] The model also calculates a separate operating cost of transporting CO_2 from a cluster and storing offshore. This cost was calibrated to average £39 per tCO_2e in line with principles set out in Section 1.7.2.[15]

- The model chooses the cheapest of pipeline or trucking. However, because it also sets a limit on CO_2 trucking of 0.1 Mt per year pipelines are the only viable transport option for most sites. The limit is based on our assessment of the number of feasible truck movements per day and analysis showing trucking is an expensive option for higher volumes of CO_2.[16]

Box 8.2
Industrial clusters

The NZIP2 model includes 11 industrial clusters as shown in Table 8.4. Clusters are geographic areas that encompass a range of emissions-intensive businesses that could benefit from CCS and hydrogen infrastructure. The cluster sites in our model are based on existing proposals from private-sector developers, some of which are being taken forward through the Government's cluster sequencing programme.[17]

- Six of the modelled cluster sites are part of industrial clusters expected to receive public funding to develop CCS/hydrogen. Merseyside, Teesside, Humberside, and Humberside 2 are attached to the more advanced Track-1 clusters – HyNet and East Coast. Grangemouth, Peterhead, and Humberside (again) are attached to the second stage Track-2 clusters – Acorn and Viking.
- A further four modelled clusters – South Wales, Southampton, Medway, and Peak District – are part of cluster plans that are at various stages of development by business groups but have yet to be identified for major public funding. The Derry/Londonderry modelled cluster was chosen for its potential to host CCS infrastructure in Northern Ireland and proximity to industrial sites that could use this infrastructure.[18]
- The model defines clusters as circles with a 30 km radius around a central point. Sites within a cluster can access hydrogen and CO_2 pipelines, with the exception of the Peak District cluster which is CCS-only. Peak District 'spur cluster' allows five cement and lime sites to pipe CO_2 to a central location in the Peak District rather to one of the coastal clusters.
- Six modelled clusters are assumed to have direct pipeline access to offshore CO_2 storage. The other clusters access CO_2 storage either via ship (South Wales, Derry/Londonderry, Medway) or inland pipeline (Humberside 2, Peak District).
- By 2032 all clusters, except the Peak District cluster, are assumed to produce hydrogen. From 2040 onwards, it is assumed that all clusters are interconnected by hydrogen transmission pipelines.

Table 8.4
Industrial clusters in our Seventh Carbon Budget modelling

	Cluster site*	CO_2 storage region	CO_2 storage – first year	Hydrogen – first year
Clusters with pipelines to offshore storage	Grangemouth (Acorn)	Northern & Central North Sea	2030	2031
	Peterhead (Acorn)		2030	2030
	Teesside (East Coast)	Southern North Sea	2028	2028
	Humberside (Viking/East Coast)		2028	2029
	Merseyside (Hynet)	East Irish Sea	2028	2028
	Southampton	Southampton Sea	2035	2032
Clusters without pipelines to offshore storage	**Cluster**	**Terminal**	**CO_2 storage – first year**	**Hydrogen – first year**
	Humberside 2 - inland	Humberside	2028	2030
	South Wales†	Merseyside or Southampton	2033	2032
	Derry/Londonderry†	Merseyside or Peterhead	2035	2032
	Medway†	Humberside or Southampton	2035	2032
	Peak District‡	Merseyside	2030	N/A

Notes: (1) *Commercial cluster names in brackets where applicable. (2) †In these clusters a small quantity of green hydrogen (<0.5 TWh) is available in the year before they have access to CO_2 storage. (3) ‡Peak District is a spur cluster and not connected to a storage location.

8.2.4 Hydrogen fuel-switching

Most gas-fired industrial processes could in principle be converted to run on hydrogen.* The elements of conversion to hydrogen are case-dependent, but might include retrofitting existing heating systems, the installation of new control and ventilation equipment, and the provision of supply infrastructure. We assumed that, in most subsectors that use gas-fired equipment, there is an alternative technology that runs on hydrogen.

- Hydrogen is assumed to be produced at the centre of industrial clusters. Hydrogen can be transported from this location to an industrial site by either new-build pipeline or truck. We have assumed hydrogen does not become available via the gas distribution grid, as our wider analysis shows hydrogen will not be required for heating buildings.
  - For each cluster there is a specified first year at which infrastructure for hydrogen production and transport becomes available. The model then assumes an annual hydrogen availability at each cluster.
- Sites incur an initial construction cost and an ongoing operational cost for hydrogen pipelines. These costs, sourced from the DESNZ Hydrogen and Industrial Carbon Capture team, are related to the pipeline capacity and distance to the production site, allowing the model to reflect economies of scale. Trucking has only an operational cost.
- It is assumed that sites within clusters access hydrogen via pipeline, those outside clusters via trucking. Our pathway includes only small amounts of hydrogen delivered by truck due to the high cost of this means of delivery.
- From 2040 onwards, it is assumed that parts of the existing gas transmission network are converted to hydrogen and provide a hydrogen pipeline network connecting all clusters. This means hydrogen availability in clusters is restricted only by the national production volume, rather than cluster-level production. The costs of this network are not estimated in our modelling.

8.2.5 Resource efficiency

By using resources more efficiently we could reduce demand for materials, thereby reducing manufacturing emissions. This can be done by material switching, increasing recycling, reducing consumption or producing goods with fewer material inputs.

- Our modelling makes assumptions about the annual abatement that can be achieved through resource efficiency from each industrial subsector. These assumptions are based on research commissioned by DESNZ in 2023-2024 to assess the potential of resource efficiency measures.[19] The research involved a literature review and expert stakeholder workshops that informed several scenarios, including a 'maximum technical' scenario and a 'business as-usual' scenario (which included only resource efficiency likely to occur without further policy intervention).
- The CCC developed our own resource efficiency scenario, building on DESNZ's research. We reviewed evidence on the deliverability of the nine measures in DESNZ's scenarios with the greatest potential to reduce territorial emissions. This allowed us to determine an appropriate level of adoption for each of these high-impact measures. Assumptions for each measure in the Balanced Pathway are detailed in Table 8.5.

* In our modelling, low-carbon hydrogen means either blue hydrogen, produced from natural gas with CCS, green hydrogen, produced by electrolysing water using renewable electricity, and BECCS hydrogen, produced by applying CCS to the process of biomass gasification to produce hydrogen.

- For all other resource efficiency measures in DESNZ's scenarios, we assume 'business as usual' level of adoption, corresponding to sector stakeholder views on the level of resource efficiency that industry will achieve by 2035, without further policy intervention. This equates to total abatement of 0-2%.

- The most significant source of resource efficiency is in the cement sector where measures reduce emissions by up to 26%.

- The start date for resource efficiency measures was determined based on whether they would occur under business as usual (2024), required changes to existing policy/relatively minor policy change (2026), or would require major new policy to be introduced (2027).

  - Resource efficiency measures were adopted from their start date, linearly out to 2035. We assumed no further abatement after 2035, as our pathway projects much of industry to be decarbonised by this date, limiting the potential of resource efficiency measures. We also excluded resource efficiency from the iron and steel sector, due to imminent site closures in domestic steel production followed by conversion to electrified production.

- Resource efficiency abatement is applied in the model before any optimisation. In the model resource efficiency has the effect of reducing industrial output. This means that the avoided emissions do not need to be addressed by another decarbonisation method.

- Resource efficiency modelling is aligned to the waste sector modelling (Section 13). Our assumptions on reduced output from food manufacturing correspond to the reduction in food waste in the Balanced Pathway for waste. We also align the reduction in material consumption from resource efficiency with our assumptions in the waste model on the quantity of materials entering the waste system, with a five-year lag.

- As we lacked good evidence on the expenditure required to deliver the resource efficiency measures, we assumed no net cost. Some measures, such as those which involve reuse or reducing waste, are likely to be cost saving. Others, such as material substitution, may increase costs, especially in the short term.

Table 8.5
Assumptions on the adoption of resource efficiency measures in the Balanced Pathway

Measure	Balanced Pathway assumption*
Reduction of Ordinary Portland cement (OPC) used in the production of concrete	Average ratio of OPC reduces from 68% to 45%
Refurbishment of current building stock to avoid new builds	Additional 9% of new builds are delivered by refurbishment
Reduction of construction process wastage	Average construction process wastage reduced from 12.5% today to 8%.
Reduction of overdesign in building structures	15.5% reduction in overdesign of construction materials and components
Use of reused content in buildings	10% of buildings material is reused
Light-weighting through reducing vehicle size	No further growth in average vehicle size
Remanufacturing, reuse and reconditioning of vehicle parts	31% of vehicle mass is remanufactured, reused or reconditioned
Substitution of virgin fossil based organic feedstocks in chemicals	26% of virgin fossil based organic feedstocks are substituted in chemicals manufacturing
Reduction in food waste	27% reduction in commercial food waste, and 28% reduction in household food waste
Business as usual resource efficiency in other sectors	See DESNZ's research for further details.

Notes: *Measures are fully achieved by 2035, after which no further abatement is achieved. Assumptions for each measure were developed from DESNZ's research in combination with the CCC's own literature review and stakeholder engagement.[20]

8.2.6 Energy efficiency

Using energy more efficiently reduces operating costs while cutting emissions. There are many potential measures for improving industrial energy efficiency such as waste heat recovery, improved process design, and energy control systems. Our modelling makes assumptions about the annual abatement that can be achieved through energy efficiency in each industrial subsector.

- These assumptions are based on research commissioned by DESNZ in 2023-2024 to assess the potential of energy efficiency measures.[21] The research involved a literature review and expert stakeholder workshops that informed several scenarios, including a 'maximum technical' scenario and 'business as-usual' scenario.

- The DESNZ research identified important limitations to quantifying the potential of industrial energy efficiency. These limitations included the lack of data on the costs and current levels of adoption of energy efficiency measures, and the complexity of accounting for interactions between energy efficiency measures and low-carbon fuel switching.

- Our recognition of these limitations, as well as the low cost effectiveness of some measures, led us reject the 'maximum technical' scenario for energy efficiency. Instead, we assumed a more plausible scenario which takes the mid-point of emissions reductions between the 'business as-usual' scenario and the 'maximum technical' scenario.

- Energy efficiency abatement is applied in the modelling after resource efficiency measures, but before the model selects technologies. Abatement from energy efficiency is

permanent and the avoided emissions do not need to be addressed by another decarbonisation method.

- We assumed that energy efficiency in the iron and steel sector would deliver little abatement because the sector largely decarbonises by 2026.

8.2.7 Supply chain and deployment constraints

We use supply chain and technology constraints to guide a feasible pace of deployment within industrial subsectors. For a given year, NZIP2 deploys whichever technology option has the lowest total cost, without delay. In reality, there could be several reasons that deployment of a specific technology, or decarbonisation across a subsector, could be delayed, such as:

- The time required to design or install new equipment.
- Emerging supply chains have limited capacity to supply and install new technologies.
- A lack of workers with the skills to design and install equipment.
- The time required to access capital.
- The time required to develop required infrastructure (e.g. pipeline for CO_2 or hydrogen, grid connection upgrade).
- The time required to acquire permits or planning permission.

Our supply chain constraints attempt to represent such delays by restricting the amount by which each subsector can reduce its emissions in a given year. For most subsectors, until 2040, this restriction is set between 5% and 10% of the current level of emissions. After 2040, we largely remove supply chain constraints, as we assume solutions have been found to the causes of delays.

- In addition to supply chain constraints on subsector adoption, we use deployment constraints for some specific technologies to ensure they are rolled out in a realistic way. Without these constraints, NZIP2 could deploy a new technology at a rate that is probably beyond the capacity of developing supply chains, even when subsector supply chain constraints are applied.
- We also used deployment constraints where we had evidence that there were limits to the application of a technology in a given subsector.
- We applied deployment constraints on heat pumps in all subsectors, as well as to some hydrogen, CCS and other electric technologies.

We developed supply chain and technology constraints for each technology based on historical deployment rates of new industrial technologies, both in the UK and internationally.

- For example, this includes the past introduction of basic oxygen furnaces and ongoing rollouts of electric arc furnaces and industrial heat pumps internationally. We modelled constraints based on maximum compound annual growth rates achieved in the deployment of these technologies, and maintained over a minimum of five years, in countries similar to the UK.

8.2.8 Attribution of emissions reduction to decarbonisation measures

A feature of NZIP2 is that it has a dynamic counterfactual scenario. This means that for any given process it does not necessarily simply switch once from a high-carbon technology to a low-carbon equivalent but can make several technology switches before 2050. Without a stable

counterfactual, NZIP2 cannot attribute emissions reductions to specific technologies or decarbonisation measures. For example, if a particular industrial site selects a heat pump, it is not possible to say definitively what technology the heat pump replaced, and therefore the quantity of emissions abated. For our pathway we need to attribute emissions reductions relative to the high-carbon baseline.

- For the industry pathway this attribution has been done in a separate step outside NZIP2, which involves performing the following calculations for each year of the model outputs:
  - Identify technologies for which energy demand has increased.
  - For each of these technologies, calculate emissions reduction by multiplying increased energy demand by the average emissions intensity for that process in the counterfactual.
  - Scaling the emissions reduction so that the total equals the difference between the total emissions for the counterfactual and the pathway (after accounting for resource and energy efficiency).
- In the attribution process, emissions reduction due to CCS is assumed to be equal to the quantity of emissions captured.

8.2.9 Pathway analysis for non-road mobile machinery

The non-road mobile machinery sector includes a wide range of machinery used in the mining, construction, ports and waste sectors. Our pathway for the decarbonisation of non-road mobile machinery was developed using a least-cost optimisation model commissioned by DESNZ in 2023.

- The NRMM model selects the least-cost option taking into account capital expenditure, fuel costs, non-fuel operating costs, infrastructure costs and carbon values.
- This sector includes hundreds of types of equipment so for modelling purposes it was necessary to categorise these into a manageable number of archetypes, as follows:
  - 36 relevant equipment types were selected from the NAEI database, such as cranes, bulldozers, excavators, forklifts, and generators. These equipment types were then categorised according to their power rating, intensity of use, and degree of mobility: hand-held equipment; mobile machinery; limited motion machinery and generators.
  - This categorisation resulted in 14 machine archetypes that are likely to have similar options to decarbonise. For all 14 archetypes the incumbent fuel was assumed to be diesel, except for low-power generators, which are assumed to run on petrol.
- For each archetype, the model identifies the range of suitable alternative, low-carbon powertrains, as well as their first year of commercial availability.
- Future growth in the stock of each type of equipment was based on historic growth trends calculated from the NAEI database. Machines are only replaced at the end of their lifetime. We do not model any early scrappage in this subsector.
- Supply chain constraints were not applied to any types of low-carbon equipment as we consider it will be available at the required rates. There were constraints on biofuels in-line with the CCC's economy-wide bioenergy constraints.
- The NRMM model assumes a certain percentage of low-carbon alternatives are ‘hard to deploy’ if they involve intensive use or are for use on a small, temporary or remote site.

- DESNZ's modelling project provided our assumptions on the capital costs of NRMM equipment and infrastructure. This project sourced capital costs of incumbent machinery from UK and US manufacturers and sellers, as well as the AFLEET model.[22,23] Costs of alternative equipment were based on many sources including the International Council on Clean Transportation.[24]

- The model delays hard-to-deploy measures by 10 years after they become commercially available, to allow for the provision of infrastructure such as charging stations. Some respondents to the UK Government's consultation on decarbonising this sector said that such options will never be deployed.[25;26] However, we have more confidence in technological innovation given recent advances in the sector, including large construction machines that can work all day and services delivering large batteries to construction sites.[27;28]

Emissions reductions in the non-road mobile machinery sector are achieved either through fuel switching or energy efficiency, as explained below.

Fuel switching in non-road mobile machinery

The NRMM model decarbonises machinery through switching to biofuels, hydrogen or electric solutions. Each of these fuel switching options has two types, resulting in six fuel switching options:

1. **Biofuels**, considered drop-in fuels available for all archetypes from 2025:
    a. hydrotreated vegetable oil (HVO) – made by adding hydrogen to waste oils such as cooking oil.
    b. biodiesel – B20 blend containing 20% bio-origin, 80% fossil diesel. B20 achieves only 20% emissions reduction compared to diesel.
2. **Hydrogen,** transported by truck to power either:
    a. hydrogen fuel cell, or
    b. hydrogen internal combustion engine.
3. **Electricity**, through:
    a. electric battery, or
    b. tethering (i.e. plugged in via a cable or bus bar).

The model defines the year in which each fuel switching option becomes available for each archetype. Some options are not considered viable for particular archetypes. For example, tethered electricity is not available as an option for more mobile machinery such as excavators, and no electric alternatives (battery or tethered) are available for generators or mobile machinery with a utilisation rate above 50%. In our NRMM pathway, use of HVO and biodiesel increases until 2032, then declines to low levels by 2050, as they eventually become less cost-effective than alternatives.

Energy efficiency in non-road mobile machinery

For energy efficiency we applied the low scenario from the Government's commissioned research. This delivers significant abatement in this sector (36% in 2040), achieved through more efficient machines, improvements in operational use (e.g. anti-idling measures) and changes to work processes to reduce machinery workload.

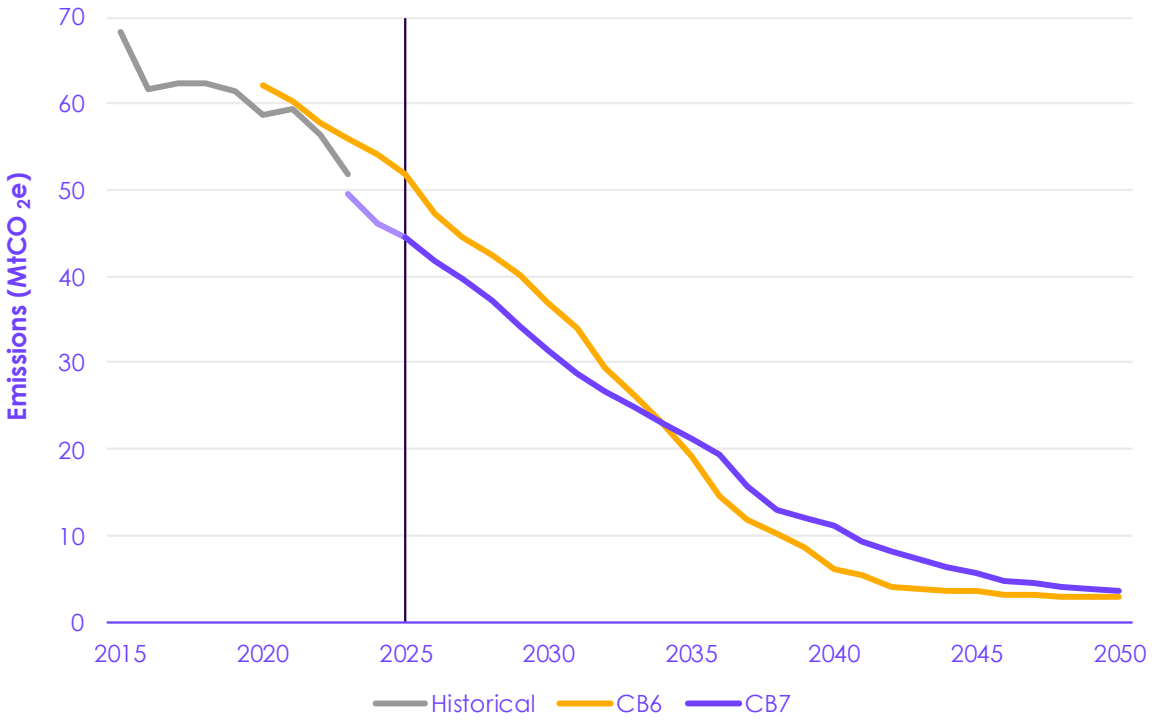
- The NRMM model does not have the ability to allocate capital costs to energy efficiency improvements, so we applied off-model estimates. As we lacked good evidence on these costs, we made our estimates based on an assumption that the capital cost of energy efficiency measures equates to 20% of the cost savings from lower fuel use.[*]

8.3 Changes since our Sixth Carbon Budget advice

8.3.1 Comparison with our Sixth Carbon Budget pathway

Emissions in industry have fallen more quickly than projected in our Sixth Carbon Budget pathway, largely due to lower output from carbon-intensive sectors.[†] Furthermore, the closure of the blast furnaces at the Port Talbot steelworks will have further reduced emissions prior to the start of our pathway. As a result, the Balanced Pathway begins at a lower starting point. In the near-term, the pace of emissions reduction is relatively similar to the Sixth Carbon Budget, although there is a larger role for electrification. Over the five years of the Seventh Carbon Budget period, cumulative industrial emissions are about 55% higher than in our previous advice (Figure 8.4).

Figure 8.4 The Balanced Pathway for industry compared to our Sixth Carbon Budget advice



Description: Historical industry emissions have fallen faster than our Sixth Carbon Budget (CB6) trajectory. Our Seventh Carbon Budget (CB7) Balanced Pathway is lower than the Sixth Carbon Budget until 2035, after which it declines less steeply.
Source: CCC analysis.
Notes: The Sixth Carbon Budget advice pathway is shown as published in our 2020 advice. These have not been adjusted to account for changes in emissions accounting since that publication.

[*] This 20% estimate was based on an assumption that on average, energy efficiency measures would pay back in five years.

[†] All comparisons in this section compare the Balanced Pathway in this advice with the Balanced Net Zero Pathway in our Sixth Carbon Budget. Our Sixth Carbon Budget advice also included four other exploratory pathways, which are not discussed here. Data for those pathways can be found in our Sixth Carbon Budget advice.

8.3.2 Emissions changes since our Sixth Carbon Budget advice

Several developments in UK industry since 2020 have caused actual industrial emissions to diverge from our Sixth Carbon Budget pathway.

- In the Sixth Carbon Budget pathway, industrial emissions were projected to fall from 62.3 $MtCO_2e$ in 2020 to 56.0 $MtCO_2e$ in 2023, due largely to resource and energy efficiency. In reality emissions fell further to 53.1 $MtCO_2e$ in 2023, with the main cause being lower output from carbon-intensive sectors, rather than decarbonisation.

- As yet, there is no substantial deployment by industry of deep decarbonisation options such as CCS, hydrogen, and electrification.

- Changes in national emissions accounting mean the industry sector no longer includes some emissions (0.7 $MtCO_2e$ in 2023) related to industrial non-road mobile machinery.

8.3.3 Key pathway differences compared to our Sixth Carbon Budget advice

There are several key areas in which the deployment rates, measures included, or underlying assumptions in our updated Balanced Pathway have been revised since publication of our Sixth Carbon Budget advice in 2020. These include:

- **Industrial electricity use.** The most significant difference is the much higher level of electrification in the Seventh Carbon Budget. The main reason for this is that we have taken account of new electrical technologies, such as industrial heat pumps, which were at an early stage of development in 2020 but which we now expect to be commercially available by or before 2030. The expected transition of the Port Talbot and Scunthorpe steelworks to electric arc furnaces delivers a large part of the increase in the early years. Industrial electricity use then starts to increase sharply in the early 2030s as sectors such as chemicals and other industry electrify (Figure 8.5a).

  - Since 2020, there has been growing recognition of the broad potential of electrification as a means of decarbonising industry.[29] Fuel switching delivers a similar amount of abatement in our Balanced Pathway as it did in our Sixth Carbon Budget pathway, as greater electrification compensates for a lower level of hydrogen.

  - The potential of electric heating options in industry may continue to grow, echoing the progress of electric technology in other sectors such as buildings and surface transport. For example, we deemed electrolytic methods of steel production as too immature to include in our modelling, but they could become commercial in the 2030s.[30]

- **Hydrogen.** Hydrogen fuel-switching delivers a significantly lower level of abatement than in our 2020 advice. Its use has become less attractive due to updated assumptions about transporting hydrogen. These include better-evidenced estimates of the costs of hydrogen compression, which have increased the costs of trucking hydrogen, and our assumption that the gas distribution grid will not convert to hydrogen (Figure 8.5b).

  - In several industrial subsectors hydrogen has been eclipsed by more cost-effective electrical heating options. For example, in the food and drink sector, electric heat pumps are always selected in preference to hydrogen boilers.

  - Due to the greater efficiency of electrical technologies, the increase in electrical energy demand is small compared to the reduction in hydrogen demand.

  - Hydrogen use is now concentrated in sectors for which electrical heating is technically challenging such as ceramics and chemicals. There is also significant hydrogen use for

heavy and intensively-used equipment in the non-road mobile machinery sector, although it is still uncertain whether this will be more viable than electric options.

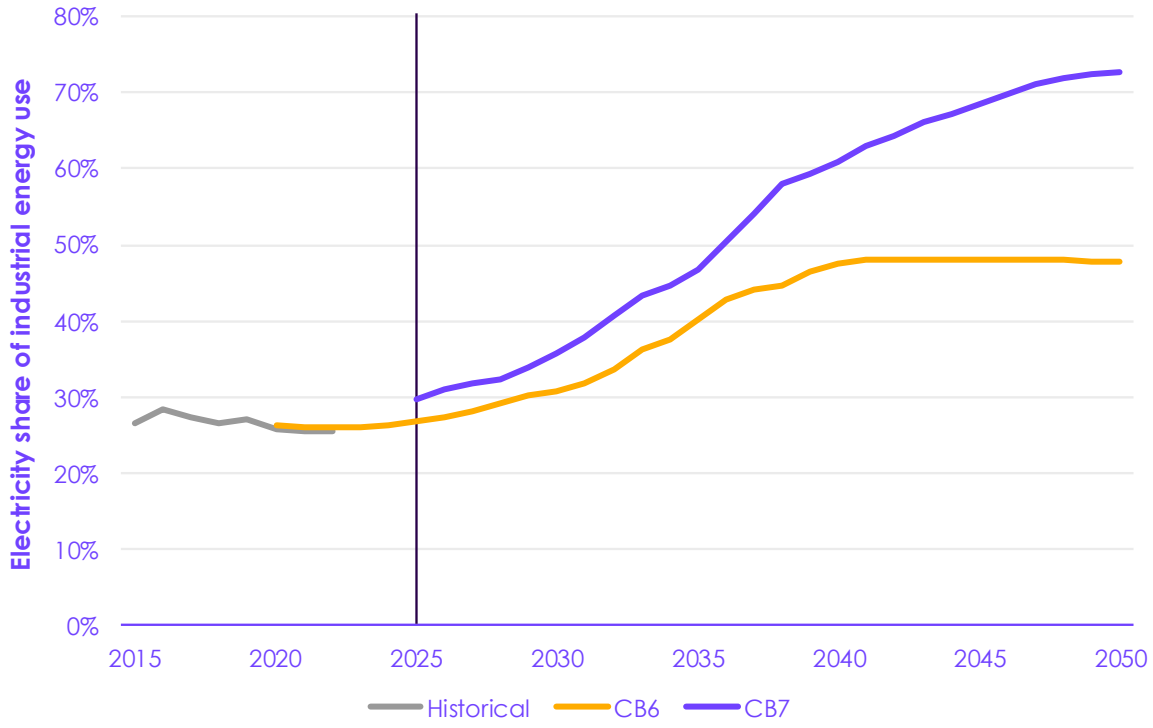
- **CCS.** CCS in industry delivers a similar level of abatement to our advice on the Sixth Carbon Budget, but is now focussed on cement, lime, and chemicals sectors - sectors which have substantial process emissions. Our pathway no longer includes, as it did in the Sixth Carbon Budget advice, CCS as a measure in the iron and steel or glass and other minerals sectors.

  - In the Sixth Carbon Budget pathway, industrial CCS started in 2025, but is now not expected to start before 2028.

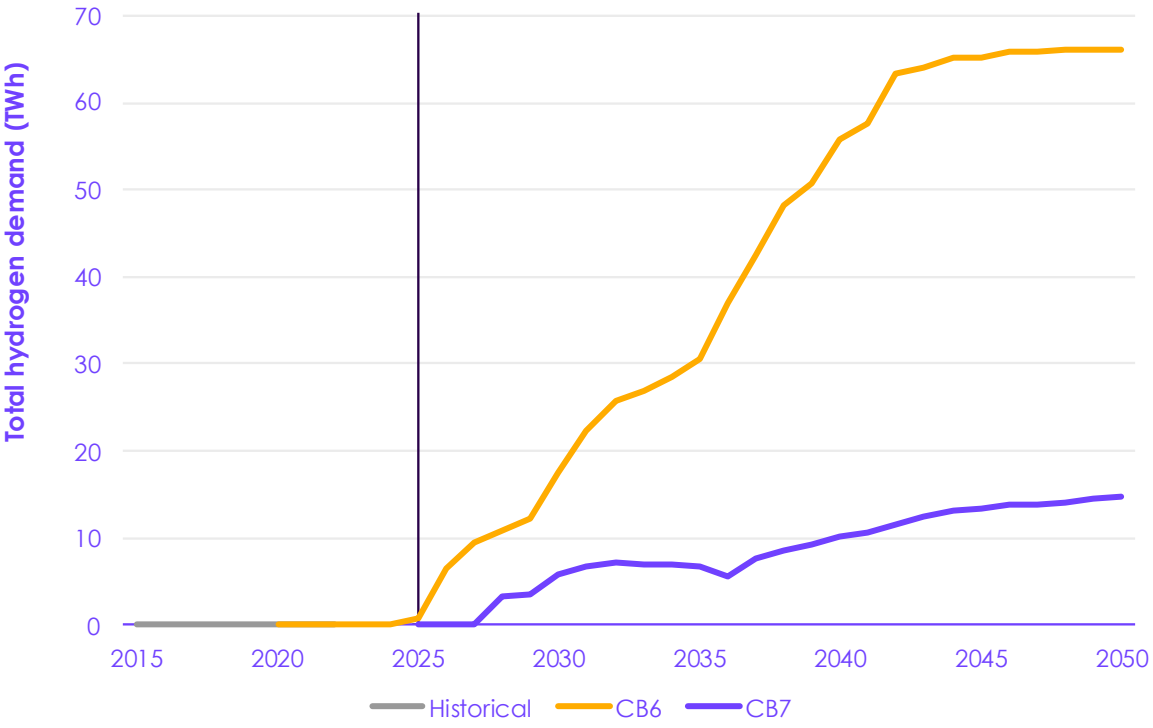
- **Resource and energy efficiency.** In our Balanced Pathway, resource efficiency and energy efficiency combine to deliver about half the quantity of emissions reduction that was included in our Sixth Carbon Budget pathway. These reduced assumptions for resource efficiency and energy efficiency deliver 35 $MtCO_2e$ less abatement during 2038-2042 and are the main reason emissions are now higher during the Seventh Carbon Budget period.

Figure 8.5 Key differences in deployment trajectories in the Balanced Pathway for industry compared to our Sixth Carbon Budget advice

(a) Share of industrial energy use that is met by electricity



(b) Hydrogen demand in industry



Description: Our Seventh Carbon Budget (CB7) Balanced Pathway has a much higher level of electrification in industry than in our Sixth Carbon Budget (CB6) pathway. Correspondingly, hydrogen demand in industry is lower in CB7 than in CB6
Source: CCC analysis.

8.4 Uncertainties and sensitivity analysis

Inevitably, there are uncertainties around how the key drivers of our pathway will develop over the next 25 years. We have undertaken several sensitivity tests to explore the impact on the Balanced Pathway for industry of some of these uncertainties, namely:

- Higher and lower costs for gas.
- Higher and lower costs for electricity.

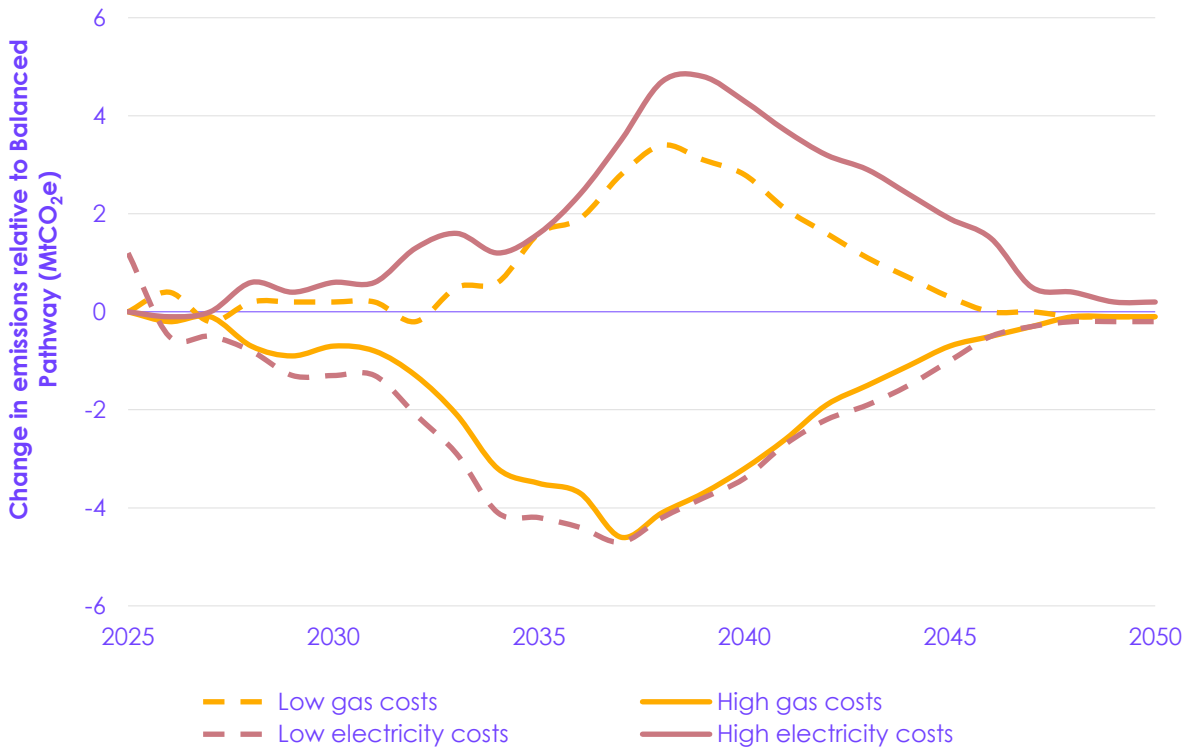
These sensitivity tests were run using the NZIP2 model, and their impact on emissions is summarised in Table 8.6 and Figure 8.6. There are other uncertainties we did not explore, including levels of future industrial output, technology costs, later technology start dates, and start dates for CCS and hydrogen. We also did not run any sensitivity tests on the non-road mobile machinery sector. The approach to, and results of, each of these sensitivity tests are described below. See Chapter 5 for our general approach to uncertainty, including descriptions of the methodology behind sensitivity tests that apply across multiple sectors.

Our sensitivity tests showed that either higher electricity costs or lower gas costs would slow the rate of industrial decarbonisation. Lower electricity costs and higher gas costs would lead to faster decarbonisation.

Table 8.6
Key sensitivity tests for industry

Sensitivity test	Description	Impact on emissions in 2040		
		$MtCO_2e$	% of sector emissions	% of total emissions
Electricity costs	Higher electricity costs	+4.4	+39%	+4%
	Lower electricity costs	-3.3	-29%	-3%
Gas costs	Higher gas costs, correspondingly higher electricity and hydrogen costs	-3.1	-28%	-3%
	Lower gas costs, correspondingly lower electricity and hydrogen costs	+2.8	+25%	+3%

Figure 8.6 Emissions impact of key sensitivity tests for industry



Description: Graph shows the effect of five sensitivity tests on the rate of industry emissions reduction from 2025 to 2050.
Source: CCC analysis.

8.4.1 Electricity costs

The Balanced Pathway for industry relies heavily on electrification. However, as there is a great deal of uncertainty over future electricity costs, we ran two sensitivity tests on this, assessing the impact of electricity costs from 2030 to 2050 being 25% higher or lower than in our Balanced Pathway (see Chapter 5). Other energy costs were unchanged from the Balanced Pathway.

- Higher electricity costs. This sensitivity test produced a pathway with slower decarbonisation. Compared to the Balanced Pathway, electricity demand decreases while demand for gas and hydrogen increases.

- Lower electricity costs. This sensitivity test produced a pathway with faster decarbonisation. Compared to the Balanced Pathway, electricity demand increases while demand for gas and hydrogen decreases, as the model opts to electrify a greater number of processes.

8.4.2 Gas costs

We ran two sensitivity tests on gas costs, assessing the impact of higher and lower gas costs, respectively (see Chapter 5). We also assumed these gas cost variations had an impact on electricity and hydrogen costs.

- Higher gas costs. This sensitivity test produced a pathway with faster decarbonisation. Compared to the Balanced Pathway, electricity demand increases while demand for gas and hydrogen decreases.

- Lower gas costs. This sensitivity test produced a pathway with slower decarbonisation. Compared to the Balanced Pathway, electricity demand decreases while demand for gas and hydrogen increases.

8.5 Contingencies in industry

Contingency measures may be required if the pace of industrial decarbonisation is too slow. It may be possible to accelerate action on resource efficiency and energy efficiency, as we have made relatively conservative assumptions for these measures. Our estimates of additional effort on these measures are based on research by DESNZ rather than model re-runs (Table 8.7). See Chapter 5 for our general approach to contingency analysis.

Table 8.7
Contingency options in industry

Contingency	Description	Potential average annual emissions savings ($MtCO_2e$)			
		2030	CB6	CB7	2050
Increased resource/energy efficiency in industry/waste	A higher level of resource efficiency and energy efficiency savings is reached	0.4	1.2	1.9	2.2

Source: CCC analysis.
Notes: The emissions savings stated relate to combined emissions from industry and waste sectors. The text below describes only the contingency assumptions for the industry sector.

8.5.1 Further action on resource efficiency

In our industry pathway we assume most resource efficiency is achieved through a high level of adoption of nine high-impact measures (see Table 8.5). For most other identified measures, we assume smaller improvements corresponding to the level of resource efficiency that industries are expected to achieve without substantial changes to policies or incentives.

- However, it is possible that more abatement could be achieved through resource efficiency. By going further on seven of the nine high-impact measures in Table 8.5, we estimate we could deliver additional abatement of 1.4 $MtCO_2e$ by 2040 (Table 8.8).

- In the Balanced Pathway we restricted resource efficiency abatement to those measures for which we have good evidence. We also took account of historic reluctance to implement policies that incentivise resource efficiency.

Table 8.8
Assumptions on the adoption of resource efficiency measures in the Balanced Pathway and in the modelled contingency measure

Measure	Balanced Pathway assumption*	Contingency assumption
Reduction of Ordinary Portland cement (OPC) used in the production of concrete	Average ratio of OPC reduces from 68% to 45%	Average ratio of OPC in production of concrete reduces to 35%
Refurbishment of current building stock to avoid new builds	Additional 9% of new builds are delivered by refurbishment	Additional 25% of new builds are delivered by refurbishment of current building stock
Reduction of construction process wastage	Average construction process wastage reduced from 12.5% today to 8%	Average construction process wastage reduced from 12.5% to 2.5%
Reduction of overdesign in building structures	15.5% reduction in overdesign of construction materials and components	Same as Balanced Pathway
Use of reused content in buildings	10% of buildings material is reused	11.5% of building material is reused
Light-weighting through reducing vehicle size	No further growth in average vehicle size	Average size of new vehicles reduces by 15%
Remanufacturing, reuse and reconditioning of vehicle parts	31% of vehicle mass is remanufactured, reused or reconditioned	40% of vehicle mass is remanufactured, reused or reconditioned
Substitution of virgin fossil based organic feedstocks in chemicals	26% of virgin fossil based organic feedstocks are substituted in chemicals manufacturing	40% of virgin fossil based organic feedstocks are substituted in chemicals manufacturing
Reduction in food waste	27% reduction in commercial food waste, and 28% reduction in household food waste	Same as Balanced Pathway
Business as usual resource efficiency in other sectors	See DESNZ's research for further details	Same as Balanced Pathway

Notes: *Measures are fully achieved by 2035, after which no further abatement is achieved. Assumptions for each measure were developed from DESNZ's research in combination with the CCC's own literature review and stakeholder engagement.[31]

8.5.2 Further action on energy efficiency

In our industry pathway, we based abatement from energy efficiency on research by DESNZ.[32] We assumed a level of emissions reductions halfway between DESNZ' 'business as-usual' scenario and their 'maximum technical' scenario.

- However, it is possible that some sectors could achieve greater abatement at higher cost and with a higher level of policy support. If we assume emissions reductions are 75% (rather than 50%) of the difference between DESNZ' 'business as-usual' scenario and their 'maximum technical' scenario we could deliver additional abatement of 0.4 $MtCO_2e$ by 2040.

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Chapter 9: Agriculture

Introduction

The agricultural sector covers emissions from the managements of soils, livestock including their waste and from the use of energy to run stationary and non-road mobile machinery. While energy use can be fully decarbonised, the dominance of non-CO_2 emissions in agriculture means that getting the sector close to zero emissions will not be possible by 2050.

However, there are a range of measures and practices that farmers and land managers can deploy, combined with changes in societal behaviour that can reduce emissions, so that by 2040 agricultural emissions fall by 39% in the Balanced Pathway, relative to 2022. The Balanced Pathway was determined by assessing the extent and pace of various measures available to reduce emissions to 2050, against a counterfactual baseline where there is an absence of policies to reduce emissions.

This chapter sets out the modelling assumptions that underpin the Balanced Pathway for agriculture.

- The analysis undertaken for our advice was based on a range of approaches that included a detailed review of available evidence, including academic research and literature, monitoring of the latest developments and trends in the sector, stakeholder engagement, modelling by the CCC, and the commissioning of three external research projects.

- We also convened two CCC independent advisory groups and a citizens' panel to test some of the assumptions underpinning our analysis.

In our advice reports on the UK's Seventh Carbon Budget, Northern Ireland's Fourth Carbon Budget, Wales' Fourth Carbon Budget, and Scotland's carbon budgets, we discussed the pathway for agriculture together with that for land use. This is because these two sectors are inherently linked, together playing an important role to deliver a transformation in UK land use. This chapter sets out our modelling for the agriculture sector; our land use methodology can be found in Chapter 17.

9.1 Baseline emissions in agriculture

9.1.1 The baseline for agriculture

Our baseline emissions for agriculture are broadly based on the Updated Energy and Emissions Projections (EEP) (2022-2040) published by DESNZ in 2023.[1] This represents a scenario in which there is no further decarbonisation action by either the Government or the market in the agriculture sector. See Chapter 1 for our general approach to baselines.

- Non-energy related emissions, mainly comprising methane and nitrous oxide emissions are derived from projections in UK agricultural activity to 2032 as modelled by Defra's UK Agricultural Market Model (UKAMM).[2]

- The UKAMM projects changes in agricultural activity data (e.g. livestock numbers, agricultural land area, production, and milk yields) based on a set of exogenous (e.g. GDP and population growth) and endogenous variables for production, trade, and UK demand. Baseline productivity improvements are only factored in for the dairy herd.

- The projected activity data is then used by Rothamsted Research (who compile the GHG Inventory for agriculture) to generate baseline emissions to 2040 for the EEP. For the years 2033 to 2040, livestock numbers are flat lined at the 2032 values, and projections for the volume of digestate to be applied to land to 2035, based on energy production projections, are provided by Ricardo. In our baseline, we hold emissions constant from 2040 to 2050.

- To account for any methodological differences in the accounting of emissions between the EEP projections and the GHG Inventory (1990 to 2022), we have aligned the 2022 emissions for the projections to match the GHG inventory values. The path then follows the annual percentage change under the EEP.

- In the absence of any published projected emissions data for Scotland, Wales and Northern Ireland, we assume annual projections are based on each nation's share of UK 2022 outturn emissions from the GHG Inventory. This is done for each of the main sources of emissions (e.g. enteric fermentation and waste manure management) and by each non-CO_2 GHG (nitrous oxide, methane).

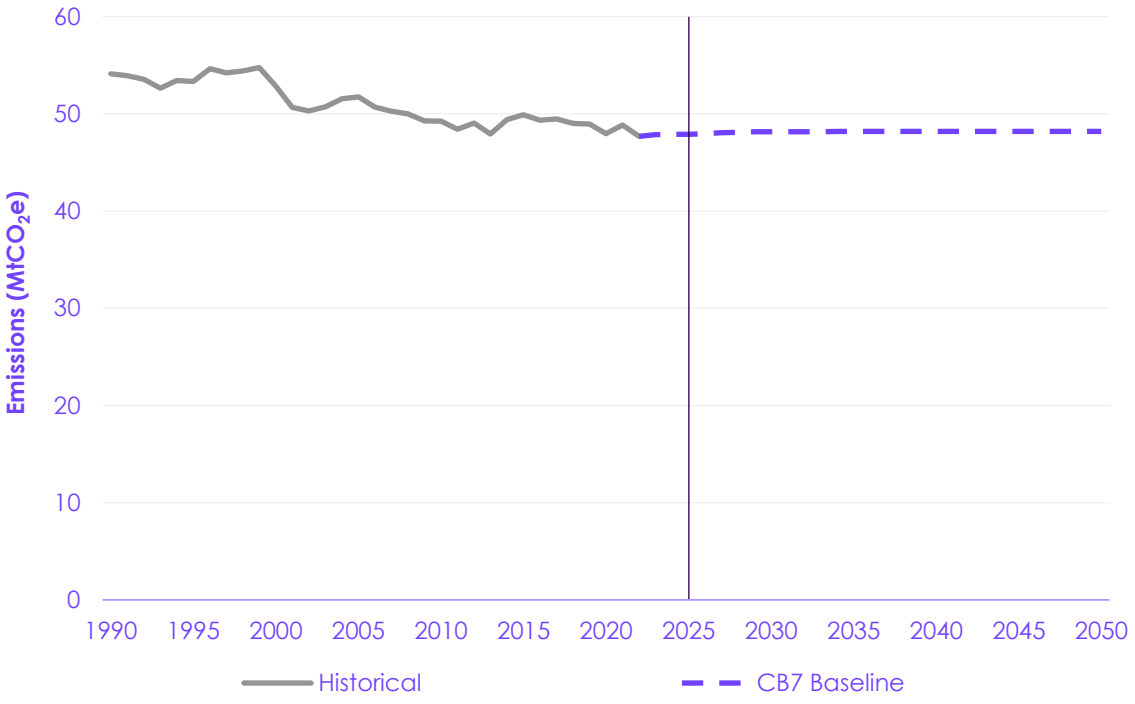
- Projected baseline energy-related emissions from stationary and non-road mobile machinery (NRMM) are aligned to the annual change in non-energy-related emissions in our modelling. We assume the current mix of fuel types are maintained, which, for stationary machinery, is predominately run using fuel oil (39%) and electricity (37%), with smaller amounts of natural gas (10%) and biomass (14%). For off-road machinery, we assume the use of gas oil (e.g. red diesel) continues to account for all the fleet's fuel demands to 2050.

- Baseline capex costs for NRMM are based on the unit costs assumed in our Sixth Carbon Budget analysis and inflated to 2023 prices. Our stationary machinery capex costs are aligned to the baseline commercial costs used in the non-residential buildings sector analysis.

- Baseline opex costs for both NRMM and stationary machinery are based on projections of 2023 prices for the fuel used in each type of machinery (primarily red diesel for NRMM and a mixture of electricity, natural gas, and fuel oil for stationary machinery), with the addition of small maintenance costs per MWh for stationary machinery.

In our baseline scenario, emissions would rise by 1% from 2022 levels by 2040 (the middle of the Seventh Carbon Budget period) which is then maintained to 2050 (Figure 9.1).

Figure 9.1 Baseline emissions in agriculture



Description: Historical agriculture emissions have fallen by 12% between 1990 and 2022. In the absence of policies to reduce emissions, baseline emissions are projected to increase by 1% by 2040.
Source: CCC analysis.
Notes: Given the EEP projections were published in advance of the 2024 UK GHG Inventory, emissions projections for 2022 are aligned to match the values set out in the GHG Inventory. The rate of change in emissions from the EEP projections are then applied from the 2022 value.

9.2 Pathway assumptions and modelling for agriculture

9.2.1 Modelling the Balanced Pathway for agriculture

Overall modelling approach

Our agriculture modelling considers the effect of a range of low-carbon farming practices and technologies and land release measures on agricultural emissions. The modelling workflow for the agriculture sector is set out in Figure 9.2. See Chapter 1 for our general approach to pathway analysis.

- **Land release measures:** we start with modelling the impact of five measures that can release land out of agricultural production: reducing livestock numbers (delivered through a shift in the consumption of lower-carbon food, that maintains the domestic share of UK production, and the availability of incentives to diversify incomes beyond agricultural production); improvements in crop yields (that maintain the same output with less land and other inputs); reducing food waste from farm to householder (which avoids agricultural production); a redistribution of livestock from the uplands to the lowlands and the shifting of some horticultural production to indoor systems.

These measures have the effect of reducing the area of land under agricultural production, alongside a reduction in livestock numbers, all of which lead to a decline in agricultural emissions. The land that is released out of agriculture is then allocated for alternative uses such as woodland creation and peat restoration to increase carbon sequestration and reduce land-based emissions. This is covered in the land use methodology (Chapter 17).

- **Low-carbon farming measures and practices** are then deployed to reduce agricultural emissions further from the area of land that continues to remain under agricultural use and the remaining livestock. As some of these measures improve productivity, we assume less livestock is required to maintain the same level of output, which leads to a further reduction in livestock numbers. This gives us our final livestock numbers and land area under the Balanced Pathway.

- **Agricultural machinery demand** is scaled back in line with the change in agricultural activity data resulting from the land release measures. We then apply abatement options that entail a shift away from fossil fuel use towards low-carbon options such as electrification.

The key elements of our modelling approach are:

- **The CCC land release model.** This is a bottom-up model that outputs changes in agricultural emissions due to changes in agricultural activity data (e.g. land area and livestock numbers) resulting from the five land release measures:

  - The model contains agricultural activity data for each nation of the UK (e.g. food production by type, area of land use by type, and livestock numbers by type). The model is updated with historic data to 2022 using official sources from Defra and counterparts in Scotland, Wales, and Northern Ireland. Baseline projections in activity data are aligned to the UKAMM projections.

  - We then model the impact of measures that can facilitate the release of land out of agricultural use. The measures are reducing livestock numbers (achieved by a shift in the consumption to lower-carbon foods and supply-side policies to incentivise farmers to diversify land use beyond food production), reducing food waste, sustainable improvements in crop yield, reducing stocking rates in the uplands and redistributing to the lowlands, and a shift in horticultural production to indoor systems (see Table 3.1).

  - These measures result in a change in agricultural activity data to 2050 compared to the baseline (e.g. a reduction in agricultural land area and livestock numbers), which reduces agricultural emissions. The main outputs from the model are the abatement savings per land release measure, the area of land released out of agriculture, and the change in livestock numbers. The remaining land area under agricultural use and livestock numbers are used as inputs into the Agricultural MACC model.

  - The area of land released out of agriculture is used as an input into the CEH land use model to derive the abatement savings from land-based measures. Details on the CEH model are covered in the land use methodology (see Chapter 17).

- **Agricultural MACC model.** We commissioned the Scottish Rural College (SRUC) to calculate the abatement potential from the take-up of on-farm measures and practices that reduce agricultural emissions from the management of livestock, livestock waste, and agricultural soils to 2050.

  - The revised area of agricultural land and livestock numbers outputted from the CCC land release model are used as inputs into SRUC's model to determine the maximum technical abatement potential. The model then calculates the abatement savings

and costs per mitigation measure for each year to 2050 and for each nation of the UK. To avoid the double counting of emissions savings, the model takes account of interaction between measures (i.e. measures that reduce emissions from the same source).

  - SRUC was able to draw on evidence from the UK and other countries with comparable agricultural environment and systems to develop a shortlist of 29 on-farm measures based on cost effectiveness against our assumed carbon values, efficacy and confidence of abatement, and which were deemed not to be high-risk nor have negative impacts (e.g. on animal welfare).

  - For each measure, an assessment is made on the current uptake rate, which could be zero for some measures. Assumptions regarding future uptake rates and the lead-in time before deployment starts (based on technical and/or policy readiness) were made by the CCC.

  - The key outputs from the SRUC model for each of the 29 measures are emission savings by gas, average abatement cost, and costs (capex and opex). Results are provided for each nation the UK.

  - A more detailed description of the SRUC model can be found in their accompanying report.[3]

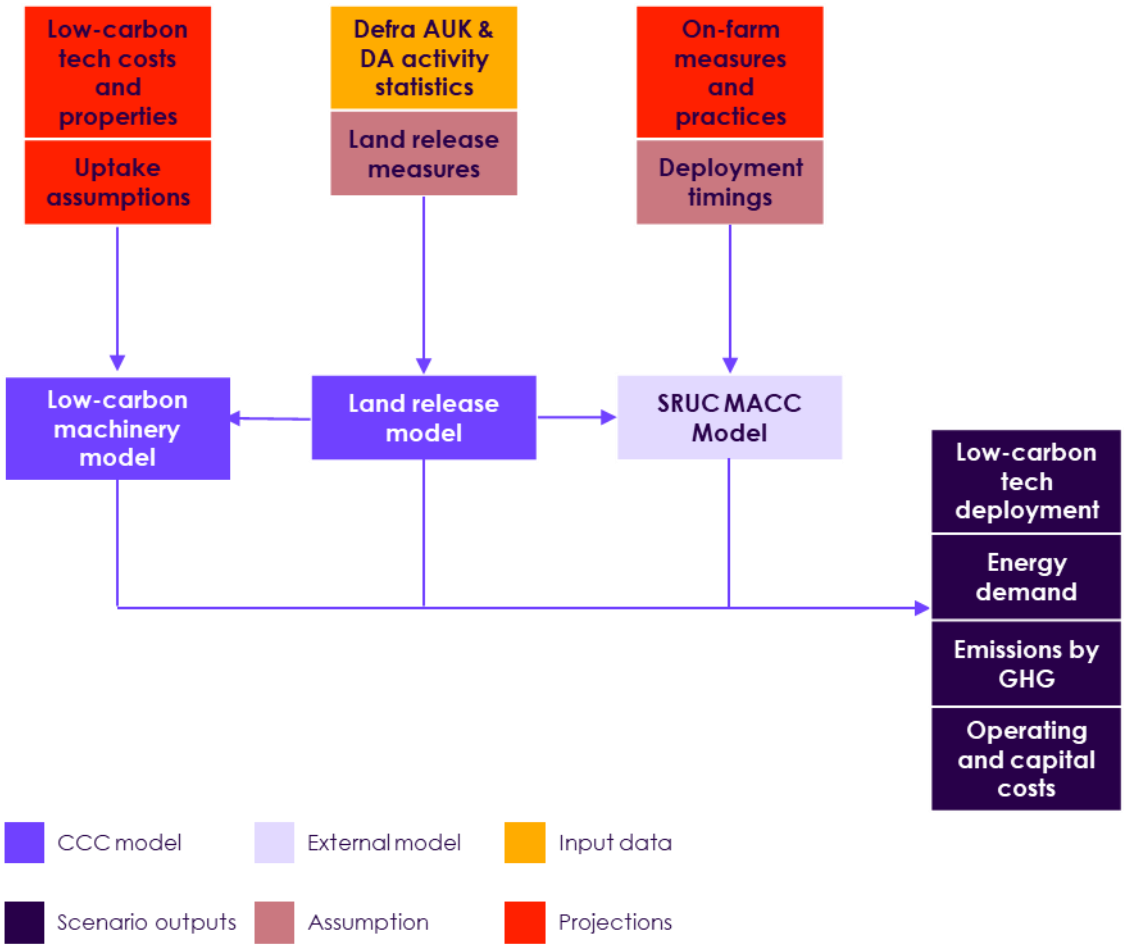
- **Low-carbon machinery (stationary and non-road mobile machinery)** work was undertaken in-house, and where possible, assumptions were aligned to CCC work in the commercial non-residential buildings sector for stationary machinery, and the non-road mobile machinery (NRMM) in industry:

  - We assumed that the revised area of agricultural land and livestock numbers derived from the CCC land release model reduces the amount of energy demand in the sector and therefore the number of machines that are left to decarbonise in our Balanced Pathway. For example, a reduction in dairy cattle numbers will reduce the energy requirements to operate milking parlours.

  - The make-up of the current NRMM fleet size and the average energy demand per unit were provided by Ricardo. We then used this to model future changes to machinery numbers in line with the changes to energy demand away from fossil fuel use.

  - For stationary machinery, we applied the relative efficiencies from switching from high-carbon to low-carbon machinery modelled for the Balanced Pathway for the commercial sector of non-residential buildings, as well as the decarbonisation pathways for each fuel type, to calculate the energy demand and transition profiles of fossil fuel technologies (gas and oil boilers) to low-carbon ones (heat pumps, direct electrification).

Figure 9.2 Modelling schematic for agriculture

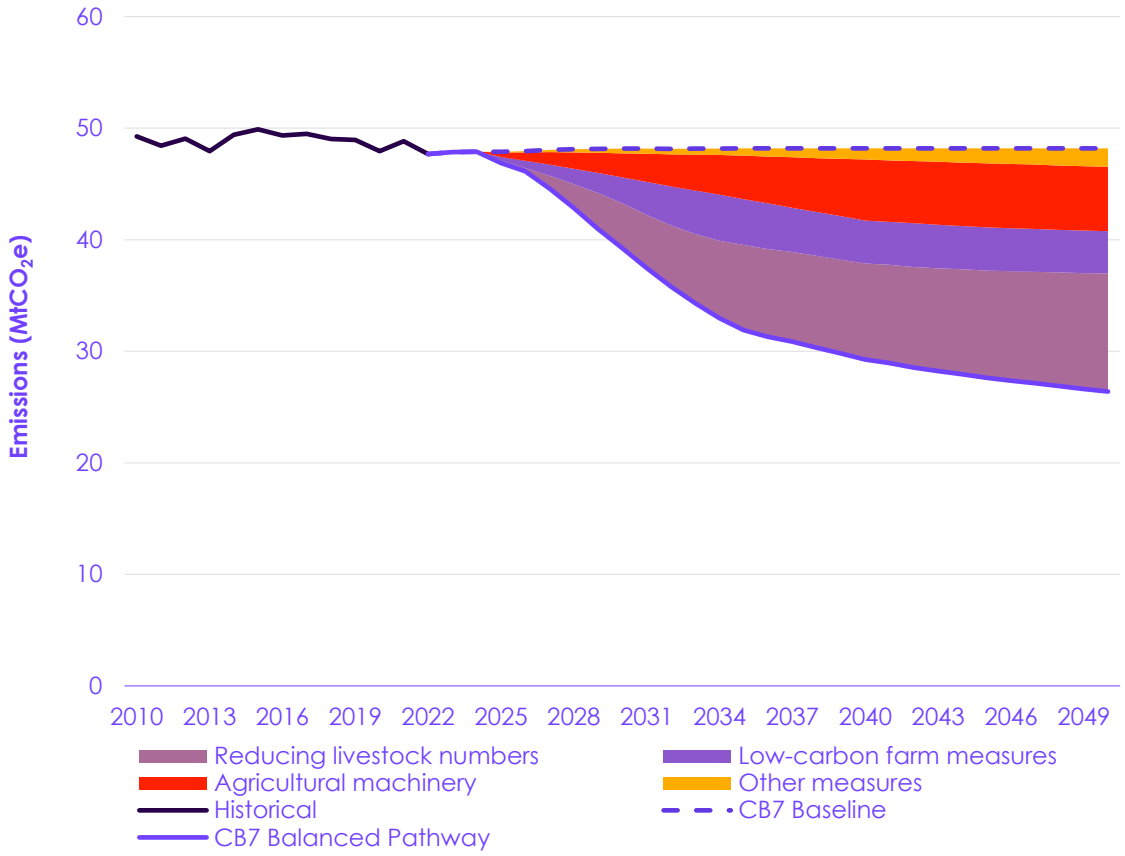


Description: Our agriculture modelling is based on three models, which assess the impact of a range of low-carbon farming practices and technologies and land release measures on emissions and costs in the agriculture sector.
Source: CCC analysis.
Notes: This diagram is illustrative and does not detail all model inputs and outputs.

The Balanced Pathway for agriculture

In our Balanced Pathway, agriculture emissions are projected to fall by 39% to 29.2 $MtCO_2e$ by 2040 (the middle of the Seventh Carbon Budget period) and to 26.4 $MtCO_2e$ by 2050 (Figure 9.3).

Figure 9.3 Sources of abatement in the Balanced Pathway for agriculture



Description: The largest share of emissions reduction in agriculture and land use comes from reducing livestock numbers. Significant contributions also come from actions to decarbonise machinery and from the take-up of on-farm measures to reduce emissions from managing soils and livestock.
Source: Department for Energy Security and Net Zero (DESNZ) (2024) *Provisional UK greenhouse gas emissions national statistics 2023*; DESNZ (2024) *Final UK greenhouse gas emissions national statistics 1990-2022*; Scotland's Rural College (2025); CCC analysis.

The measures in our pathway

Table 9.1 summarises the measures to reduce emissions in the agriculture sector that are considered within our modelling, how these lead to emissions reductions in our modelling, and the key factors that influence their uptake. The methodology used to develop the assumptions and analysis underpinning these is described in the rest of this section.

Table 9.1
Measures considered within our modelling for agriculture

Decarbonisation measure	How does this measure influence emissions in our modelling?	What are the key factors that affect uptake in our modelling?
Reducing livestock numbers – shifting to lower-carbon foods **Reducing livestock numbers – supply-side policies**	An average reduction in meat and dairy consumption reduces the demand for UK-produced (and imported) meat and dairy. This, combined with supply-side policies to incentivise UK farmers to diversify their operations and incomes beyond food production,	Our pathway assumes going faster than the existing long-term trend of reduced meat and dairy consumption, supported by a combination of policy levers to encourage a shift towards lower-carbon foods. We assume this happens in tandem with supply side policies to support and incentivise farmers to reduce overall livestock numbers. We assume

	leads to a reduction in UK livestock numbers and associated agricultural land area (grassland and cropland to grow animal feed).	that the share of consumption met by domestic production is maintained.
Low-carbon farming measures – livestock feed and additives	This captures two types of feed measures: 3NOP for beef and dairy cattle, and nitrate feed additives for beef, dairy, and sheep. Both reduce enteric methane from cattle and sheep, and a third measure, the use of precision feeding tools for dairy cattle improves the feed conversion ratio thereby lowering emissions.	3NOP and nitrate feed additives are only applicable to livestock when housed, and under non-organic systems. For applicable livestock, we assume a 50% and 50-60% uptake rate for 3NOP and nitrate feed additives respectively, which is reached within 10 years of the measure being deployed. Precision feeding of dairy cattle is applicable to 50% of the herd.
Low-carbon farming measures – livestock health	Reducing the vulnerability of beef cattle and sheep to endemic diseases reduces the emissions intensity of production by improving the feed conversion ratio, fertility, and a reduction in mortality.	Measures start in 2025 and are applicable to 80% of beef and sheep. Improved livestock health is modelled via changing the productivity of the animals.
Low-carbon farming measures – livestock breeding	Comprises three types of measures: genomics tools for beef and dairy cattle; lower emissions breeding goals for beef and dairy cattle, and current breeding goals for sheep. Allows for the selection of beneficial traits (e.g. to improve health and fertility), which can also lower emissions intensity of production.	Use of genomics and lower emissions breeding goals is applicable to 90% of dairy and 20% of beef cattle respectively, although the improvement in dairy yields already assumed in the baseline means that the impact of these two measures is reduced. These two measures are mutually exclusive so the take-up of one would greatly reduce the savings of the other measure.
Low-carbon farming measures – waste & manure management	There are four measures that reduce methane and nitrous oxide emissions from waste storage. This includes the flaring of methane from stored pig, dairy, and beef waste; the anaerobic digestion of pig waste; the covering of slurry tanks with impermeable lids for pigs, dairy, and beef cattle; and the adding of acid to slurry tanks for pigs, dairy, and beef cattle.	The non-AD measures are assumed to reach an uptake rate of between 50-75% ten years after deployment, which with the exception of impermeable lids (2025) starts in 2027. Unlike AD cattle, AD pigs is included in our Balanced Pathway because it has a higher methane content per unit of waste which makes it a cost-effective measure.
Low-carbon farming measures – faster finishing beef	Slaughtering beef cattle three months earlier (at around 21 months), without compromising on slaughter weight, avoids three months' worth of enteric and waste management emissions.	Applicable to all beef cattle that are slaughtered. This measure is modelled by reducing the number of animals in the relevant categories (7.3%, 7.3% and 7.5% of steers, cereal fed bulls, and females respectively) for slaughter that are over 24 months. We assume this measure is deployed from 2025.
Low-carbon farming measures – robotic milking	This allows for increased milking frequency from typically two to three times a day. As such, milk yields are increased, and	Robotic parlous are rolled out from 2025 and have a lifetime of around 15 years. We assume 60% of all dairy cattle is milked using this method by 2035.

	emissions intensity of output is reduced.	
Low-carbon farming measures – managing soils	Planting of cover crops, grass-legume mix, and triticale and more efficient use of nitrogen reduces fertiliser needs with a corresponding reduction in nitrous oxide emissions. The soil carbon savings from cover crops are captured in the land use GHG Inventory.	Planting of cover crops is currently estimated to be 6% of the applicable area, and we assume this increases to 75% by 2035; around 26% of improved grassland currently uses nitrogen fixing legumes, and we estimate this rises to 75% by 2035; the current area of triticale (an arable crop) in the UK is very small and going forward we only assume a small uptake, taking it to 0.6% of the wheat area. This reflects limited market expectations compared to wheat.
Low-carbon machinery	Replacement of fossil fuel use in mobile and stationary machinery with low-carbon options such as electrification and hydrogen reduces CO_2 emissions.	Use of biofuel as in interim fuel in mobile machinery is phased out completely in 2040. Low carbon options include electrification and hydrogen of the fleet. Stationary machinery is fully electrified by 2050.
Land release measure – crop yield improvements	Sustainable productivity improvements enable the same level of production with less land and other inputs. This feeds through to a reduction in agricultural emissions.	We assume good agronomy and use of breeding can lift yields sustainably, combined with the impact of increased CO_2 fertilisation rates and longer growing seasons. 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.
Land release measure – reducing food waste	A reduction in food waste along the supply chain from farm to fork reduce agricultural emissions by avoiding unnecessary food production, while enabling land to be released out of agriculture.	We have aligned the reduction to the UN Development Goal 12.3 and Courtauld Commitment to reduce food waste by 50% per capita reduction by 2030 compared to 2007. We increase ambition to 60% by 2050.
Land release measure – destocking in the uplands	A reduction in stocking rates in the uplands with a redistribution to lowland grassland enables the release of upland area out of agriculture. As there is no reduction in livestock numbers there is no change in emissions.	Stocking rates on lowland grasslands increases by 3.8% by 2035 and by 10% by 2050 to accommodate the destocking of livestock from the uplands. We assume there is sufficient capacity on the lowlands to accommodate this increase.
Land release measure – indoor horticultural production	Moving some horticultural crops to indoor systems enables the release of land out of agriculture. This reduces emissions associated with soil and crop management (e.g. the application of fertiliser).	10% of horticultural crops are shifted to indoor systems by 2050. This low level acknowledges that based on current technology not all horticultural crops can be grown indoors, due to cost (which favours higher valued salad crops) and/or technical limitations (may not suit deep rooting crops).
Lowland crop peat restoration and management	Water table management and restoration of agricultural soils on peatland reduce nitrous oxide emissions. These savings are captured in the Agriculture GHG Inventory.	By 2050, 75% of deep cropland peats and 40% of wasted peat is under rewetted or under sustainable management. Annual uptake rates are based on analysis and stakeholder engagement that considered availability of land and feasibility of action.

9.2.2 Low-carbon farming practices and technologies

The take-up of farm practices and technologies combine to reduce emissions from managing agricultural soils and livestock, and from machinery use.

Soils and livestock measures

Based on the current state of technology, it is not possible to reduce non-energy related emissions in agriculture to zero due to the biological processes inherent in crop and livestock production. However, there are a range of farming practices and technological options available to farmers to reduce methane and nitrous oxide emissions.

We commissioned the Scottish Rural College to update and build on their modelling work previously undertaken for our Sixth Carbon Budget advice to estimate the abatement potential for each nation of the UK. The abatement potential was estimated using a bottom-up Marginal Abatement Cost Curve (MACC) model. Updated evidence was taken from a wide range of sources at the UK level and countries with comparable agricultural environments such as Ireland. A final list of 29 measures spread across seven categories were included in the Balanced Pathway. A more detailed description of each measure and the modelling approach is set out in the accompanying SRUC report:[4]

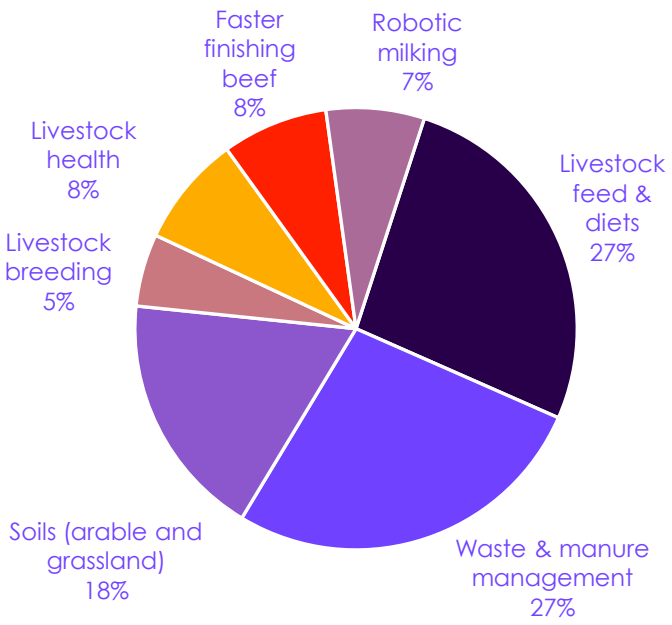
- The final 29 measures were selected based on their cost effectiveness each year against our assumed carbon values, efficacy and confidence of abatement, while posing low risks to livestock (e.g. animal welfare) and the wider environment. For this reason, we exclude the measure asparagopsis, which despite offering the highest abatement savings of all the livestock feed measures, has potential environmental concerns around its use.

- The modelling takes account of productivity improvements in the baseline (higher milk yields) and the land release measure under the Balanced Pathway, 'crop yield improvements', by either excluding abatement measures from the Pathway that entail an improvement in productivity such as improving dairy cattle health and improved drainage of cropland area, or when productivity measures are included (e.g. genomics for dairy cattle) reducing the respective yield improvements. This avoids an over-estimate of emissions savings and productivity gains in our Balanced Pathway.

- Several of the livestock measures imply an improvement in agricultural productivity (e.g. more output per animal). The model therefore assumes that current output is maintained which leads to a corresponding reduction in livestock numbers.

Figure 9.4 shows the share of emissions savings grouped across the seven main categories of abatement that make-up the 29 measures. For example, the livestock feed and diet category consist of three types of measures (3NOP, nitrate feed additives, and precision feeding tools), which are then disaggregated by livestock type.

Figure 9.4 Share of emissions savings from soil and livestock measures, 2040



Description: Under the Balanced Pathway, livestock feed and waste management account for over half of the emissions savings in 2040 from the take up of on-farm practices and measures. The three measures that reduce nitrous oxide emissions from soils account for just under a fifth of the abatement.
Source: CCC analysis; SRUC.

The MACC also provides the abatement potential under a scenario which assumes no take-up of any land release measures. This enables us to compare the emissions savings based solely on the take up of on-farm measures versus the Balanced Pathway (which includes both on-farm and land release measures e.g. a reduction in livestock numbers) (see Section 9.4). Under this scenario, we have three additional measures compared to the Balanced Pathway:

- Improving soil drainage, optimising soil pH, and reducing soil compaction, all of which improve crop yields in addition to reducing emissions.

Given our Balanced Pathway includes crop yield improvement (as a land release measure), these three measures are excluded to avoid double counting of productivity gains and emissions savings.

Decarbonising mobile and stationary machinery

Non-road mobile machinery comprises*such as combine harvesters, sprayers and tractors. Currently these are fuelled by diesel, although there exist some smaller hybrid-electric auxiliary vehicles and ones run on biodiesel. Bottom-up data indicate a current fleet size of around 473,000 units spread

across different power rating bands ranging from 8kW to over 560kW, with the higher power ratings reflecting the specific operational requirements of farm vehicles.*

For our Balanced Pathway, we assume that smaller machinery (with a power rating of up to 78kW) will decarbonise through electrification. Larger machinery (over 78kW), which includes medium and large sized tractors and combine harvesters, is projected to decarbonise through a switch to hydrogen-fuelled engines.

- We assume that the use of hydrogen could overcome some of the limitations associated with electrification, such as running time and power required to lift, pull, and drag.
- Should technology develop however, then electrification could be used to decarbonise the whole fleet.
- Bioenergy used as a transitional fuel is phased out completely by 2040.

Stationary machinery is required for a range of activities such as the drying and storage of arable crops, heating, lighting, and ventilation for indoor livestock and the pumping of water and nutrients for covered horticultural products. In 2022, electricity accounted for around 37% of energy use in stationary machinery, bioenergy around 14%, and natural gas and fossil fuels the remainder.

In our Balanced Pathway, energy use for stationary machinery is decarbonised through electrification, mirroring developments (e.g. efficiencies of heat pumps) and costings in the commercial buildings sector (see Chapter 14).

- There is scope to increase the thermal efficiency of the fabric of farm buildings, although this was not modelled in our pathway.
- Additional energy efficiency measures such as building systems and controls and energy management practices are also excluded in the modelling.

9.2.3 Reducing UK livestock numbers

Our Seventh Carbon Budget advice entails a reduction in UK sheep and cattle numbers by 27% between 2023 and 2040. This is achieved through a combination of supply side measures, a shift from meat and dairy consumption to lower-carbon foods and productivity improvements delivered through some of the on-farm measures deployed for livestock (see Section 9.2.2).

Shift to lower-carbon foods

The Seventh Carbon Budget advice includes a reduction in average meat and dairy consumption, which constitutes a shift away from meat and dairy to lower-carbon foods (see Table 9.1) and feeds through to a reduction in livestock numbers.

We model an acceptable and achievable reduction in meat and dairy consumption, based on projected forwards trends in meat and dairy consumption and evidence on the potential additional impact of policy levers on meat and dairy consumption. We take into consideration impacts of an average reduction in meat and dairy on health and feedback on these policy levers from a citizens' panel. As part of this analysis, we made evidence-based assumptions about what meat and dairy would be replaced with, which feed into emission, land use, and cost modelling.

* Power rating is a measure of an engine's ability to produce power.

Impact on domestic meat production

Given the UK represents the largest market for domestic meat output, for UK producers in total and in Scotland, Wales and Northern Ireland, we assume that changes in UK consumption towards lower-carbon foods will impact production at both the UK and nation level:

- For all meat types, the UK is the largest market for UK output, while exports of beef, lamb, and pork accounted for 15%, 31%, and 18% of UK output respectively in 2023.[5]

- For each of Scotland, Wales and Northern Ireland, the UK is also the largest market for meat sales. For example, the UK accounted for 82% of Northern Ireland's beef and sheep meat sales in 2021 (15% of sales were made within Northern Ireland).[6;7] For Scotland, the UK accounted for 92% and 80% of beef and sheep meat sales respectively in 2023,[8] while in Wales, 80% and 60% of respective beef and sheep meat sales in 2021 were made to the rest of the UK.[9]

- The largest UK export market is the European Union accounting for 89% and 93% of beef and lamb and sheep meat exports respectively in 2023. The European Commission included an objective to reduce red and processed meat consumption and move to a more plant-based EU diet in their 'Farm to Fork Strategy', and the 'Strategic Dialogue on the future of EU agriculture' highlights the need to support an existing EU consumer trend away from animal-based to plant-based products. [10;11]

In our Balanced Pathway, we assume that a shift to lower-carbon foods would impact meat and dairy imports first.[12] UK livestock farmers would require time to adjust output levels given livestock production life cycles and we have therefore incorporated a three-year lag before a reduction in meat and dairy consumption feeds through to a change in domestic output and associated territorial emissions reduction. We also assume a constant domestic share of consumption is met by UK production once UK livestock numbers start to fall due to diet change.

We tested some of these assumptions with the CCC convened independent Food and Trade Advisory group, who concluded that shifting to lower-carbon foods as a means of changing UK agriculture, to free up land and reduce its emissions, is certainly feasible; and that a range of policy levers could be used to influence demand while minimising the risk of carbon leakage from imports.[13]

Trends in consumption and purchases

We take long-term trends from the Family Food Survey into account when assessing what reduction in average meat and dairy can be expected without further policy action. Long-term trends show a steady, but small reduction in overall meat and dairy consumption. A forward projection of this trend from 2020 to 2030 informs our assessment of a feasible shift in meat and dairy consumption without additional policy levers.

- We use food purchase data from the Family Food Survey (FFS), combining data from the eating out and household consumption datasets.[14] This is used to estimate the grams of meat and dairy products purchased per person per week.*

- Long-term trends in FFS data show a decreasing trend in the consumption of dairy (-11%) and meat (-9%) between 2002 and 2019. The long-term reduction of overall meat consumption is made up of a larger reduction in red meat consumption and an increase in white meat consumption.[15]

* FFS data is reported in financial years. For our indicators, we make an adjustment to report consumption estimates in calendar years, which excludes some of the data included in the FFS 2022/23 reporting.

- The existing long-term trend projected forward would achieve an overall 5% reduction in meat consumption (from 2019 levels) by 2030, with an 11% reduction in red meat consumption and a 4% increase in white meat consumption, and an 8% decrease in dairy consumption.[16]

Recent years show a steeper reduction in meat and dairy consumption (compared to long-term trends), but it is unclear whether this is temporary. As a result, we use 2019 as a starting point in estimating the percentage reduction in meat and dairy consumption.

- In recent years, meat purchases have fallen more steeply than the previous long-term trends, with a 10% fall in overall meat consumption and 11% fall in dairy consumption between 2020 and 2022 (Figure 9.5). A similar steep reduction trend for 2020 to 2022 can be observed in retail tracker data for GB household purchases for in home consumption (excluding eating out data).[17]

- It is too early to indicate whether this steeper than projected trend will continue in the long-term or is a temporary response to the cost-of-living crisis, which saw an 11% decrease in overall food purchases by weight between 2020 and 2022. Due to this uncertainty, in the Balanced Pathway we leave room for the consumption of meat and dairy to rebound to some extent.

Review of potential impact of policy levers

We undertook an evidence review (Table 9.2) and stakeholder engagement to determine a feasible reduction in meat and dairy consumption and to understand the type of policy levers that could achieve a reduction in meat and dairy consumption.

- We reviewed the evidence to identify the extent to which policy could encourage further reductions in meat and dairy consumption beyond the continuation of historic trends of declining meat and dairy consumption from 2020 to 2030.

- Priority was given to evidence that looks at changes in actual purchase behaviour (rather than intentions or attitudes) and evidence gathered in real-world settings where this was available. We focused on policy levers that are realistically available to policy makers. We included evidence from studies conducted in the US and European countries where appropriate and where UK evidence was not available.

- We used the synthesis of available evidence to assign an approximate feasible overall percentage reduction in meat and dairy consumption to each group of policy levers and considered the overall feasible reductions, taking into account that policy levers may not be additive.

- We tested this approach with expert stakeholders and the evidence synthesis for meat reductions was peer reviewed by researchers from the London School of Hygiene and Tropical Medicine (excluding the evidence for further innovation in alternative proteins).

- When assessing each policy lever, we also assessed a likely mix of low-carbon replacements (plant whole foods, already existing alternative proteins and more novel alternative proteins), although the future mix of replacements remains uncertain.

- We further assessed what this assumed mix of low-carbon replacements means for health and nutritional impacts (see Chapter 9 in the Seventh Carbon Budget advice report) and household costs (see Chapter 3) to ensure the levels included in the Balanced Pathway are compatible with healthy diets and have regard to their likely impact on consumer costs.

- We deliberated different policy levers to achieve a reduction in average meat and dairy consumption with a citizens' panel. The results of this deliberative research are published on the CCC website.[18]

Table 9.2 provides a summary of the evidence synthesis, highlighting the most impactful levers described in the literature that a government could apply. Much less evidence is available on levers to achieve a reduction in average dairy consumption. We therefore describe the levers in more detail for a reduction in meat consumption and then consider how they may apply to a reduction in dairy consumption.

Table 9.2
Evidence on impact of policy levers on meat and dairy consumption

Policy lever	Description of levers for a reduction in meat consumption, and applicability to dairy consumption
Product and choice levers for meat and dairy consumed when eating out	**Meat** We estimate that 9% of meat is consumed outside of the home (e.g. in restaurants).[19] Available levers for a shift from meat and dairy to lower-carbon foods include: • Plant-based defaults on menus. [20] Studies trialling default menus on online ordering forms or special menus in a restaurant found large reductions in meat orders, while studies trialling gentler nudges by labelling the plant-based dish as 'dish of the day' or changing the order of meat-free and meat dishes tend to find potential, but small (and sometimes no) reductions in meat consumption. [21;22;23;24;25;26;27] • Increasing the availability of plant-based dishes in eating-out settings may achieve a small to moderate shift away from meat consumption.[28;29;30] Permanent introduction of plant-based alternatives at restaurants and fast-food outlets do tend to attract 15% to 20% in the share of sales towards these products, but it is unclear whether this results in an overall reduction in meat consumption.[31] • A small (e.g. 10–15%) reduction of the meat and dairy component of dishes in eating-out settings reduces meat consumption without affecting customer satisfaction.[32;33] Larger reductions may lead to reduced satisfaction and backfiring effects.[34;35] It is less clear whether the use of vegetarian or carbon labels on menus would lead to a shift towards lower-carbon foods, with studies finding mixed results.[36;37;38] **Applicability to dairy** FFS data suggests that a very small proportion of overall dairy is consumed outside of the home, so these levers would only achieve a very small reduction in dairy consumption. [39]
Product and choice levers for meat and dairy purchased in a super-market or similar setting	**Meat** We estimate that 91% of meat is consumed in the home and therefore purchased in a supermarket or similar setting (although some of these are take-out foods).[40] Available levers for a shift from meat and dairy purchases to lower-carbon foods include: • Small changes in the formulation of dishes such as ready meals to replace a small amount of meat and dairy (e.g. 10–15%) with plant-based alternatives. A substantial proportion of meat consumed in the UK is consumed as non-carcass meat.[41] Consumer studies suggest that consumers are open to blended products, especially where these have health benefits over meat only products.[42] Where blended products already exist, they currently only serve a niche market.[43] • Changes to supermarket layouts to 'nudge' a replacement with lower-carbon foods may have an impact. Online shopping experiments suggest that this kind of change in choice environment may reduce a small amount of meat consumption. [44] • Increased availability and better promotion of plant-based products consistently increases sales of these products, but is not necessarily associated with a decrease in meat purchases.[45;46;47] However, experts highlight that this would likely be the case in the longer-term.

	Due to limited evidence in real world settings and limited focus on meat products, it is not clear whether eco or carbon labels would facilitate a shift towards lower-carbon foods. Eco food labels can change consumer behaviour when they are noticed, but show the highest impact on consumers who already have some degree of concern and knowledge in relation to sustainable food choices.[48] **Applicability to dairy** Experiments suggest that supermarket promotions of plant-based milk increased the sales of plant-based milk, but is unclear whether this leads to a decrease in dairy milk sales.[49]
Levers that increase information and normalise a shift towards lower-carbon foods	**Meat** In addition to applying levers directly where meat and dairy is purchased, government can also increase information and shift norms: • Information on the health and environmental impacts of meat consumption is important to address a lack of knowledge and awareness. However, a single focus on information is unlikely to achieve big shifts towards lower-carbon foods.[50;51;52] • Governments can support normalising and therefore support a shift towards lower-carbon foods through many of the levers listed above.[53] In addition, experts highlight that showing leadership on the issue, including a desired reduction in meat and dairy consumption in dietary guidelines and using public procurement in hospitals and schools to increase the availability and exposure to meat-free meals could support a shift in norms and habits. Extensive knowledge, skills, and motivation interventions (e.g. cooking classes, offering free plant-based alternatives) are shown to be effective, but may not form a feasible policy lever. [54;55] **Applicability to dairy** Information levers may be less effective in achieving a reduction in dairy consumption, as the health and environmental benefits are less pronounced.[56]
Changes in relative prices of meat and dairy and lower-carbon foods	**Meat** • Evidence suggests that currently plant-based meat alternatives (especially where they allow for similar preparation and are closer to texture and taste parity of meat products) are sold at a price premium in the UK.[57;58;59;60] • Overall, changes to relative pricing (e.g. plant-based meat alternatives being priced significantly lower than equivalent meat products) are likely to result in a shift towards lower-carbon foods (depending on how the change in relative pricing is achieved).[61;62;63;64;65;66;67;68;69;70;71;72;73;74;75] **Applicability to dairy** • Evidence suggests that currently plant-based dairy alternatives (especially where they allow for a similar preparation and are closer to texture and taste parity of dairy products) are sold at a price premium in the UK.[76] • Overall, changes to relative pricing (e.g. plant-based dairy alternatives being priced significantly lower than equivalent dairy products) are likely to result in a shift towards lower-carbon foods (depending on how the change in relative pricing is achieved).[77;78;79;80;81;82;83;84;85;86]
Further innovation in alternative proteins	Innovation in existing alternative proteins and development of more novel alternative proteins could ensure that these become more directly substitutable for meat and dairy in taste and texture, and has the potential to reduce the price of alternatives and aid a shift to lower-carbon foods.[87;88] Market scenarios predicting alternative protein adoption in the future vary greatly, as do expert predictions.[89]

Source: CCC evidence synthesis.
Notes: The table summarises the evidence for the most frequently discussed levers. It focuses on the main evidence sources but does not include all levers or all evidence sources included in the CCC evidence synthesis.

Overall reduction in meat and dairy consumption

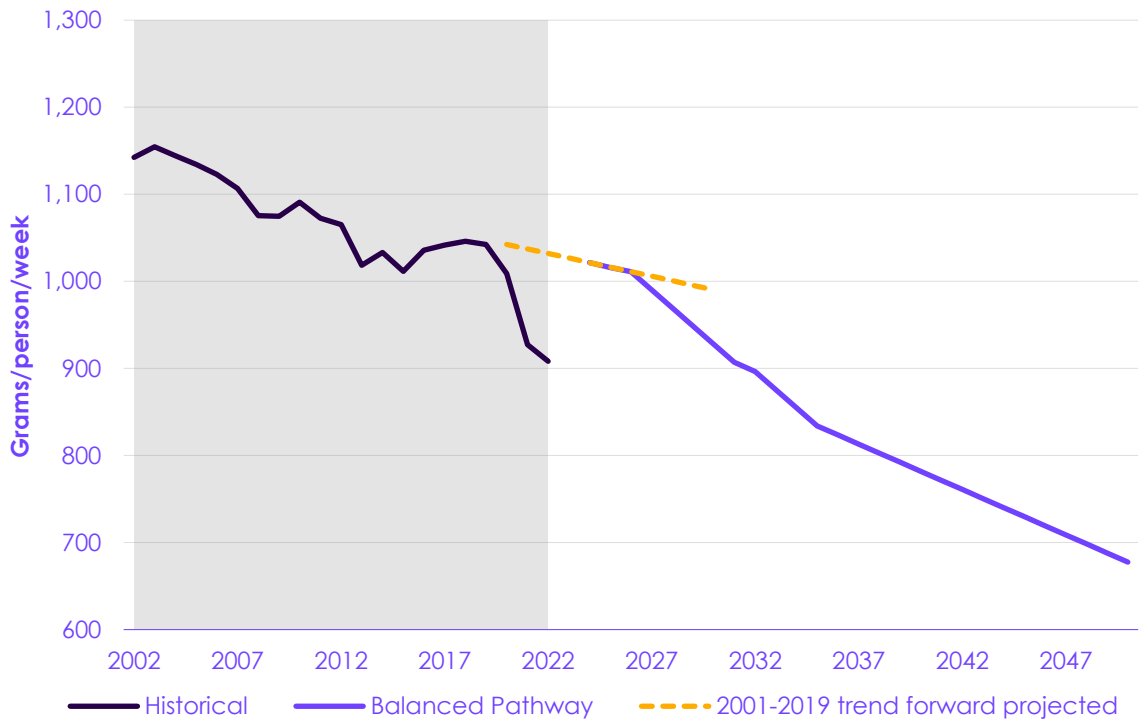
Based on the above assumptions, we assess that the existing long-term trend in a reduction in meat and dairy consumption projected forward to 2030 and a combination of levers presented in Table 9.2 will enable an average 35% reduction in meat consumption and an average 20% reduction in dairy consumption by 2050. Policy levers are only modelled as having an effect from 2027 (Figure 9.5)

Table 9.3
Key assumption values in the Balanced Pathway for meat and dairy consumption

Variable	2030	2035	2040	2050
Reduction in average total meat consumption	11%	20%	25%	35%
Reduction in average red meat consumption	15%	25%	30%	40%
Reduction in average white meat consumption	5%	15%	20%	30%
Reduction in average dairy consumption	12%	20%	20%	20%

Source: CCC analysis.
Notes: Percentage reductions are in comparison to 2019 levels. Red meat is defined as beef, lamb and pork, while white meat is poultry. We group pork with beef and lamb, due to data availability constraints for long-term consumption trends at the time of analysis.

Figure 9.5 Reduction in average meat consumption under the Balanced Pathway



Description: The Balanced Pathway requires going beyond the existing UK long-term trend, which shows a gradual reduction in meat consumption. More recent purchases between 2020 and 2022 fell more steeply, representing a faster decline than our Balanced Pathway. It is too early to tell if this is a temporary response to the cost-of-living crisis or will continue.
Source: CCC analysis; the 2001-2019 trend forward projected is taken from Pastorino et al. (2023).
Notes: We assume that any policy interventions to support a shift towards lower-carbon foods requires time to design and implement. The reduction in meat and dairy consumption included in our Balance Pathway in the years 2025 and 2026 therefore consists only of the reduction assumed based on the forward projected long-term trend.

Expected replacement pattern

In our assessment we consider three main low-carbon alternatives that people may replace meat and dairy with:

- **Plant whole foods**, such as vegetables and legumes, which tend to already be cheaper than meat and dairy products.[90]
- **Already existing alternative proteins**, such as plant-based milk (e.g. oat milk or almond milk) or plant-based burgers or sausages. Existing alternative protein products currently carry a price premium.[91;92]
- **More novel alternative proteins**. In future years we expect the development and market introduction of more novel alternative protein products that mimic the texture and taste of meat products more closely.[93;94] These novel alternative proteins may utilise new technologies such as precision fermentation or the cultivation of protein and are likely to initially be used as ingredients to enhance existing alternative protein products (rather than to produce bulk protein).

Based on the levers available we assess that only a small proportion of meat and dairy consumption is replaced by plant whole foods. The biggest proportion is replaced by existing alternative proteins and in later years a small proportion is replaced by more novel alternative proteins (likely products where new technologies enhance existing alternative protein products such as plant-based burgers). We expect that the majority of meat products that will be replaced are processed meat products. This is an assumption made to inform our modelling on land use and health impacts, but is not a recommendation or core component of the Balanced Pathway.

Table 9.4
Assumed replacement patterns

	Replacement pattern	Rationale	Impact on emissions
Meat			
Plant whole foods	Around 5% of meat is replaced with plant whole foods.	This is only a small proportion as the available levers may work more effectively when replacing meat products with products that can be consumed and prepared in a similar way.	This replacement assumption feeds through into emissions reductions in the agriculture and land model by replacing the equivalent grams of meat protein with plant whole food protein and the associated lower emissions.
Existing alternative proteins	20% of meat is replaced with existing alternative protein products (e.g. replacing a meat burger with a plant-based burger).	We assess that this is a more likely shift, as it taps into the increase in convenience food consumption and policy levers can target a lower-effort replacement. [95]	As most existing alternative proteins have a plant basis (e.g. pea or soy) the majority is a replacement of grams of protein of meat with grams of protein of plant whole foods and the associated emissions. A small proportion of existing alternative proteins are based on biomass fermentation (e.g. mycoprotein products) and emissions which occur post-farm gate are calculated

			separately for these products.
More novel alternative proteins	10% of meat is replaced with products that include novel alternative proteins. We assess it likely that 8% of meat will be replaced with existing alternative protein products (e.g. a pea burger) that are enhanced through technologies like precision fermentation. In the latter years a small amount of meat (2%) may be replaced with products mainly or solely produced through novel technologies (e.g. cultivated meat).	More novel alternative proteins would not only enable a low-effort replacement, but will also likely be closer in texture and taste to meat and dairy products. However, there may initially be barriers in scaling up production, and potential regulatory and consumer acceptance barriers.	For the agriculture and land use model this means that a proportion of replacement is through grams of protein of plant whole foods (the existing alternative protein part of products that combine existing alternative proteins with new technologies).
Dairy			
	We expect that the main replacement will be of milk, rather than milk-based products such as yoghurt and cheese and that milk will predominantly be replaced by already existing plant-based alternatives such as oat or almond milk or more novel alternative proteins utilising precision fermentation. However, where precision fermentation is used, this will likely only make up a small proportion of the actual product.	Based on the FFS data by far the majority of dairy is consumed in the form of liquid milk (although there are limitations to this non-disaggregated reporting). In addition, cow's milk already has an established plant-based alternative that has increased in popularity and consumer acceptance (which is not the case for other dairy products).	This translates into emissions reductions in the agriculture and land model by replacing 20% of dairy protein by weight with 18% of plant whole foods by weight (e.g. the oat in oat milk) and associated emissions and 2% of protein by weight produced through fermentation and cultivation.

Differences in reductions by nation

Our assumptions for the average reduction in meat and dairy consumption are the same for England, Wales, Scotland, and Northern Ireland. While there may be cultural differences in preferences around meat and dairy consumption (although data comparing attitudes and preferences is lacking) and some differences in current consumption patterns, we consider it appropriate to maintain a UK-wide average assumption, which already recognises that reductions will vary between individuals.[96]

9.2.4 Other land release measures

Sustainable crop yield improvements

Crop yield improvements through better agronomic practices and crop breeding can deliver productivity improvements on farm, enabling the same level of production with less land and other

inputs. In our Balanced Pathway, we assume that average yields increase by around 10% by 2050. This assumption was tested with expert stakeholders.

Reducing food waste

In our Balanced Pathway, food waste falls by 39% from farm to household by 2030 compared to 2021, and by 45% by 2040. This level of reduction is consistent with the UN Development Goal 12.3 and the Courtauld Commitment to deliver a 50% per capita reduction in all food waste by 2030 compared to 2007. We assume a larger reduction of 60% by 2050.

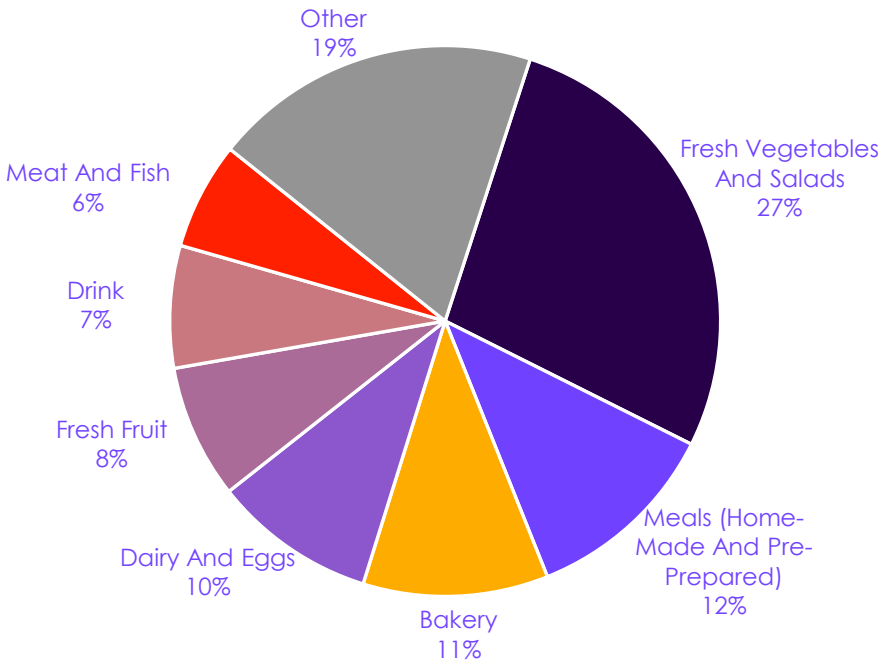
On-farm abatement savings result from avoided agricultural production which allows for some land to be released out of agriculture. The small level of abatement (0.3 $MtCO_2e$ by 2040) is due to the composition of food that is wasted and the share of UK consumption that is met by UK production versus imports (Figure 9.6):

- By weight, fresh vegetables and fruit and drink account for over a third of the food wasted. Reductions in their waste lead to small emissions savings given the high import ratio of both vegetables and fruit (51% and 85% respectively of UK demand in 2023), and the small land footprint of UK produce.[97]

- Meat only makes up 6% of the food that is wasted by weight, of which pork and poultry make up the bulk of the waste.[98] Given the lower emissions intensity of these meat products compared to beef and lamb, the emissions savings are also very small.

- Reducing the waste of bakery products (11% of food waste by weight) would be more significant, given the large area of land used to grow cereals, and the near self-sufficiency of cereal demand in the UK (~93% in 2023).

Figure 9.6 Composition of household food waste by weight, 2021



Description: By weight, the largest category of food wasted in 2021 was fresh vegetables and fruit and drink accounting for over a third of the waste. This was followed by homemade and pre-prepared meals (12%) and bakery products (11%).
Source: WRAP 2023; CCC analysis.
Notes: Composition of edible parts only.

Shift horticultural production to indoor systems

In our Balanced Pathway, based on judgement we assume that 10% of these products are moved to indoor systems by 2050. Emissions savings are quite small due to the small land footprint of horticultural production but focusing on those products that are grown on lowland peat, which is the most carbon intensive land would deliver the highest emission savings (see Chapter 17).

Livestock stocking density

In our Balanced Pathway, based on stakeholder feedback, we retained the Sixth Carbon assumption that stocking rates on lowland grasslands increase by 3.8% by 2035 and by 10% by 2050 to accommodate the destocking of livestock from the uplands. Consideration would need to be given on appropriate breeds suitable for lowland grazing. As the overall number of livestock is maintained, we assume that there is no associated agricultural emissions savings from this measure. However, this measure facilitates the release of upland area out of grazing for alternative land-based sequestration measures such as tree planting.

We assume that there is sufficient capacity on the lowlands to accommodate this based on the fall in stocking rates since 1990 and estimates that most grassland in the UK is underutilised (i.e. the grass that is eaten) by as much as half:[99]

- Data show that while cattle and sheep numbers fell by just over a quarter between 1990 and 2010, grassland area only fell by 5% over the same period. [100] This was probably due to reform of the subsidy payments under the Common Agricultural Policy in the 1990s that replaced payments based on head of livestock with area-based payments.

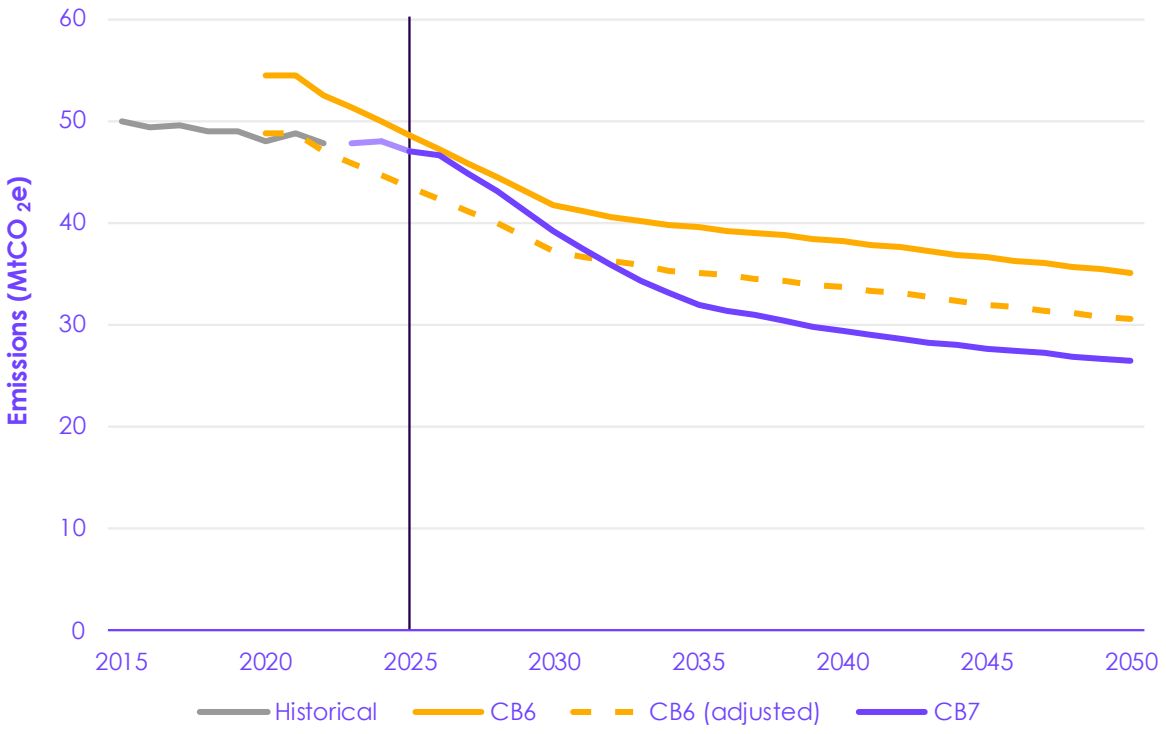
- Under-utilisation can be attributed to the current grazing management system of set stocking, which is the most common grazing system in the UK. This system allows livestock unrestricted access within a given area but delivers lower dry matter yields of utilised grass (50%) compared to more intensive grazing systems such as paddock (80%) and rotation grazing (60%). These systems allow for better control of the type of grass that is eaten (e.g. optimum sward height and quality), which can maximise livestock and grassland productivity.[101]

9.3 Changes since our Sixth Carbon Budget advice

9.3.1 Comparison with our Sixth Carbon Budget pathway

Our Balanced Pathway for agriculture starts higher than our Sixth Carbon Budget analysis would have, reflecting a lack of progress over recent years. Similar changes to those that had been assumed for 2020 to 2030 are now required over the coming decade instead. These deliver a slightly steeper reduction in emissions as we have assumed a steeper reduction in beef and lamb consumption (within a similar overall meat consumption reduction) than in our previous advice, to reflect existing relative trends and the higher carbon intensity of ruminant livestock (Figure 9.7).

Figure 9.7 The Balanced Pathway for agriculture compared to our Sixth Carbon Budget advice



Description: Changes in the methodology for reporting GHG Inventory since 2020 account for the lower starting point for our Seventh Carbon Budget (CB7) Balanced Pathway compared to our Sixth Carbon Budget (CB6) pathway.
Source: Climate Change Committee (2020) *Sixth Carbon Budget advice*; DESNZ (2024) *Final UK greenhouse gas emissions national statistics: 1990 to 2022*.
Notes: Estimates of emissions in this sector have been substantially affected by changes in emissions accounting methodologies in the inventory since our Sixth Carbon Budget advice (in particular, the fact that our Sixth Carbon Budget advice was based on GWP AR5-high, while the current GHG Inventory is aligned to GWP AR5-low). Therefore, to enable easier comparison, we have included a 'CB6 (adjusted)' series estimating what the Sixth Carbon Budget pathway would look like if they had used the latest inventory accounting.

9.3.2 Emissions changes since our Sixth Carbon Budget advice

Since our Sixth Carbon Budget advice was published in 2020, there have been changes to the methodology for measuring agricultural emissions:

- The adoption of Global Warming Potential AR5-low into the GHG Inventory since our Sixth Carbon Budget advice was published has reduced agricultural emissions, which for 2018 (the most recent reporting year at the time of our Sixth Carbon Budget advice) is 10% lower.
- A change in the method for allocating non-road mobile machinery emissions between sectors in the 2024 GHG inventory saw emissions from this source increase for agriculture (and decline in the industry sector) by 23% for the reporting year 2021 compared to the previous GHG inventory published in 2023.
- The sector's emissions reported under the 2024 GHG inventory have remained broadly flat, declining by 3% between 2018 and 2022. Most of that change was due to a reduction in soil emissions due to less fertiliser use in 2022, which was mainly attributed to high fertiliser prices due to the invasion of Ukraine.[101] Levels of fertiliser use for 2023 have increased, although are still short of pre-2022 levels.

9.3.3 Key pathway differences compared to our Sixth Carbon Budget pathway

There are several key areas in which the deployment rates, measures included, or underlying assumptions in our updated Balanced Pathway differ from those in our Sixth Carbon Budget advice. These include:

- **On-farm measures.** We now have 11 more measures, most of which are due to better disaggregation of measures across livestock types. For example, we now have emissions savings per feed type measure estimated separately for dairy cattle and beef. The same is true for breeding measures and waste management measures. Other assumptions including costs have been updated based on other projects SRUC have delivered in the intervening years since our Sixth Carbon Budget advice. Their report that accompanies our advice provides further details.

- **Livestock reduction.** Our Balanced Pathway assumes an equivalent overall level of reduction in meat consumption to that in our Sixth Carbon Budget pathway. But within this, we now assume a greater share comes from reducing consumption of beef and lamb, reflecting existing relative trends and the higher emissions intensity of ruminant livestock. When coupled with appropriate incentives for farmers to diversify their income streams, this creates scope for slightly higher levels of reductions in cattle and sheep livestock numbers than in our Sixth Carbon Budget analysis.

- **Updated modelling approaches.** Based on stakeholder engagement, we have reduced our ambition on the scope to increase average crop yields from 11 tonnes/hectare (for wheat) to 10 tonnes/hectare by 2050.* We commissioned Rothamsted Research, who compile the national GHG Inventory for the agriculture sector to update over 300 emission factors in the CCC land release model for the sources of methane and nitrous oxide based on the most recent GHG methodology.

9.4 Uncertainties and sensitivity analysis

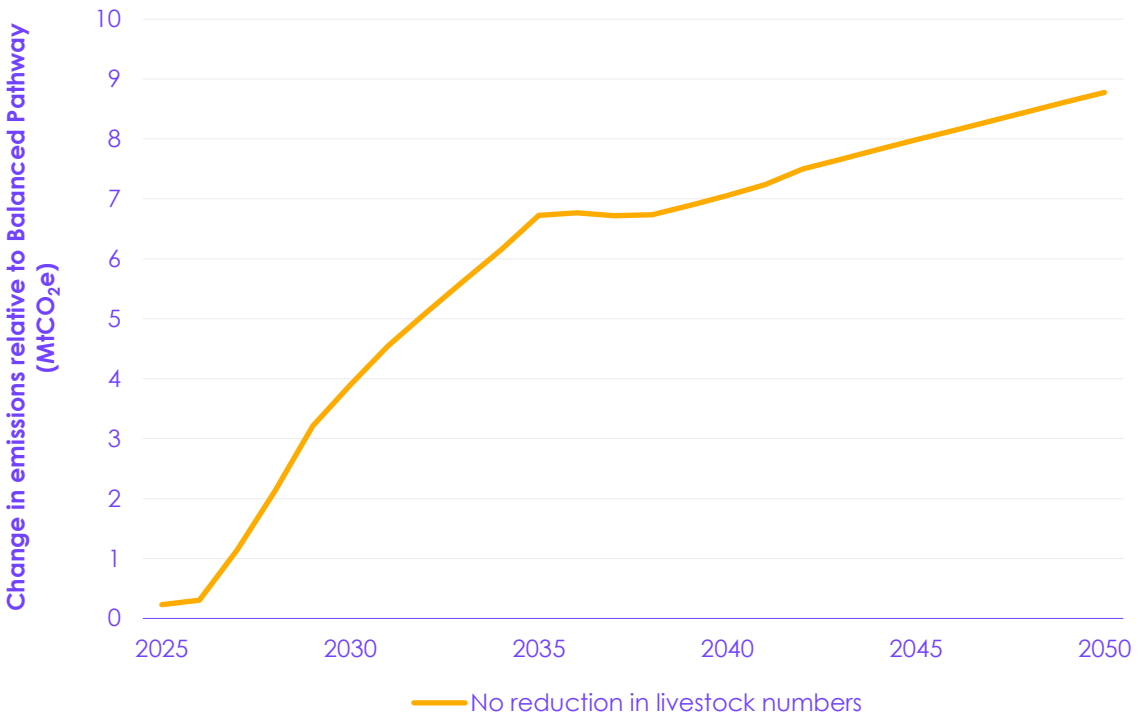
This section considers a key sensitivity test undertaken for the agricultural sector, which is shown in Table 9.5 and Figure 9.8. See Chapter 5 for our general approach to uncertainty, including descriptions of the methodology behind sensitivity tests that apply across multiple sectors.

Table 9.5
Key sensitivity test for agriculture

Sensitivity test	Description	Impact on emissions in 2040		
		$MtCO_2e$	% of sector emissions	% of total emissions
A reduction in livestock numbers does not happen	The levers for reducing livestock numbers (i.e. a shift towards the consumption of lower-carbon food and supply-side policies to diversify farmer incomes) are absent which leaves livestock numbers unchanged.	+7.1	+24%	+7%

Notes: The impact is only considering agricultural emissions. The impact on land use emissions from no reduction in livestock numbers is an increase of around 2 $MtCO_2e$.

Figure 9.8 Emissions impact of key sensitivity test for agriculture



Description: Under a sensitivity where there is no reduction in livestock numbers, emissions would be 7 $MtCO_2e$ higher by 2040 compared to our Balanced Pathway.
Source: CCC analysis.

9.4.1 A reduction in livestock numbers does not happen

This sensitivity assesses whether the take-up of low carbon farming practices and measures could compensate for the loss of emission savings if livestock numbers remain unchanged:*

- In the absence of a reduction in livestock numbers, there would be more residual agricultural emissions to abate as there are more livestock and land in agricultural use compared to the Balanced Pathway. This increases the emissions savings that could be delivered from the take-up of soils and livestock practices and measures compared to the Balanced Pathway by 1.6 $MtCO_2e$ in 2040 (5.4 $MtCO_2e$ rather than 3.8 $MtCO_2e$).

- However, these emissions reductions remain limited based on the current state of technology and does not compensate for the absence of emissions savings of 8.6 $MtCO_2e$ by 2040 due to livestock numbers remaining unchanged. The net result is that agricultural emissions are 7.1 $MtCO_2e$ higher compared to the Balanced Pathway in 2040.

- In addition, there would be a loss of emissions savings in the land use sector (around 2 $MtCO_2e$ in 2040) from the repurposing of land released out of agriculture due to a reduction in livestock numbers for measures such as tree planting and peat restoration (see Chapter 17).

* We assume that there is a reduction in livestock numbers linked to the uptake of on-farm measures that improve livestock productivity.

9.5 Contingencies in agriculture

The contingencies that we have modelled in the agriculture sector are shown in Table 9.6. See Chapter 5 for our general approach to contingency analysis.

Table 9.6
Contingency options in agriculture

Contingency	Description	Potential average annual emissions savings ($MtCO_2e$, % of sector emissions)			
		2030	CB6	CB7	2050
Higher reduction in meat consumption	A higher level of diet change beyond 2035, with average meat consumption declining to 45% by 2050			0.4 1%	1.9 7%
Additional use of livestock feed additives (Asparagopsis)	Asparagopsis is deployed from 2035 as a feed additive for beef and dairy cattle			1.3 4%	1.7 6%

Source: CCC analysis.
Notes: We have blanked out cells where the contingency measure in question is estimated to deliver less than 0.3 $MtCO_2e$ in potential emissions savings, to focus on high-yield options.

9.5.1 Higher reduction in average meat consumption

From 2035, we model a contingency with a higher level of reduction in the average consumption of all meat types compared to the Balanced Pathway:

- By 2050, average consumption of meat in this contingency fall by 45% compared to 2019 levels. This reduction increases to 50% for red meat (beef, lamb, and pork) and to 40% for chicken.
- Meat is replaced with a mix of whole plant-based food, including existing proteins (35%) and more novel protein sources (10%).
- We assume that this steeper reduction in meat consumption is achieved through substantial development in novel alternative proteins and changes in relative pricing to ensure lower-carbon foods are significantly cheaper than meat products.

This delivers a higher reduction in agricultural emissions from 2035 onwards due to the larger reduction in livestock numbers and land area released out of agricultural use.

9.5.2 Asparagopsis as a feed additive

Asparagopsis, a type of red seaweed, is a livestock feed additive that can reduce enteric emissions in ruminant livestock. There is no current uptake of the measure in the UK and deployment in our contingency modelling is assumed to start from 2035, as more research would be required to address possible environmental concerns regarding its impact. For these reasons, we have excluded asparagopsis from our Balanced Pathway.

In terms of emissions savings, this contingency would offer the most abatement of all the feed measures modelled, accounting for two-thirds of the abatement by 2040 in the contingency scenario.

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Chapter 10: Electricity supply

Introduction

The electricity supply sector comprises electricity generation, storage, and networks.

The analysis undertaken to develop the Balanced Pathway for the electricity supply sector was based on combined electricity and hydrogen supply modelling commissioned from the consultancy AFRY.

- The modelling determines the least-cost system subject to the UK Government's 'target-consistent' carbon values and security of supply constraints.
- This was supported by additional analysis on distribution network requirements as well as commissioned research into weather patterns from Newcastle University.

This builds on the analysis published in our 2023 report Delivering a reliable decarbonised power system.

10.1 Baseline emissions in electricity supply

The baseline represents a scenario in which there is no further decarbonisation action by either the Government or the market in the electricity supply sector. See Chapter 1 for our general approach to baselines.

Our baseline for electricity supply is based on the following assumptions:

- **Electricity demand.** The level of electricity demand in the baseline increases by 29% between 2025 and 2050, reflecting growth in population and GDP in sector modelling.
  - In 2025, gross annual electricity demand in the baseline is 275 TWh. This is approximately the same as the latest historical data of 274 TWh in 2023. Existing demand is mostly from lighting, heating, and appliances in buildings and industry.
  - Demand increases to 357 TWh by 2050, largely reflecting growth in population, GDP, and the number of buildings. Growth in baseline demand is concentrated in buildings and industry (see Chapters 7, 8, and 14).
- **Technology mix.** We assume that the capacity of low-carbon electricity supply technologies remains at 2023 levels.
  - We assume that retiring technologies are replaced like-for-like in the year that they retire, except for nuclear.
    - The transition to low-carbon electricity is already well underway. In the baseline, we assume that the capacity levels of variable renewables, biomass, grid storage, and interconnection are fixed at 2023 levels out to 2050 to reflect a baseline with no additional decarbonisation. Technologies not yet deployed (e.g. hydrogen-fired turbines) are not included in the baseline.

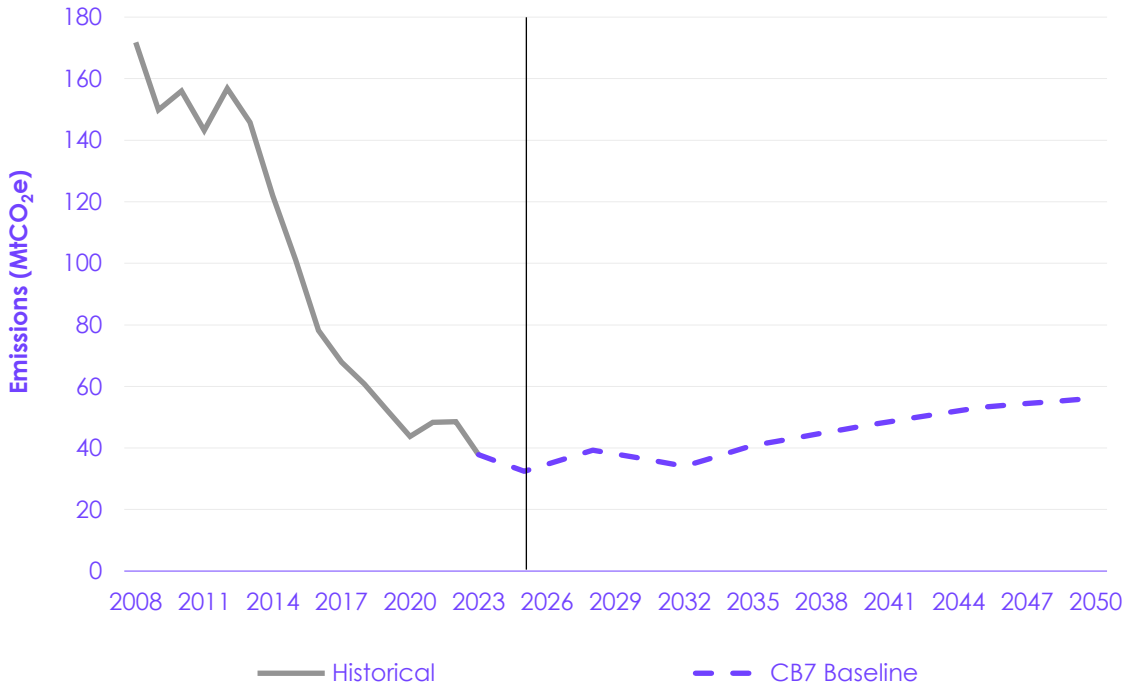
- Most of the existing nuclear fleet is expected to retire by around 2030. However, there is currently only one new plant under construction, Hinkley Point C. Due to the long lead times associated with nuclear projects, we assume that no additional plants are constructed to replace this retiring capacity beyond Hinkley Point C. Therefore, nuclear capacity in the baseline falls from 6 GW today to 4.5 GW in 2040.

- Unabated gas capacity increases to meet the rising demand. Modelling commissioned for this report suggests an additional 5 GW of new capacity would be required in the baseline scenario.

– We assume that technology costs are constant over time.

In the baseline scenario, emissions rise by 25% from 2023 levels by 2040 (the middle of the Seventh Carbon Budget period) and by 49% by 2050 (Figure 10.1).

Figure 10.1 Baseline emissions in electricity supply



Description: Electricity supply emissions have fallen significantly since 2008. In the baseline, emissions increase to 2050.
Source: DESNZ (2024) *Provisional UK greenhouse gas emissions national statistics 2023*; DESNZ (2024) *Final UK greenhouse gas emissions national statistics: 1990 to 2022*; CCC and AFRY analysis.
Notes: (1) The pathway is modelled using historical data up to 2023. Emissions changes prior to 2025 (shown in a pale shade in this chart) are based largely on existing trends; emissions changes only begin to be applied in our modelling from 2025 (indicated in this chart with a vertical line). (2) Emissions associated with energy from waste are accounted for in the waste sector. Emissions associated with combined heat and power are accounted for in the industry and fuel supply sectors. (3) Projected emissions are based on an average weather year.

10.2 Pathway assumptions and modelling for electricity supply

10.2.1 Modelling the Balanced Pathway for electricity supply

Overall modelling approach

For the analysis underpinning this report we used AFRY's BID3 Model.[1] We supplemented this with analysis on distribution network requirements and additional research on weather patterns from Newcastle University. See Chapter 1 for our general approach to pathway analysis.

- **AFRY BID3 Model.** We commissioned the consultancy AFRY to undertake modelling to inform the Balanced Pathway for the electricity and low-carbon hydrogen supply sectors. The modelling incorporates the following high-level features:
  - Hourly representation of electricity demand and generation, optimising the electricity and hydrogen production and storage systems simultaneously, and accounting for transmission constraints. Technologies are deployed and dispatched at a plant level.
  - Simultaneous modelling of the UK and pan-European interconnected markets, accounting for the geographic coverage of weather systems, with weather patterns (including wind speeds and impacts of temperature on demand) at 15 km^2 resolution.
  - Investment (e.g. by type and location for new generation capacity, transmission grid reinforcement, and the production and storage of hydrogen) and dispatch decisions are determined endogenously to give the economically optimal, least-cost system subject to the UK Government's 'target-consistent' carbon values (see Chapter 1).
  - The following constraints must be met:
    - Security of supply required to ensure lower than three hours of loss of load expectation* in line with current government requirements.[2]
    - Roll-out of technologies required to respect resource potentials and assessed build rate limits.
    - Ancillary service requirements, including short-term operating reserve, regulating reserve, and frequency response and inertia.
  - In order to account for uncertainty and to stress-test the results, a range of sensitivities were undertaken. These are presented in Section 10.4.
- **Distribution networks.** As distribution networks are not considered within the BID3 model, we worked with DESNZ to estimate the costs of reinforcing and maintaining distribution networks out to 2050.

* Loss of load expectation is defined in 'DECC (2013) *Annex C: Reliability Standard Methodology*' to represent the number of hours per annum in which, over the long-term, it is statistically expected that supply will not meet demand under normal system operation. It is noted that a certain level of loss of load is not equivalent to the same amount of blackouts. In the majority of cases, it is expected that loss of load can be managed by the system operator without significant impacts to consumers.

- We adapted published modelling of distribution network costs from the DESNZ Electricity Networks Strategic Framework, aligning costs to our Balanced Pathway and baseline based on peak demand outputs from the BID3 modelling.[3]

- The Electricity Networks Strategic Framework only covers Great Britain. We uplifted costs for Great Britain based on the share of UK electricity demand in Northern Ireland to estimate UK-wide and Northern Ireland distribution network costs.

- **Weather patterns.** We commissioned research from Newcastle University on anticipated periods of weather-driven high electricity demand and low renewables generation, accounting for changing UK weather patterns due to climate change.[4] The results from this study informed the weather patterns used in the modelling undertaken for this report. Box 10.1 sets out our approach to modelling weather in this report, and Box 10.3 sets out the approach to managing multi-year wind droughts.

In developing the Balanced Pathway, we provided inputs for the BID3 modelling that covered demand, flexibility assumptions, feasible roll-out rates, costs, and carbon values. We drew on a combination of government research, engagement with external stakeholders, and reviewing the literature in developing assumptions.

- **Electricity demand.** These inputs reflect the use of electrification to decarbonise other sectors and the availability of smart technology for demand flexibility. This, in turn, was predominantly determined by the modelling carried out in those sectors, including surface transport, industry, buildings, fuel supply, greenhouse gas removals, aviation, and shipping. These demands already consider demand side measures including energy and resource efficiency and modal shift, thus helping to limit total demand.

- **Deployment timelines and roll-out rate limits.** These were informed by supply-side and demand-side constraints for individual technologies, and consider planned developments, construction timelines, technology maturity*, availability of skills and infrastructure (e.g. CCS and hydrogen infrastructure), and resource constraints (e.g. land and seabed availability). Historical build rates for comparable technologies were also used to support the limits. Some capacity assumptions were determined exogenously to BID3 to manage modelling degrees of freedom (e.g. interconnector capacity).

- **Cost assumptions.** These included costs associated with capital expenditure, operation and maintenance as well as fuel. Capital costs took into account the potential for cost reductions due to global deployment driving experience and learning curve effects (Box 10.2).

The modelling schematic for electricity supply can be seen in Figure 10.2.

* We base this judgement on the internationally recognised system of technology readiness levels (TRLs). We apply a guiding threshold of TRL 6 - generally only including technologies that we assess as being already at or above this level (see Section 1.5.1). This represents those that have reached the stage of being demonstrated in a relevant environment.

Box 10.1
Approach to modelling of weather

We commissioned Newcastle University to analyse historical weather years and projected future climate, and their effect on renewables generation in different iterations of the electricity system to 2050. We used this research to inform our pathway modelling. This box explains our overall approach to incorporating weather in the pathway analysis, and describes the Newcastle research and how we used it.

Overall methodology

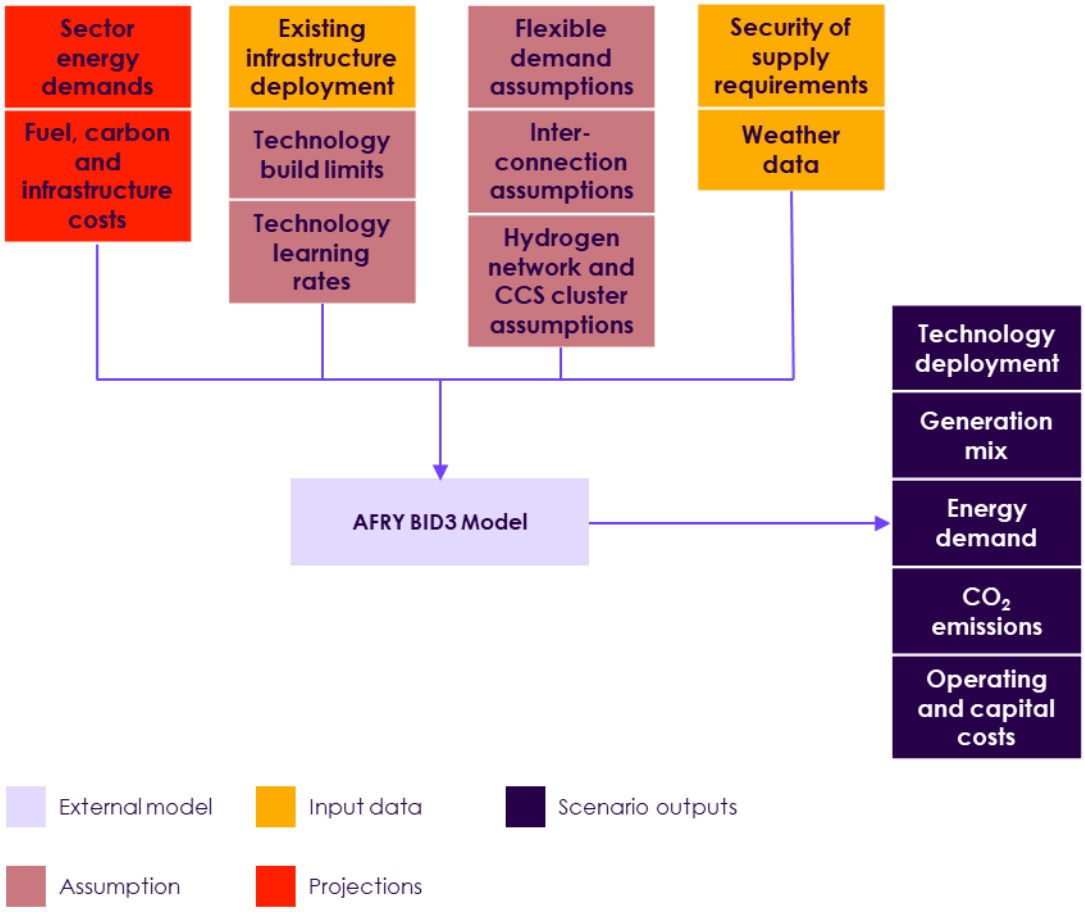
- The government has a security of supply standard for electricity generation (three hours loss of load expectation), which the Seventh Carbon Budget modelling for electricity supply has to meet.
- At a system level, the amount of backup capacity required in a given year to account for the weather-variability of renewables generation should be sized to meet peak residual demand (i.e. demand net renewables generation). Non-weather dependent generation, storage, interconnection, and smart demand flexibility can reduce this requirement. In principle, the assessment of capacity requirement should be made taking into account a large number of 'weather years'.
- We sized the amount of backup capacity required to a 1-in-20 low renewables generation year. This is similar to the current standard used in the design of the gas transmission network.[5] There remains a decision for Government around security of supply and how much allowance to build into the system to account for uncertainties around future weather.
- The resulting system sized to a 1-in-20 year was then run with the weather associated with an average emissions year, to give the emissions, generation, and variable costs for the Balanced Pathway. We also explored the implications of a more stringent standard, running the designed system against the worst-case weather year in the dataset.

Weather assumptions for Seventh Carbon Budget modelling

- The Seventh Carbon Budget electricity and hydrogen modelling was conducted using AFRY's BID3 model. This has an hourly resolution, with weather variables represented on a 15 km^2 grid basis across Europe.
- To inform the weather years used in the AFRY BID3 modelling, we commissioned Newcastle University to identify the return period of 83 historical weather years covering the period 1940-2022, for different iterations of the future electricity system. The research quantified how the magnitude of future energy system uncertainty compared to projected future changes in climate, using state-of-the-art climate data from the UK Met Office. We then selected the historical weather years that were the best proxy for 1-in-20 and the most adverse weather years under the future electricity system, and used these in the BID3 modelling to determine the capacity of low-carbon backup generation required to ensure security of supply.
- The high-level approach to characterising return periods in the Newcastle research was as follows:
  - Calculate hourly residual demand under the design of the electricity system in 2025, 2035, and 2050 across all 83 historical weather years.
  - Aggregate residual demand over each simulated historical year for each iteration of the electricity system. Years with higher residual demand (i.e. lower renewables generation, and therefore higher requirement for non-renewable generation) are more challenging.
  - To calculate return periods, rank all years for each iteration of the electricity system in order of residual demand.
- Using the Newcastle research, for the BID3 modelling we selected 1987 as representative of a 1-in-20 weather year, and 2010 as representative of the most adverse weather year for stress-testing.
- The approach to determining an average emissions weather year was as follows:
  - We commissioned AFRY to dispatch the Balanced Pathway electricity system against six weather years reflecting a range of return periods (selected based on the predicted residual demand insights from Newcastle University). We then used the outputted modelled emissions alongside the annual aggregated residual demand outputs from Newcastle University to estimate what the annual emissions would be across the remaining 77 weather years.
  - The average emissions profile of all 83 weather years was then used to select an appropriate weather year to act as the average emissions weather year. The emissions, generation, and variable costs in the Balanced Pathway are based on this weather year. We selected 2012 as representative of the average emissions weather year.

Source: Bloomfield, H. (2025) *Reasonable worst-case stress test scenarios for the UK energy sector in the context of the changing climate*.

Figure 10.2 Modelling schematic for electricity supply

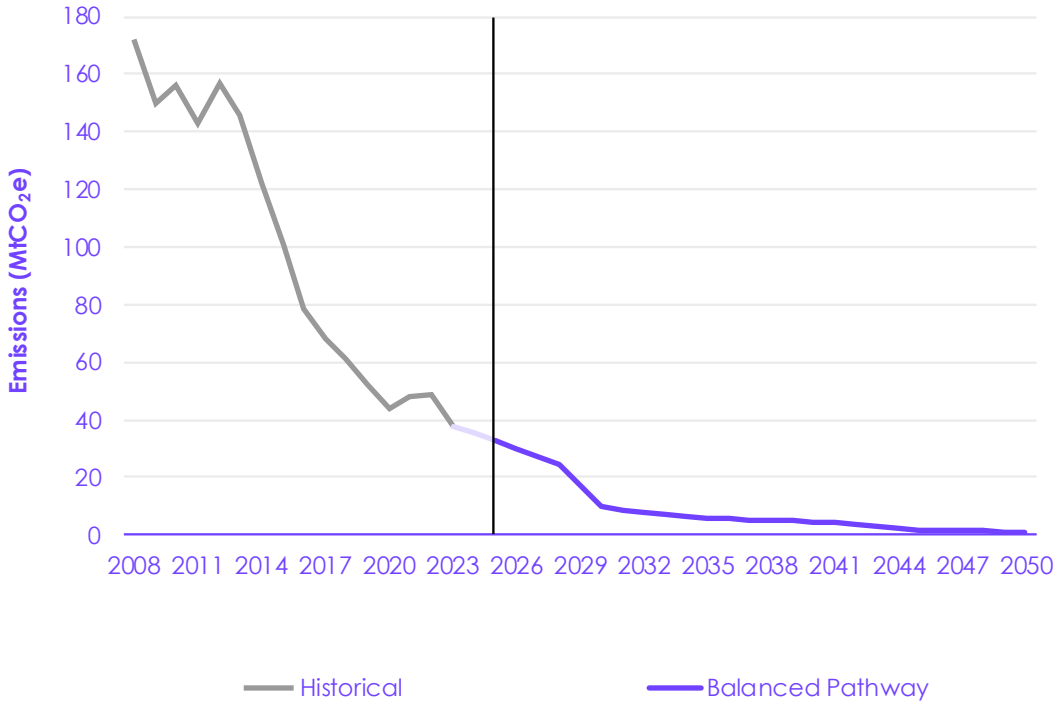


Description: Our electricity supply modelling is based on AFRY's BID3 model, which we have supplemented with additional analysis.
Source: CCC analysis.
Notes: This diagram is illustrative and does not detail all model inputs and outputs.

The Balanced Pathway for electricity supply

In the Balanced Pathway, electricity supply emissions are projected to fall by 88% from 37.8 $MtCO_2e$ in 2023 to 4.6 $MtCO_2e$ by 2040 (the middle of the Seventh Carbon Budget period), and by 97% to 1.0 $MtCO_2e$ by 2050 (Figure 10.3).

Figure 10.3 Emissions in the Balanced Pathway for electricity supply (2008-50)



Description: Electricity supply emissions have fallen significantly since 2008. In the Balanced Pathway, emissions continue to fall, reaching close to zero by 2050.
Source: DESNZ (2024) *Provisional UK greenhouse gas emissions national statistics 2023*; DESNZ (2024) *Final UK greenhouse gas emissions national statistics: 1990 to 2022*; CCC analysis.
Notes: (1) Our pathway is modelled using historical data up to 2023. Emissions reductions in the Balanced Pathway prior to 2025 (shown in a pale shade in this chart) are based largely on existing trends; additional decarbonisation measures only begin to be applied in our modelling after 2025 (indicated in this chart with a vertical line). (2) Emissions associated with energy from waste are accounted for in the waste sector. Emissions associated with combined heat and power are accounted for in the industry and fuel supply sectors. (3) Emissions are based on an average weather year.

The measures in our pathway

Table 10.1 summarises the key elements of the Balanced Pathway for electricity supply that are considered within our modelling, how these lead to emissions reductions, and the key factors that influence their uptake. The methodology used to develop the assumptions and analysis underpinning these is described in the remainder of this section.

Table 10.1
Key elements considered within our modelling for electricity supply

Decarbonisation measure	How does this measure influence emissions in our modelling?	What are the key factors that affect uptake in our modelling?
Variable renewables	Variable renewables ramp up to displace unabated gas generation and provide low-cost, zero-carbon electricity.	The rollout of variable renewables is largely driven by deployment constraints (e.g. existing pipelines, development timelines, and supply chains), as well as resource limits. The availability of network infrastructure and flexibility options (e.g. grid storage) also limits deployment.

Nuclear	Nuclear plants can provide valuable zero-carbon generation at scale.	The deployment of nuclear considers costs, the existing pipeline of projects, construction timescales, and technical readiness of innovative new types of nuclear.
Bioenergy with carbon capture and storage (BECCS)	BECCS from sustainable feedstocks provides both decarbonised electricity generation and a form of engineered greenhouse gas removals.	Sustainable bioenergy resources are finite and must be focused on those applications that maximise its contribution to Net Zero (see Chapter 12). Power BECCS capacity scales up to provide around 10 TWh of generation in our pathway.
Low-carbon dispatchable generation	Low-carbon dispatchable generation sources (e.g. gas with CCS or hydrogen-fired turbines) can provide flexible, controllable electricity and fill demand gaps during periods of low renewables generation.	Deployment of low-carbon dispatchable capacity is dependent on the availability of CCS and/or hydrogen infrastructure. Economic viability is also a key factor given plants will typically operate in flexible load profiles.
Grid storage	Grid storage (e.g. batteries, pumped hydro, and compressed/liquid air) can provide flexibility by capturing energy, typically when it is cheap, and discharging power when it is more valuable, helping to support security of supply over short-to-medium term timescales when renewable output is low.	Grid storage rollout is influenced by the requirement for flexibility services and the technical readiness of new and innovative forms of energy storage (e.g. liquid air storage and flow batteries). Deployment is also influenced by the availability of smart demand flexibility, given the similar system roles it and short-term storage are likely to play.
Smart demand flexibility	Voluntary smart management of demand helps to reduce the need for generation (e.g. from unabated gas), storage, and network build by smoothing demand in peak periods. In doing so, it can both reduce costs and improve security of supply.	Smart demand flexibility is dependent on the deployment of electric vehicles, heat pumps, thermal storage and hot water storage in the pathway. Commercial and industrial demand reduction can also occur in periods of very high prices.
Interconnection	Connection of the electricity grid to neighbouring markets enables imports of electricity when it is cheaper to do so and provides a market for surplus generation.	Interconnector deployment must factor in country-specific conditions, long-development cycles, and costs. We align deployment with our 'Delivering a reliable decarbonised power system' report.
Networks	Network capacity is required to connect generation with demand, providing consumers with access to low-carbon electricity. Greater network capacity avoids wasted supply, and increased costs and/or emissions where additional generation is required closer to the demand source.	In-train development plans and construction timelines largely dictate the near-to-medium term build. In the longer-term, network build out is influenced by the location of generation, storage, and demand sources (including smart flexibility) and the capacity on the existing networks and boundaries.

Notes: (1) This table categorises the main options for reducing electricity supply emissions. There are other sources of generation not presented in this table, such as from unabated biomass, combined heat and power, and energy-from-waste. We consider emissions from combined heat and power and energy-from-waste in the industry and fuel supply sectors and the waste sector, respectively.

Table 7.5.1 of the Seventh Carbon Budget advice report sets out key technology values included in the Balanced Pathway. For variable renewables and battery storage, we use learning rates to inform projected technology costs – see Chapter 1 for further details on learning rates and Box 10.2 for further details on how we apply this approach to electricity supply technologies.

Box 10.2
Learning rate approach to technology costs for key energy supply technologies

For many technologies (including solar, wind, and batteries), consistent and rapid cost reductions have been seen over the past 20 years (see Section 1.7.3). We project how costs could develop in our pathway based on observed learning rates and expectations about how these may continue. Learning rates represent the rate of cost reduction per doubling of deployment.

We apply learning rates to wind (offshore and onshore), solar PV, and battery storage using the following approach:

- Identified a global capacity deployment pathway for each technology, using the 2023 IEA Net Zero Emissions by 2050 scenario.[6]
- Identified an appropriate global capex learning rate for each technology, based on reviewing the literature (see Table 10.2).
  - Learning rates for certain technologies are available in the literature for parameters such as opex and load factors. However, we limited our approach to considering learning rates for capex only to improve consistency in approach across the different technologies. Capex is the main cost element for each of the technologies considered.
  - We identified a range of learning rates for each technology, calculated based on different observed time periods and geographies. We selected learning rate sources based on global projects and over longer time periods. Where multiple sources fit these criteria, we selected the median learning rate so as not to be overly optimistic or conservative.
- Applied learning rates to the Department for Energy Security and Net Zero's (DESNZ) latest published estimates of capex for each technology, based on the global deployment pathways.[7] For offshore wind, we applied a 25% uplift to the capex estimate to reflect recent supply chain inflation.[8;9;10] We assumed that the impact of this inflation is temporary and unwinds by 2030.
- For opex, we did not apply learning rates. Instead, we took opex projections directly from the UK Government's latest published estimates.

Source: International Energy Agency (2023) *World Energy Outlook 2023;* NREL (2022) *A systematic framework for projecting the future cost of offshore wind energy;* IRENA (2023) *Renewable power generation costs in 2022;* IEA (2023) *Global energy and climate model;* Bolinger, M., Wiser, R. and O'Shaughnessy, E. (2022) *Levelised cost-based learning analysis of utility-scale wind and solar in the United States;* Schmidt, O., Melchior, S., Hawkes, A. and Staffell, I. (2019) *Projecting the Future Levelised Cost of Electricity Storage Technologies;* RMI (2023) *X-Change: Batteries;* DESNZ (2023) *Electricity Generation Costs 2023.*

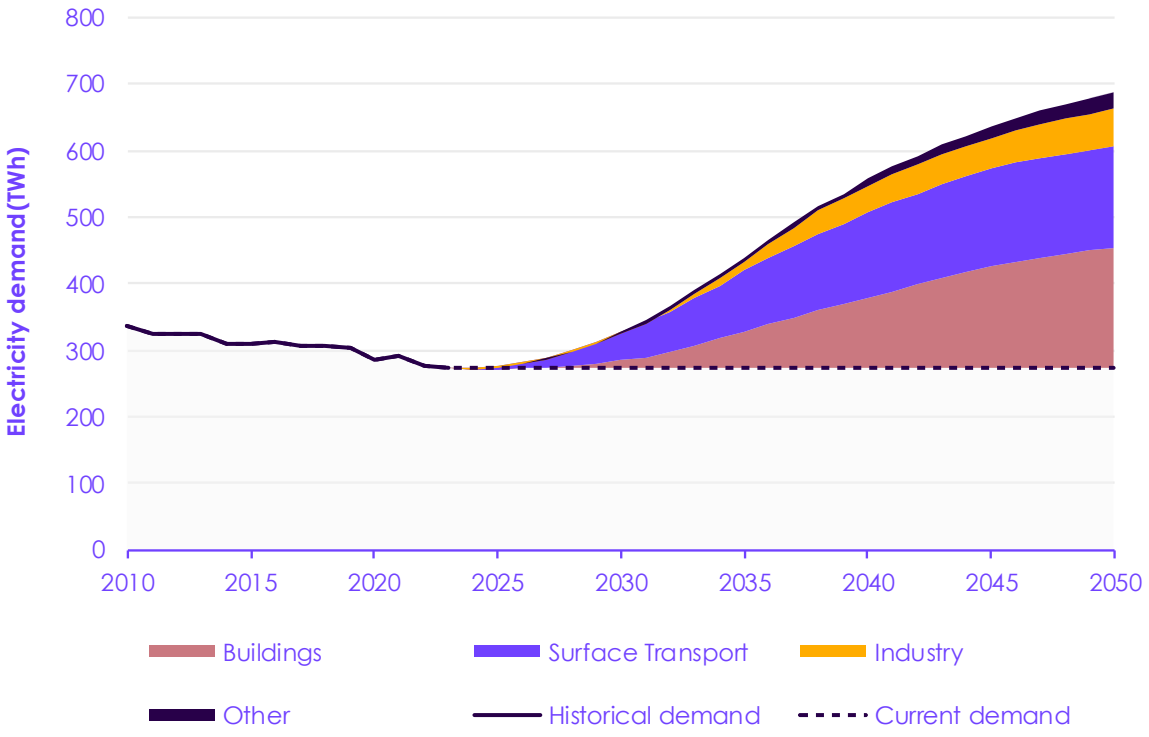
Table 10.2
Learning rate assumptions from literature review

Technology	Lower bound learning rate	Learning rate used in Balanced Pathway	Upper bound learning rate
Offshore wind	9%	12%[11]	15%
Onshore wind	5%	7%[12]	9%
Solar PV	19%	20%[13]	33%
Battery storage	10%	16%[14]	29%

10.2.2 Future demand for electricity

Electrification represents a key abatement option to reduce emissions in other sectors. In the future we expect overall energy demand to fall, but electricity demand to increase significantly as key sectors switch from fossil fuels to electricity (Figure 10.4). Given potential limits to the pace of deployment of low-carbon capacity, it will be important to focus on direct uses of electricity (such as using EVs and heat pumps) as opposed to indirect uses (such as electrolytic hydrogen in cars and boilers) – see Chapter 10 of the Seventh Carbon Budget advice report.

Figure 10.4 Contribution by sectors to increased electricity demand in the Balanced Pathway



Description: Electricity demand increases out to 2050 in the Balanced Pathway. This is driven by the buildings, surface transport, and industry sectors.
Source: DESNZ (2024) *Digest of UK Energy Statistics (DUKES)*; CCC analysis.
Notes: The 'Other' category includes agriculture, aviation, direct air capture, and shipping.

Alongside the changes in demand that we can expect to see from electrification as we decarbonise, demand will also be affected by the changing climate. The UK climate is set to change over the period to 2050, regardless of UK progress towards Net Zero.

Some of the changes in climate and weather patterns will drive changes in energy demand, including an increased demand for cooling in summer and a likely reduction in demand for heating in winter. These changes have been accounted for in our Seventh Carbon Budget analysis (see Chapter 7). Despite these changes, future electricity demand is still likely to be highest in winter, as is the case today.

10.2.3 Variable renewables

In the future, we expect electricity demand to be met primarily through zero-carbon generation at scale, with variable renewables forming the backbone of the system as the cheapest form of new electricity generation capacity.

The deployment of variable renewables in our analysis is guided by resource availability (i.e. wind and sun resource), technology deployment pipelines, and development timelines.

- We consider a number of deployment limits for variable renewables in our analysis.
  - Deployment rates in our analysis reflect the current pipeline of variable renewable projects (Figure 10.5), deployment timelines, and attrition rates. In considering timelines, we evaluate opportunities for current timelines to be shortened (e.g. through

accelerating the planning and consenting process), and the extent and timeliness to which barriers can be removed.

- Offshore wind projects currently take around 10 years to progress from completing pre-development (the point at which they enter the planning and consenting process) to beginning operation. This could be reduced to 5-6 years by accelerating aspects of the development timeline, primarily through speeding-up planning and grid connection timelines.[15] This would need to be underpinned by accelerating the expansion of electricity transmission network capacity to ensure timely grid connections. Given there is minimal scope to accelerate already consented projects and changes to planning and grid connection timelines may take time to filter through to the pipeline, our analysis aligns with the expected deployment pipeline in the near-term before gradually accelerating the deployment of projects in planning and development that are aiming to deliver around the end of this decade.

- Onshore wind projects can take up to 8 years to move through the planning process between the end of pre-development to operation. Addressing barriers on planning and permitting could approximately halve this time.[16] As a result of - now removed - planning barriers for onshore wind, installations in England have been minimal since 2015.[17;18] As such, the existing pipeline is largely concentrated in Scotland.[19] While there may be some previously rejected projects in England that can be quickly revived, the majority of near-term growth is expected to be in Scotland. We assume onshore wind can be deployed at around its historical peak by the end of this decade, with this growth coming primarily in Scotland.

- Solar projects typically have the shortest timelines to deployment and have seen significant global deployment in recent years.[20] Solar deployment in the UK has been relatively limited since 2016 due to planning barriers in England and the removal of incentives. However, deployment is beginning to recover, with a similar total capacity installed across 2022 and 2023 as in the five years prior. We expect significant potential for growth in the UK, especially in areas where solar can be connected to less-constrained parts of the distribution network. Our analysis assumes 70 GW of solar is deployed by 2035, implying a compound annual growth rate of 13% over the next decade.

– We incorporate upper limits on variable renewable deployment based on regional restrictions (e.g. land or seabed limits) taking into account existing leasing rounds (e.g. ScotWind) and the future repowering of sites.

– Furthermore, the commissioned research into weather patterns highlighted how a large spatial diversity in wind farm locations greatly increases the chances of generation being available at times of increased demand. We increased the geographical diversity of offshore wind, in particular, by considering a range of suitable locations alongside existing deployment and leased areas (e.g. The North Sea, English Channel, The Celtic Sea, and The Irish Sea).

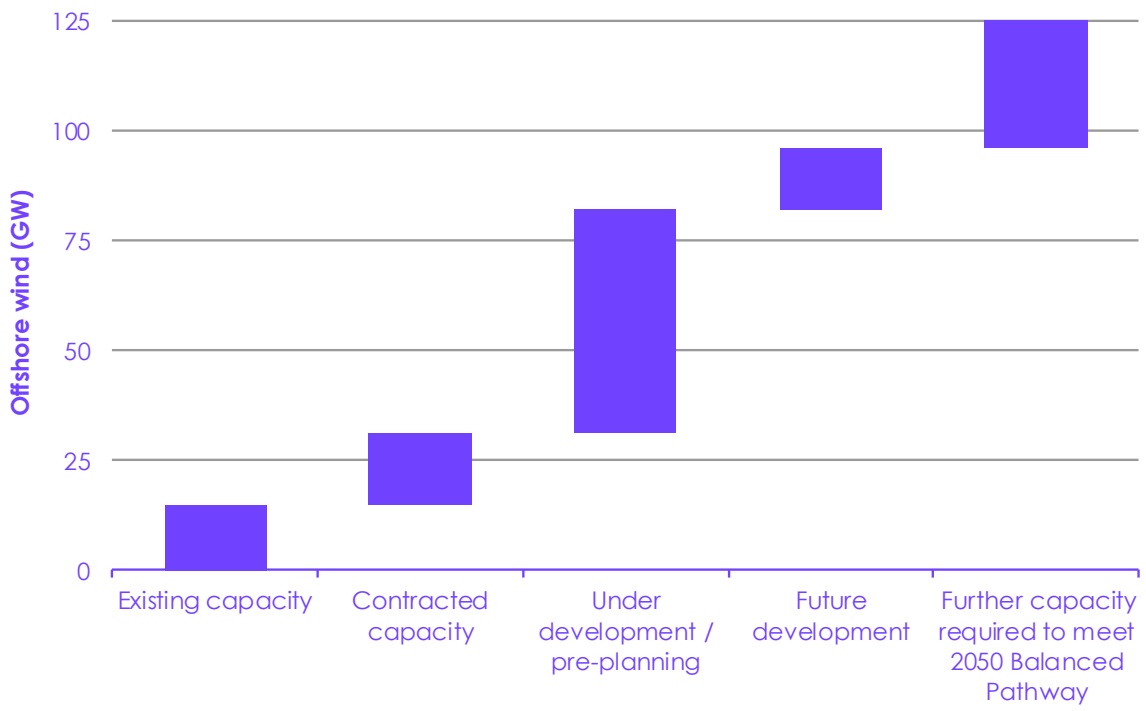
– The modelling commissioned for this report did not define the balance of fixed-bottom and floating offshore wind. Nevertheless, a large portion of the fleet could be delivered through floated projects. Although these are currently more expensive than their fixed-bottom counterparts, if around 30% of the 2050 capacity were to be floating, we estimate that this would increase the annualised system cost per unit of electricity by only 0.1 p/kWh (1%) in 2050. [21;22]

- There are other options for expanding renewable energy in the UK that we did not consider in detail for this analysis.

- Deploying solar on rooftops or other developed places (e.g. car parks) can provide an additional deployment route for expanding solar energy in the UK. While large-scale solar is more cost effective, small-scale solar could provide valuable benefits particularly where local grid capacity is constrained.

- Other renewables (e.g. tidal and geothermal) may be able to play a minor role and provide predictable generation but are currently relatively expensive. For example, tidal stream projects awarded a Contract for Difference in Allocation Round 6 received strike prices of £222/MWh, significantly more than wind and solar projects.[23]

Figure 10.5 Delivering offshore wind to 2050 in the Balanced Pathway



Description: The current development pipeline meets the majority of the 2050 offshore wind capacity in the Balanced Pathway.
Source: The Crown Estate (2024) *UK Offshore Wind Development Pipeline, September 2024*.
Notes: (1) 'Contracted capacity' refers to projects under construction or that have government support on offer. (2) 'Future development' refers to the potential from current leasing rounds and additional capacity requests, including Innovation and Targeted Oil & Gas (INTOG) and Leasing Round 5.

10.2.4 Storable energy

There are a broad range of storable energy options that can complement variable renewables and displace unabated gas generation. The deployment of storable energy in our analysis is based on economic assessments, deployment pipelines, technology readiness and the availability of supporting infrastructure. Storable energy plays an important role in balancing the system, including during periods of extended high residual demand (see Box 10.3).

Nuclear

Nuclear can provide valuable zero-carbon generation at scale, which can make it an important part of the generation mix. There is currently 6 GW of nuclear capacity in the UK. However, an ageing fleet means that nearly 5 GW is expected to retire by the early 2030s.

- Lifetime extensions have recently been confirmed at four of the five operating nuclear sites.[24] These came too late to be included in our analysis.

- Two projects are underway to replace retiring nuclear plants, Hinkley Point C and Sizewell C. Hinkley Point C is under construction, while Sizewell C is awaiting final investment decision.

Our pathway is aligned with the latest timelines for Hinkley Point C with further capacity provided by either large- or small-scale projects.[25] The Balanced Pathway reaches 11 GW of capacity by 2050. We align with publicly available cost data on existing projects and include a learning effect of 20% for cost reduction in further nuclear capacity beyond Hinkley Point C.[26]

Bioenergy with carbon capture and storage (BECCS)

BECCS from sustainable feedstocks provides both decarbonised electricity generation and a form of engineered greenhouse gas removals. BECCS projects have not yet been deployed at scale and UK generation from bioenergy is currently without CCS (unabated).

The deployment of BECCS is dependent on the availability of CCS infrastructure and contingent on sourcing sustainable biomass.

- Our pathway sees large-scale unabated biomass plants no longer run at high load factors on the conclusion of their policy support in 2027, with plants switching over to using CCS (i.e. becoming BECCS) or retiring in the early 2030s. All unabated biomass generation is phased out by 2037.

- BECCS is expected to run inflexibly, similarly to nuclear, due to the value of the removals it provides (see Chapter 18) alongside the electricity and so operates at high-load factors in our analysis. BECCS could be provided by retrofit of existing biomass power plants, or by new-build projects. We consider the availability of sustainable feedstocks supplies in Chapter 12.

Low-carbon dispatchable

Low-carbon dispatchable sources of generation can be planned with a high degree of confidence to provide, flexible, controllable and low-carbon electricity. Options include gas with CCS and hydrogen-fired turbines. Low-carbon dispatchable projects have yet to be deployed at significant commercial scale. However, there are a number of new-build projects in development.

- Several gas CCS projects in development were shortlisted to proceed to the due diligence stage of the Phase-2 Cluster Sequencing process, with the first project securing a final investment decision and aiming for delivery in 2028.[27,28]

- It appears technically feasible that retrofits to existing power plants could be made to convert some unabated gas plants to operate with CCS or convert to hydrogen.[29] However, the suitability of plants will need to be assessed on a case-by-case basis. New and substantially refurbished gas plants could be designed that consider future conversion such that they are built 'low-carbon ready'.[30;31]

Deployment is based on the commercial readiness of projects in development and the availability of CCS and hydrogen infrastructure.

- The deployment of low-carbon dispatchable plants in our analysis is driven by the technology readiness of the technologies as well as the availability of CCS and/or the fuel (i.e. low-carbon hydrogen) and access to fuel storage sites and transmission networks. We assume a subset of projects in development can deliver by 2030 with deployment thereafter considered in relation to historical unabated gas build rates.

- The value of gas CCS is dependent on the ability to efficiently capture CO_2. Our analysis assumes capture rates improve from 90% in 2030 to 95% in 2050 (see Sections 1.7.2 and 5.2.6). If those rates were to be lower, the value of gas CCS as an abatement option would decrease.

- The modelling commissioned for this report favours the use of gas CCS over hydrogen, with gas CCS making up 76% of low-carbon dispatchable capacity in 2050. However, due to uncertainty on their future costs and efficiencies, the precise future balance between gas CCS and hydrogen remains unclear.

  - At least until the 2040s, additional hydrogen demand at the margin might need to be met through blue hydrogen production (see Chapter 12). As such, the choice initially might be between either pre- or post-combustion CCS (i.e. providing low-carbon dispatchable capacity through hydrogen-fired capacity fuelled by blue hydrogen versus gas CCS plants).

  - Gas CCS plants have higher capital costs than hydrogen-fired plants, but are expected to have lower operating costs (given a slight advantage in efficiency in going from fossil gas to electricity compared to use of blue hydrogen in hydrogen-fired plants). At higher load factors, the lower operating costs of gas CCS might be sufficient to justify the higher upfront investment, while hydrogen looks preferable at lower load factors.

  - The modelling commissioned for this report does not consider the blending of hydrogen with fossil gas in power stations or the use of dual-fuel machines that can switch between 100% hydrogen and 100% methane. These could provide a flexible demand for hydrogen, which may help to relax coordination challenges of growing hydrogen supply and demand in tandem. While this flexibility is useful, it is as a short-term measure to manage the hydrogen supply-demand balance rather than as a long-term solution compatible with Net Zero, which will require 100% decarbonised solutions.

Grid storage

Grid storage options can operate on short (minutes to hours) and medium (hours to days and weeks) timescales to provide flexibility when it is most valuable.

- Lithium-ion batteries can provide flexibility by discharging power on timescales from seconds to hours. Currently around 4.5 GW of grid connected battery storage is operational in the UK. Pumped storage is a mature technology, with around 3 GW currently installed in the UK.

- A range of other storage technologies exist at different – and generally earlier - stages of commercialisation. These include compressed air storage, liquid air storage, flow batteries, flywheel and gravity storage, and thermal storage technologies.

- There is a strong pipeline for storage, with 29 GW of new battery storage projects securing Capacity Market contracts in the last five T-1 and T-4 auction rounds.[32] Additionally, storage projects are understood to constitute a significant portion of the connections queue with 268 GW in the queue for GB as of February 2025, far exceeding the storage levels in our Balanced Pathway.[33]

Our analysis considers a range of storage durations reflecting technologies available now and expected to be available on the pathway to 2050. Projects with a Capacity Market agreement are included in the Balanced Pathway, with further deployment considered as part of the BID3 optimisation process.

- The modelling commissioned for this report included a range of batteries with storage durations up to nine hours.

- Storage technologies with durations beyond nine hours become available in 2030. We included storage durations up to 100 hours. Given the range of technology options under development, we group grid storage technology types together.

- The deployment of grid storage capacity, particularly short-duration batteries, is influenced by the availability of smart demand flexibility, given the similar system roles they play.

Box 10.3
Multi-year wind droughts and the need for energy storage

We cannot rule out multi-year periods of low renewable output (e.g. wind droughts), so we need to plan for them. Our pathway is secure and robust to extended periods of wind drought through the use of storable fuels and diversity in supply:

- The capacity mix in the Balanced Pathway is secure to muti-year periods of low wind, since each year is modelled to be able to meet electricity demand in extended low wind periods independently. It is therefore robust to consecutive low wind years.
- Our analysis considers a wide portfolio of technologies, complementing variable renewables with a range of storable fuels, including nuclear, natural gas, hydrogen, and bioenergy, as well as grid storage, demand flexibility, and interconnection.
  - Storable fuels, used both flexibly (e.g. as gas CCS or hydrogen) and inflexibly (e.g. as nuclear), play an important role in managing extended periods of high residual demand – including multi-year challenges.
  - Across our Balanced Pathway and 'Low-carbon dispatchable balance' sensitivity (see Section 10.4), storable fuels provide 163-178 TWh of generation under the 1-in-20 weather year and 145-155 TWh under the average weather year in 2050, compared to 151-224 TWh across NESO's FES24 scenarios for 2050 and 76-85 TWh in the Royal Society's recent report (Table 10.3).

Our Balanced Pathway includes a diverse supply, incorporating a wide portfolio of technologies and a geographically varied distribution of renewable sources (both UK-wide and in interconnected markets). This diversity enhances system resilience by mitigating the proportional impact of any single failure and ensures renewable energy shortfalls are less likely due to the widespread distribution of sources of renewable electricity supply.

Table 10.3
2050 comparison of our Balanced Pathway to other published generation mixes

(All values shown are for 2050)	Electricity demand (TWh)	Renewable generation (TWh)	Generation from storable fuels (TWh)				
			Nuclear	Low-carbon dispatchable		Other	Total
				Gas CCS	Hydrogen		
Balanced Pathway	692	668-721	79-80	14-64	5-32	28	145-178
FES24	630-660	534-593	77-151	22-42	6-25	27-34	151-224
Royal Society	570	740-800	0	0	76-85	0	76-85

Source: NESO (2024) *Future Energy Scenarios*; Royal Society (2023) *Large-scale electricity storage*; CCC and AFRY analysis.
Notes: (1) Generation figures are before losses through transmission, distribution, and storage. (2) The balance of gas CCS and hydrogen-fired turbines is uncertain given uncertainty on the relative future costs and efficiencies for these technologies. Given they can play similar system roles, we presented these together as one 'Low-carbon dispatchable' category in our Seventh Carbon Budget advice report. (3) 'Other' includes generation from energy-from-waste, bioenergy, and Combined Heat and Power. (4) Contributions from interconnection, grid storage, and demand flexibility are not presented. These are all present in CB7 and FES24, while some grid storage is present in the Royal Society report. (5) CB7 values reflect the generation range under the average and 1-in-20 adverse weather year for our Balanced Pathway and 'Low-carbon dispatchable balance' sensitivity. (6) Royal Society values reflect their upper and lower values. (7) FES24 values reflect the range across their three decarbonisation scenarios: Holistic Transition, Electric Engagement, and Hydrogen Evolution. (8) Royal Society hydrogen generation represents the delivery capability of the stores.

10.2.5 Smart demand flexibility

Voluntary provision of smart demand flexibility can help reduce the need for use of generation or storage (particularly at peak demand periods) as well as minimising the amount of network capacity needed, without affecting consumers' quality of service provision. In doing so, smart demand flexibility can both reduce costs and improve system reliability.

Our analysis assumes that pre-heating and storage in buildings, and smart charging in transport can provide flexibility to the power system by shifting electricity demand away from peak hours.

- Demand inputs included assumptions on flexibility provided by heat and transport. 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 by up to 8 hours (see Section 7.2.2). In transport, we assume that 80% of residential charging demand can be shifted up to eight hours.

- Commercial and industrial demand can also be reduced (i.e. 'turn-down') in response to price signals.

- There are other smart demand flexibility options not modelled in our Balanced Pathway, including vehicle-to-grid (where energy can be supplied to the grid from the battery of an electric vehicle, thereby effectively increasing grid storage capacity) and further industrial demand flexibility (see Box 7.3.3 of the Seventh Carbon Budget advice report). These could further increase the amount of flexibility available, although may substitute for other storage deployment modelled in the scenario.

10.2.6 Interconnection

Interconnections between the UK and neighbouring countries have a total current capacity of around 10 GW.[34] These allow the sale of surplus energy to neighbouring markets and provide access to resources in other countries. We maintain the capacity of interconnectors from our 2023 'Delivering a reliable decarbonised power system' report, reaching 28 GW in 2050. European generation also decarbonises in our modelling.

10.2.7 Networks

As electricity generation is increasingly decarbonised and demand grows, network requirements will also rise.

Transmission and distribution networks both undergo significant strengthening in our analysis.

- The BID3 modelling undertaken for this report considered the transmission-level network needs associated with the scenarios.

  - Planning and identification of transmission investment needs involves splitting the UK transmission system into 'zones', with the boundaries* between these zones reflective of where the main bottlenecks lie. These change over time as the network is reinforced and network users' needs change.

  - We aligned transmission network build with the NESO's Beyond 2030 report with model optimisation allowed beyond.[35] All the transmission network boundaries examined

* While capacity can be defined as the physical MW capacity of the asset, boundary capability is defined as the maximum MW flow that can be transferred across a boundary while maintaining compliance with the National Electricity Transmission System Security and Quality of Supply Standards. Limiting factors on transmission capacity include thermal circuit ratings, voltage constraints and dynamic stability.

would be expected to require some level of reinforcement, with an average doubling by 2035 and a tripling by 2050.

- We worked with DESNZ to adapt published modelling of distribution network costs from the Electricity Networks Strategic Framework (ENSF) to estimate the costs of reinforcing and maintaining distribution networks out to 2050. We scaled these based on the difference in peak demand in the BID3 modelling compared to the ENSF. Further detail on the DESNZ modelling approach and methodology can be found in Appendix 1 of the ENSF publication.[36]

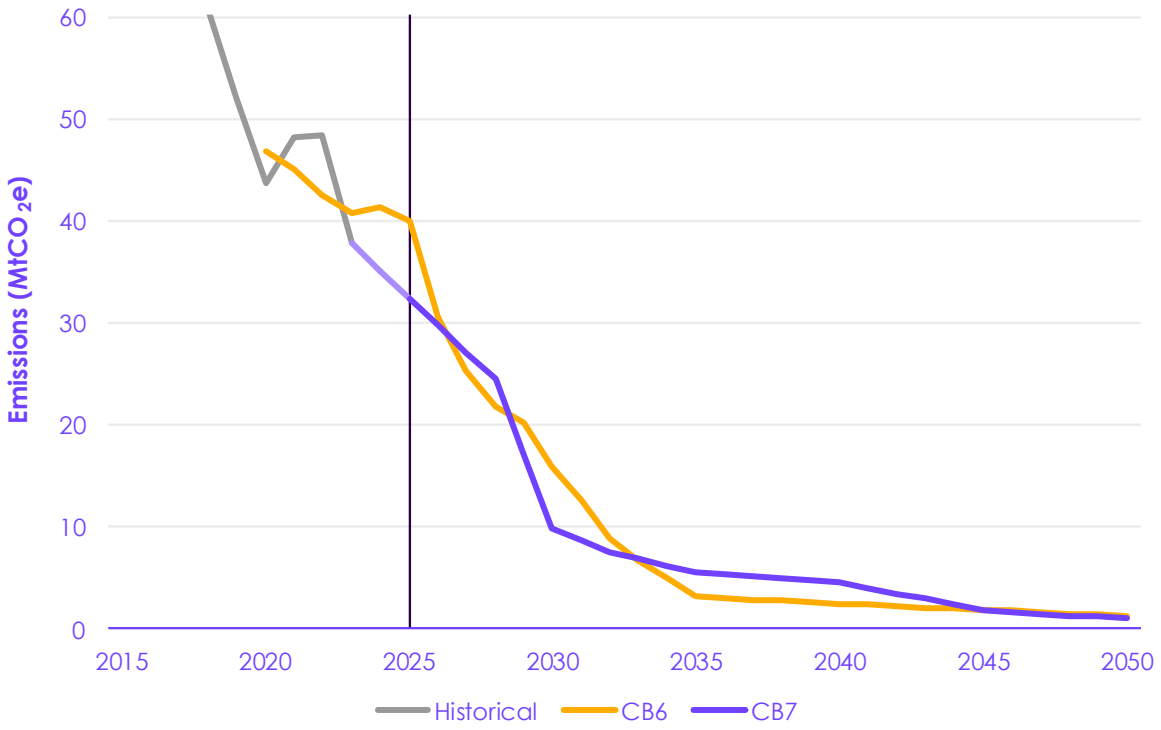
10.3 Changes since our Sixth Carbon Budget advice

10.3.1 Comparison with our Sixth Carbon Budget pathway

Electricity demand in 2023 was lower than projected in the Balanced Net Zero Pathway in our Sixth Carbon Budget (CB6) advice, resulting in lower emissions than projected.* As a result, our pathway starts at a slightly lower emissions level than our Sixth Carbon Budget pathway, although the two are similar in the following years. Both pieces of advice see a rapid fall in emissions this decade, with action thereafter focused on meeting rising demand with low-carbon supply. In both pathways, low-cost variable renewables form the backbone of the future system, with these supported by storable energy, smart demand flexibility, and interconnection (Figure 10.6).

* All comparisons in this section compare the Balanced Pathway in this advice with the Balanced Net Zero Pathway in our Sixth Carbon Budget. Our Sixth Carbon Budget advice also included four other exploratory pathways, which are not discussed here. Data for those pathways can be found in our Sixth Carbon Budget advice.

Figure 10.6 The Balanced Pathway for electricity supply compared to our Sixth Carbon Budget advice



Description: The Sixth (CB6) and Seventh Carbon Budget (CB7) Balanced Pathways show similar rates of emissions reductions for the electricity supply sector.
Source: DESNZ (2024) *Provisional UK greenhouse gas emissions national statistics 2023*; DESNZ (2024) *Final UK greenhouse gas emissions national statistics: 1990 to 2022*; CCC (2020) The *Sixth Carbon Budget*; CCC analysis.
Notes: The Sixth Carbon Budget advice pathway is shown as published in our 2020 advice. These have not been adjusted to account for changes in emissions accounting since that publication.

10.3.2 Emissions changes since our Sixth Carbon Budget advice

Electricity supply emissions in 2023 were 7% lower than projected in the Sixth Carbon Budget analysis. This is largely due to lower-than-expected electricity demand, which was 9% lower in 2023 than in the Sixth Carbon Budget pathway.

- Emissions in 2020 were lower than expected in the Sixth Carbon Budget analysis, largely due to lower demand due to the COVID-19 pandemic. Demand was also lower than expected in 2022 and 2023, likely reflecting the impact of increased electricity prices following Russia's invasion of Ukraine, which incentivised consumers to reduce their consumption.

- Despite lower-than-expected demand, emissions in 2022 were higher than projected in our Sixth Carbon Budget advice. This was largely due to increased unabated gas generation to meet higher demand for electricity exports. Exports returned to more typical levels in 2023, leading to lower emissions than projected in our Sixth Carbon Budget advice when combined with lower demand.

- While actual demand is lower, the percentage share of fossil fuel generation is consistent with our Sixth Carbon Budget analysis. We aligned with the UK Government's 2024 commitment to phase out coal generation, which was successfully achieved with the closure of Ratcliffe-on-Soar in September 2024, while the actual and projected unabated gas share of generation in 2023 were both at around one-third.

10.3.3 Key pathway differences compared to our Sixth Carbon Budget advice

There are several key areas in which the deployment rates, measures included, or underlying assumptions in our updated Balanced Pathway have been revised since publication of our Sixth Carbon Budget advice in 2020. These include:

- **Demand.** Our Seventh Carbon Budget has greater electricity demand, with the ramp-up delayed slightly and resulting in a steeper increase during the 2030s.
  - Electricity demand in 2050 is 13% higher than in our Sixth Carbon Budget Balanced Pathway, reflecting an increased role for electrification across the economy and updated end-use efficiency assumptions.
  - Achieved deployment rates for low-carbon technology (particularly heat pumps) have been lower than in our Sixth Carbon Budget advice. These delays are reflected and the increase in electricity demand occurs a few years later in our Seventh Carbon Budget advice. This results in a steeper increase in demand over the 2030s, with demand increasing by 23 TWh/year as opposed to 18 TWh/year across the 2030s in the Sixth Carbon Budget.
- **Capacity.** Deviations in the capacity mix represent delays to the rollout of large infrastructure and a continued establishment of variable renewables as a low-cost and deliverable generation source.
  - Progress in CCS and hydrogen infrastructure has been slower than modelled in our Sixth Carbon Budget advice. As a result, the availability of low-carbon dispatchable technology has been pushed back towards the end of the decade in our Seventh Carbon Budget advice, several years later than in our previous advice where CCS infrastructure is available from 2026. Similarly, continued delays to the development of nuclear projects sees lower nuclear capacity across the 2020s and 2030s than in our Sixth Carbon Budget advice (the 2050 capacity for nuclear is comparable, 11 GW vs 10 GW). We explore a sensitivity with further delays to these technologies in Section 10.4.
  - Our Seventh Carbon Budget advice increases variable renewable deployment from our previous advice, recognising, their ability to be rapidly scaled at relatively low cost, the increased levels of economy-wide electricity demand, and the relative progress of other technologies. We have increased offshore wind deployment rates from an average of 3 GW per year between 2030 and 2050 in our previous analysis to 5.7 GW per year out to 2030 and then an average of 4.0 GW per year out to 2050. Onshore wind and solar also see slight increases in near-term growth.
- **Baseline assumptions.** In our Sixth Carbon Budget advice, we assumed that low-carbon technologies already in the baseline would be replaced with high-carbon alternatives when they reach the end of their lifetimes. Since low-carbon measures are becoming more mainstreamed, we now assume that the stock of low-carbon technologies that exist today (primarily renewable energy and EVs) generally remains constant in our baseline and are replaced like-for-like over time. This means that our Balanced Pathway does not incur costs or cost savings for deploying renewables that have already been sunk, which is one factor behind the differences in our assessment of the cost of the transition.

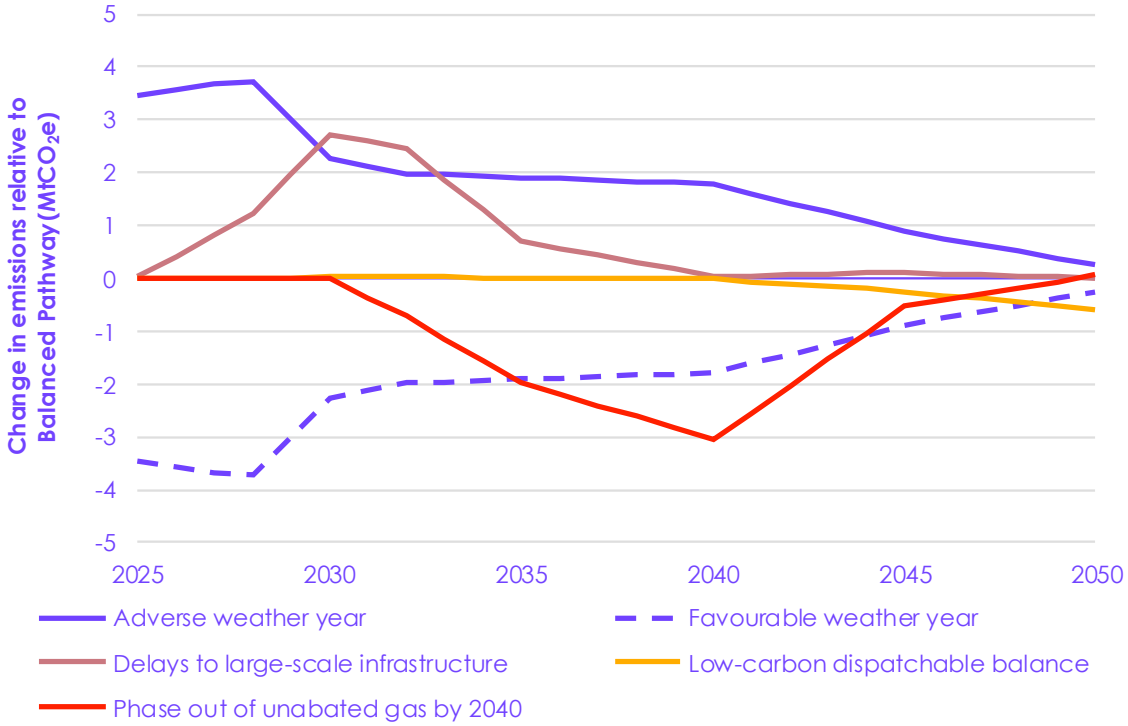
10.4 Uncertainties and sensitivity analysis

There are inevitably uncertainties around how the key drivers of the Balanced Pathway will develop over the next 25 years. To account for this, we have undertaken a range of sensitivity tests exploring the impact on our Balanced Pathway of weather and delivery uncertainties. These represent the main factors influencing emissions in the pathway or are assessed to have a high level of uncertainty associated with them. The approach to - and results of - each of these sensitivity tests are described in this section and shown in Table 10.4 and Figure 10.7. See Chapter 5 for our general approach to uncertainty and contingency analysis, including descriptions of the methodology behind sensitivity tests that apply across multiple sectors.

Table 10.4
Key sensitivity tests for electricity supply

Sensitivity test	Description	Impact on sector emissions in 2040 ($MtCO_2e$)		
		$MtCO_2e$	% of sector emissions	% of total emissions
Weather	One-standard deviation on the adversity of weather variability	±1.8	±39%	±2%
Delivery	Delays to large-scale infrastructure	+0.0 (+2.7 in 2030)	+0% (+28% in 2030)	+0% (+1% in 2030)
	Low-carbon dispatchable balance	+0.0	+0%	+0%
	Phase out of unabated gas by 2040	-3.1	-66%	-3%

Figure 10.7 Emissions impact of key sensitivity tests for electricity supply



Description: Adverse weather and delays to large-scale infrastructure would results in an increase in emissions, while favourable weather and the phase out of unabated gas by 2040 would result in a decrease in emissions.
Source: CCC and AFRY analysis.

10.4.1 Weather

The pathway for electricity supply emissions will be influenced by the weather in any given year. Renewable generation will vary year-to-year depending on the number of windy and sunny days. Years with lower-than-average renewable generation are likely to require greater use of dispatchable generation at the margin, including the occasional use of unabated gas where available and resulting in in higher-than-average emissions. The inverse is also true with higher-than-average renewable generation reducing the need for dispatchable generation and resulting in lower-than-average emissions.

- Emissions and costs in the Balanced Pathway are based on the weather corresponding to an average weather year (see Box 10.1).

- We have quantified the influence of different weather conditions on emissions in 2040 (the middle of the Seventh Carbon Budget period) through modelling a range of weather years and using insights from the commissioned research on weather patterns.

10.4.2 Delivery

Achieving a decarbonised electricity system is a critical pillar of delivering Net Zero. Delivering this requires high levels of deployment across a range of technologies, including some that have not yet been deployed commercially in the UK. Notably, key uncertainties exist around the timing of large-scale infrastructure projects, such as nuclear and CCS and the relative balance of low-carbon dispatchable technologies. There may also be policy questions on the approach to managing the unabated gas fleet and any timelines for phasing its use out. Each of these could have a large influence on the resulting pathway.

Delays to large-scale infrastructure

Nuclear and CCS both play important roles in our pathway with the former providing valuable, zero-carbon electricity and the latter essential to enable the deployment of low-carbon dispatchable generation (whether in post-combustion power plants or blue hydrogen production). In developing assumptions on the rollout of nuclear and CCS, we consider a range of factors, including construction timelines, historical trends, and technology readiness. However, both represent complex infrastructure projects, and as such, can face delivery challenges.[*] Delays beyond what we have assumed in our Balanced Pathway could have an impact on emissions, particularly the achievement of the 2030 Nationally Determined Contribution (NDC).

- In the Balanced Pathway, 3 GW of nuclear and 3 GW of low-carbon dispatchable capacity are operational in 2030. By 2040, 8 GW of nuclear and 15 GW of dispatchable generation projects are operational.

- As a sensitivity, we tested the impact of delaying the deployment of all new nuclear and CCS projects by 3 years, and therefore beyond 2030. In this sensitivity, 1 GW of nuclear and 0 GW of low-carbon dispatchable capacity are operational in 2030. By 2040, 8 GW of nuclear and 14 GW of low-carbon dispatchable capacity are operational.

Low-carbon dispatchable balance

Generation from low-carbon dispatchable technologies (e.g. gas with CCS or hydrogen-fired turbines) is a key source of flexibility in the Balanced Pathway, helping to provide security of supply, in particular during periods of low production from variable weather-dependent renewables. There is uncertainty on the future costs and efficiencies for gas CCS and hydrogen-fired turbines, and

[*] For example, Hinkley Point C nuclear power station was originally due to be delivered in 2025 but is now not expected to start generating until 2030.

given they can play similar system roles, we presented these together in our Seventh Carbon Budget advice report. Nevertheless, their relative deployment will strongly influence the required CO_2 and hydrogen infrastructure (e.g. transport, storage and hydrogen production, as well as the location of these) and must be considered in strategic decisions on infrastructure build.

- In the Balanced Pathway, 15 GW of low-carbon dispatchable capacity are deployed by 2040, and 38 GW by 2050. The modelling commissioned for this report typically favours the use of gas CCS over hydrogen, with gas CCS making up 76% of low-carbon dispatchable capacity in 2050.

- As a sensitivity, we have tested the impacts of deploying a higher balance of hydrogen-fired turbines (72% of capacity in 2050) in providing low-carbon dispatchable capacity. While this shows up as an emissions saving in the electricity supply sector, there is minimal impact across the whole economy as the emissions move from gas CCS to blue hydrogen production, which is accounted for in the fuel supply sector.

- We discuss the implications for low-carbon hydrogen supply further in Chapter 12.

Phase out of unabated gas by 2040

Unabated gas generation is the main source of emissions in electricity supply. The Balanced Pathway rapidly phases out the use of unabated gas, with its occasional use acting to balance the system and ensure security of supply (4% of generation in a 1-in-20 adverse year in 2040 and less than 1% in a favourable year, compared to less than 2% in an average year). It is for government to decide how much headroom capacity to build into the system to account for uncertainty on future weather patterns.

The Balanced Pathway retains a reserve of unabated gas capacity into at least the 2040s, which can be drawn on if needed, with its use phased out by 2050. As a sensitivity, we have explored a scenario which phases out unabated gas generation by 2040.

- Compared to our Balanced Pathway, this requires an additional 12 GW of low-carbon dispatchable capacity and 5 GW / 113 GWh of grid storage to be deployed in the 2030s.

- It will also require additional accompanying infrastructure (e.g. CO_2 transport and storage, hydrogen production and storage).

- This may be possible but is likely to increase delivery risks.

10.5 Contingencies in electricity supply

By the Seventh Carbon Budget, electricity supply is expected to be very largely decarbonised (see Figure 10.3). However, additional decarbonisation actions in electricity supply could provide contingency for other nearer-term target periods, primarily the 2030 NDC (Table 10.5). See Chapter 5 for our general approach to contingency analysis.

Table 10.5
Contingency option in electricity supply

Contingency	Description	Potential average annual emissions savings ($MtCO_2e$, % of sector emissions)			
		2030	CB6	CB7	2050
Accelerated deployment of low-carbon power	Accelerated deployment of low-carbon capacity	2.2 22%	0.7 12%	0.8 18%	

Source: CCC and AFRY analysis.
Notes: We have blanked out cells where the contingency measure in question is estimated to deliver less than 0.3 $MtCO_2e$ in potential emissions savings, to focus on high-yield options.

10.5.1 Accelerated deployment of low-carbon power

Electricity supply decarbonisation is in the short-term more limited by feasible rollout rates and available technology rather than cost effectiveness. Therefore, to go further on decarbonisation, the deployment of key technology needs to be increased and/or achieved earlier. Due to their relatively short lead times and scalability, the primary route to accelerating the decarbonisation of the electricity supply sector is likely to come from variable renewables. This will require the removal of more extensive barriers than are assumed to be overcome in our Balanced Pathway. We have examined how this could be delivered:

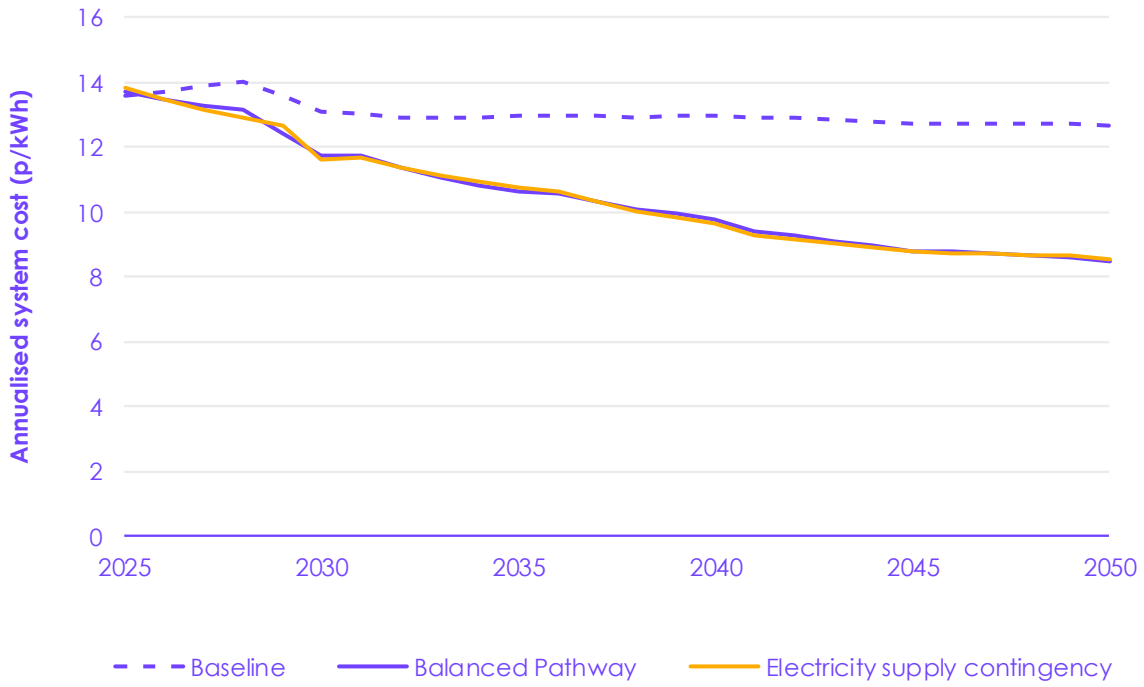
- We updated offshore wind deployment to NESO's highest view from their 2024 Future Energy Scenarios, reflecting a further 7 GW of capacity in 2030 beyond our Balanced Pathway of 46 GW.[37] This will require a greater dependence on the procurement of capacity in the next two-to-three Allocation Rounds (AR) - AR7, AR8, and depending on the speed at which projects deploy, AR9. Development timelines will also need to be reduced to a minimum where possible.

- Onshore renewables, particularly solar, can be constructed quickly and, in some cases, be located in places where the grid already has capacity to accommodate it, for example by connecting to the distribution network. For onshore wind, most of the near-term growth is expected to be in Scotland with the existing pipeline largely concentrated there. We included a further 1 and 12 GW of onshore wind and solar, respectively, by 2030, on top of the 26 GW and 38 GW deployed in the Balanced Pathway.

Going further on the decarbonisation of electricity supply could deliver a total of 2.2 $MtCO_2e$ of additional emissions reduction in 2030.* Our analysis suggests that this further abatement – and the additional co-benefits it provides (e.g. energy security) – can be achieved with a negligible impact on the annualised system cost per unit of electricity (Figure 10.8). However, a number of delivery risks would need to be carefully managed.

* Our contingency actions to accelerate the roll-out of low-carbon technology in the electricity supply sector would result in unabated gas providing 5% of generation under an average weather year in 2030.

Figure 10.8 Annualised system cost per unit of electricity in the Balanced Pathway, the baseline, and for contingency actions



Description: The Balanced Pathway and the electricity supply contingency result in a lower annualised system cost than in the baseline, which remains broadly flat to 2050.
Source: CCC and AFRY analysis.
Notes: (1) The annualised system cost per unit of electricity is calculated as the sum of total annualised capital expenditure and operating costs (including projected UK ETS carbon costs) of electricity generation, storage, and network capacity on the system in a given year per unit of electricity supplied. (2) The annualised system cost per unit of electricity does not include transfers between groups in society (for example, legacy policy costs and taxes) and, as such, is different to the retail price of electricity.

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Chapter 11: Aviation

Introduction

Aviation analysis models projected baseline and Balanced Pathway aviation demand, and abatement and costs from efficiency improvements, new aircraft and sustainable aviation fuel (SAF).

- We assume the polluter pays principle by adopting the UK Government's carbon values as a proxy for currently high and uncertain technology costs. We use the high, rather than central, values to allow for non-CO_2 effects.
- The carbon values are passed through to ticket prices, which in turn impacts demand for flying.
- We then apply abatement from efficiency improvements, SAF, and low and zero emission aircraft, and assume that by 2050 all residual aviation emissions are offset by engineered removals.

To conduct this analysis, we use in-house and external models, consider the latest evidence across all abatement and offsetting options for aviation, engage widely across the sector, and consider evidence from the citizens' panel and stakeholder roundtables.

11.1 Baseline emissions in aviation

11.1.1 The baseline for aviation

Historic aviation emissions to 2023 use National Atmospheric Emissions Inventory data. From 2024, emissions are forecasted using the Department for Transport's (DfT) aviation modelling suite.[1]

Our baseline for aviation uses the following assumptions:

- **Demand**. Aviation demand increases in the baseline in response to multiple model inputs, such as UK GDP.[2] This leads to terminal passengers increasing by 64%, from 315 million to 518 million, between 2025 and 2050; and passenger-km increasing by 80%, from 799 billion passenger-km to 1,436 billion passenger-km (departing and arriving flights).* Other baseline demand assumptions include:
  - All planned airport capacity expansions as of 2024 proceed.
  - Carbon pricing assumptions affect ticket prices and therefore demand in the DfT model. For the CCC's baseline, the Department for Energy Security and Net Zero (DESNZ) market carbon price forecast is used for ETS carbon prices and a DfT CORSIA price forecast is used for flights covered by CORSIA.[3;4]

* A terminal passenger refers to a passenger joining or leaving an aircraft at the reporting airport. A passenger travelling between two reporting airports is counted twice, once at each airport. In CCC modelling, terminal passengers are halved to reflect greenhouse gas inventory accounting rules, where fuel sold in the UK is used to calculate UK aviation emissions.

- We assume there is no shift away from flying to alternatives such as rail transport or video conferencing in the baseline.

- Aviation demand projections are uncertain. See Section 5 for more information on aviation emissions sensitivities.

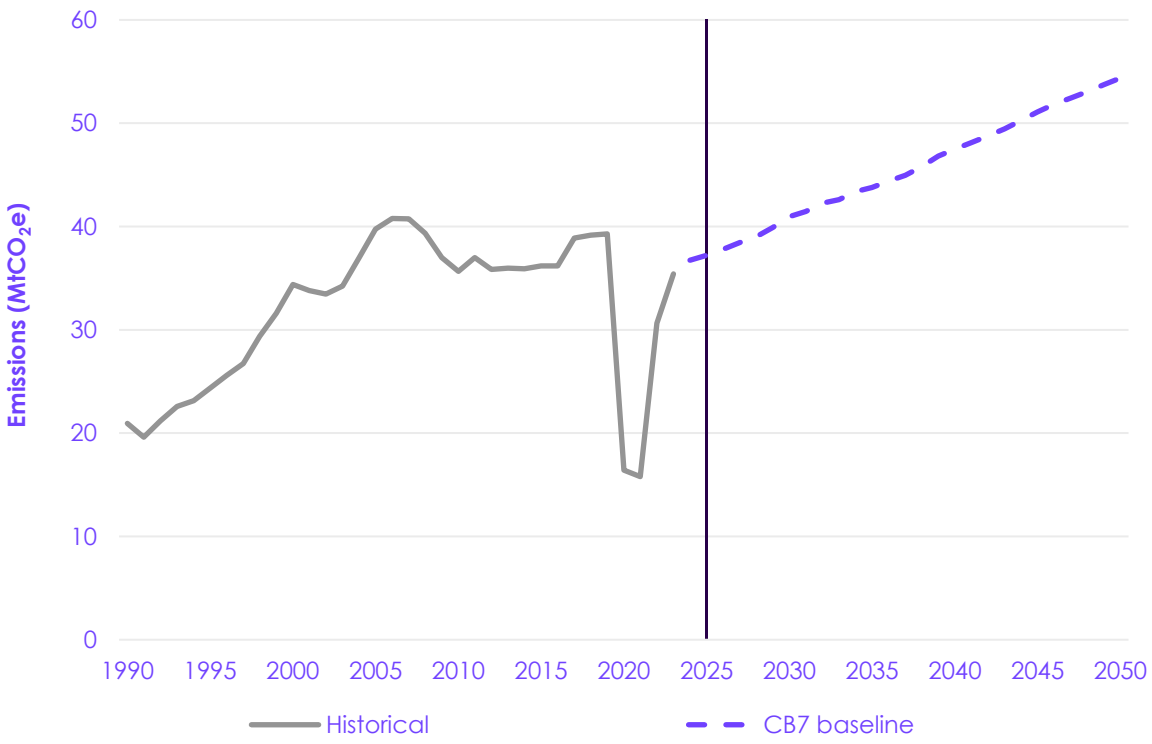
- Between 2025 and 2050, fuel, operational, and air transport movement efficiency improvements increase seat-km per tonne of fuel by 0.5% per year.

- No hybrid- and zero-emission aircraft are deployed.

- SAF uptake and abatement is modelled in-house and uses CCC's fuel supply methodology and assumptions (see Chapter 12). In the baseline, 2023 historic SAF data is assumed and projected forward at a constant level to 2050 at 1 TWh/year of hydroprocessed esters and fatty acids (HEFA) fuel.[5]

This represents a scenario in which there is no further decarbonisation action by either the Government or the market in the aviation sector. In this baseline scenario, emissions would rise by 34% from 2023 levels by 2040 (the middle of the Seventh Carbon Budget period) and 54% by 2050 (Figure 11.1). See Chapter 1 for our general approach to baselines.

Figure 11.1 Baseline emissions in aviation



Description: Aviation sector baseline emissions increase between 2025 and 2050.
Source: DESNZ (2024) Provisional UK greenhouse gas emissions national statistics 2023; CCC analysis; DfT aviation modelling suite.

11.2 Pathway assumptions and modelling for aviation

11.2.1 Modelling the Balanced Pathway for aviation

Overall modelling approach

Our aviation analysis uses the latest data on historic trends in aviation demand, academic and grey literature, stakeholder engagement, expert workshops, and external and in-house models. See Chapter 1 for our general approach to pathway analysis.

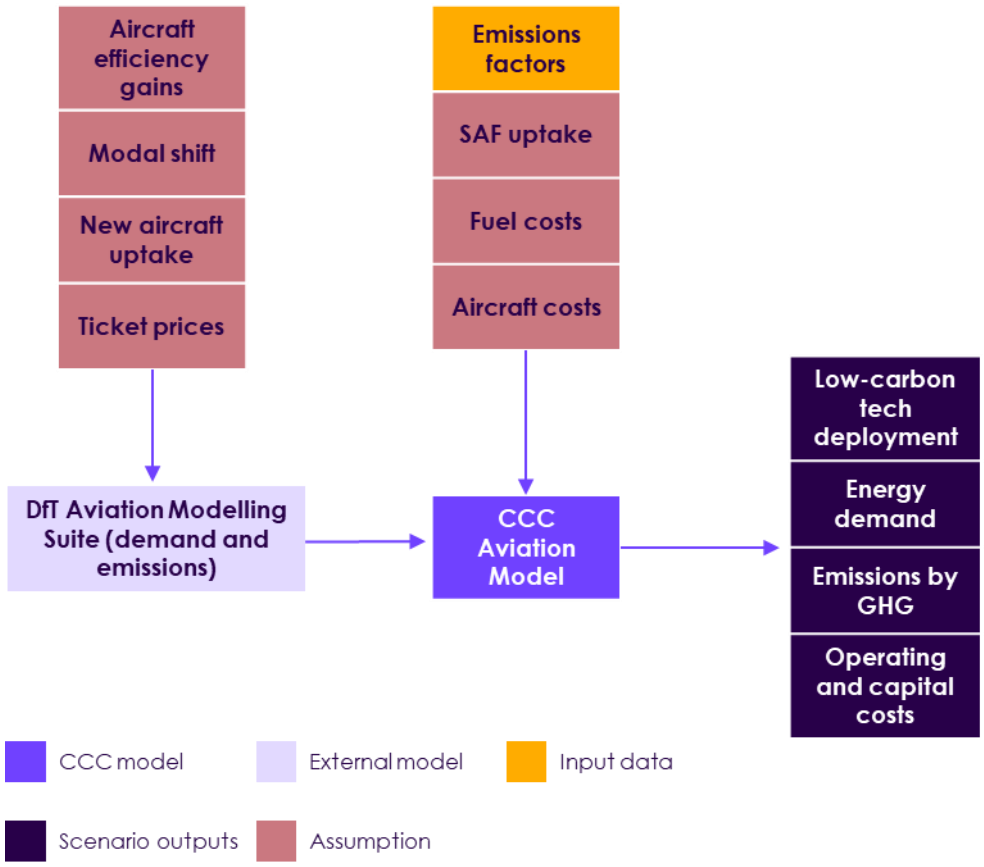
The key elements are:

- **DfT aviation modelling suite.** This model produces outputs for the CCC's aviation model. It includes aviation demand and abatement from managing the increase in projected demand, efficiency improvements, and new aircraft. Figure 11.2 details the input assumptions and model outputs.
  - **Demand.** We input the high carbon value into the cost to fly in the DfT model to proxy technology costs and non-CO_2 effects. This passes on decarbonisation costs through to ticket prices, which then impacts forecasted demand.
  - **Efficiency improvements.** For efficiency improvements and hybrid electric aircraft, the DfT model can choose between a 'pessimistic', 'likely', and 'optimistic' assumption, which respectively increase seat-km per tonne of fuel by an average of 0.5%, 1.3%, and 2% between 2025 and 2050.[6] Our modelling uses the 'likely' efficiency improvement scenario.
  - **Hybrid electric aircraft.** Hybrid electric aircraft are represented as an efficiency improvement in DfT's aviation model. Within the 'likely' efficiency improvement scenario, hybrid electric aircraft enter the fleet in 2040.
  - **Zero-emission aircraft.** Battery electric aircraft and hydrogen aircraft input assumptions use entry into service dates. Battery electric aircraft are assumed to enter the fleet in 2040, and hydrogen aircraft are excluded from the pathway. It was not possible to disaggregate battery electric aircraft emissions from total efficiency improvement abatement. However, the emissions impact will be small given that battery electric aircraft will likely replace small, regional aircraft models.
- **SAF**. Evidence on current and future SAF deployment rates by fuel type, domestic and international policy, and costs determine the level of SAF in the Balanced Pathway. This SAF volume is input into CCC fuel supply analysis, which applies assumptions to each fuel type, such as biomass import constraints and the deployment of domestic synthetic fuel in line with domestic deployment of direct air capture (DAC), to output the share of each SAF type. See Chapter 12 for more information on CCC fuel supply analysis.
- **CCC model.** The CCC's aviation model takes abatement from demand management, efficiency improvements, and new aircraft from the DfT model; calculates abatement from SAF; and outputs resulting aviation pathway emissions.
  - **Costs.** The model outputs costs for aviation abatement measures: demand management, SAF, efficiency improvements, and new aircraft. The inputs for costing

these measures include long-run variable costs (LRVCs) for fuels, aircraft maintenance costs, and new aircraft capital costs.*

- **Engineered removals.** Residual aviation emissions are a key determinant of economy-wide residual emissions, accounting for around 60% of total residual emissions in 2050, and therefore around 60% of engineered removals. CCC sectors input residual emissions into engineered removals analysis. See Chapter 18 for more detail on how the level of removals in the pathway is set and costed.

Figure 11.2 Modelling schematic for aviation



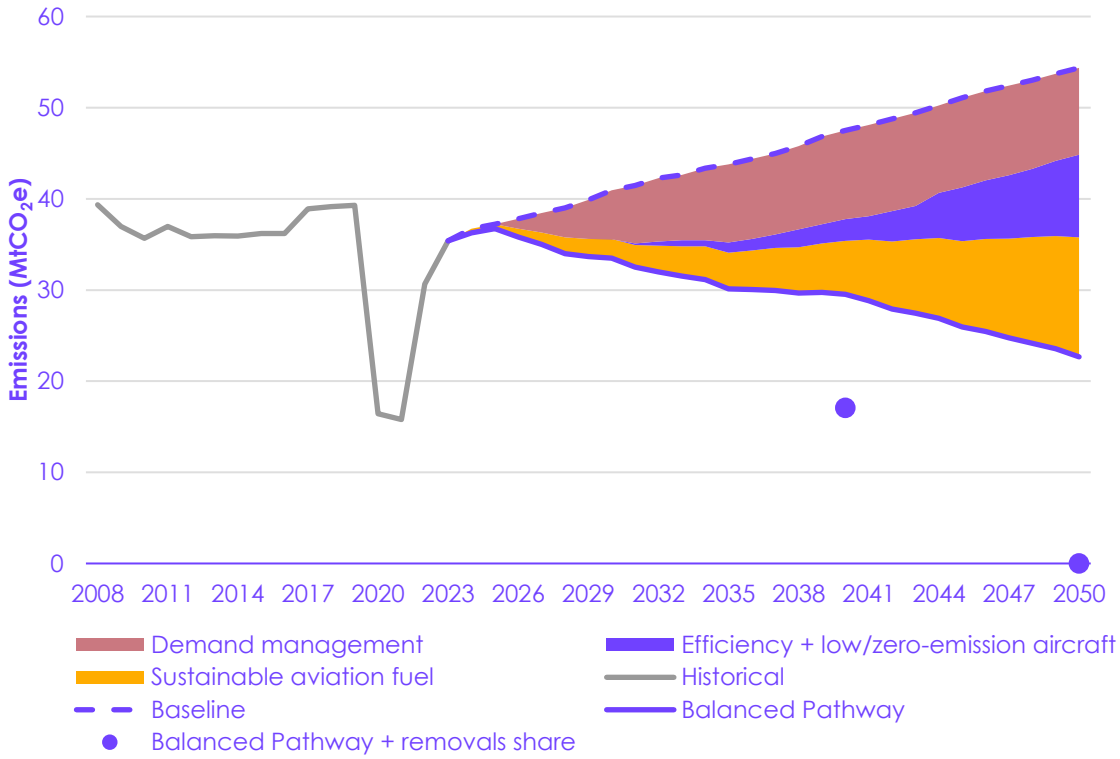
Description: CCC aviation analysis adopts assumptions and uses input data in the DfT aviation modelling suite and CCC in-house model to output sector emissions, abatement, and costs.
Source: CCC analysis.
Notes: This diagram is illustrative and does not detail all model inputs and outputs.

The Balanced Pathway for aviation

Aviation is currently the sixth highest-emitting sector in the UK economy. In 2023, aviation accounted for 8% of UK emissions, 35.4 $MtCO_2e$ (Figure 11.1). By 2040, aviation emissions fall by 17% in the Balanced Pathway, relative to 2023 (Figure 11.3). At this point, aviation will account for 29.5 $MtCO_2e$ of UK greenhouse gas (GHG) emissions and will be the UK's highest-emitting sector. The sector will also be contributing financially to engineered removals.

* Long-run variable costs include the components of the retail price that represent costs to society as a whole, and vary according to the level of consumption. They do not include transfer payments, such as taxes.

Figure 11.3 Sources of abatement in the Balanced Pathway for aviation



Description: During the Seventh Carbon Budget period, the largest share of emissions reduction in aviation is from managing forecasted aviation demand growth. By 2050, it is SAF. Contributions also come from efficiency improvements and low- and zero-emission aircraft. All residual emissions are offset by engineered removals by 2050.
Source: CCC analysis.
Notes: (1) It was not possible to separate abatement from efficiency improvements and low- and zero-emission aircraft in Department for Transport aviation model runs for the CCC. (2) By 2050, all remaining aviation emissions are offset using engineered removals. This corresponds to aviation accounting for an indicative share of around 60% of the total engineered removals in 2050. This chart shows this with purple circles, which assumes that aviation also receives around 60% of available permanent removals in 2040 (equating to 13.5 $MtCO_2e$ of removals). This is highly uncertain as the shares of removals, SAF, efficiency improvements, and new aircraft will be determined by their individual technology development progress, relative costs, and the market.

The measures in our pathway

Table 11.1 summarises the measures that reduce emissions in the aviation sector that are considered within our modelling, how these lead to emissions reductions, and the factors that influence their uptake. The methodology used to develop the assumptions and analysis underpinning these are described in the rest of this section.

Table 11.1
Measures considered within our modelling for aviation

Decarbonisation measure	How does this measure influence emissions in our modelling?	What are the key factors that affect uptake in our modelling?
Demand management	Managing the forecasted increase in baseline aviation demand.	Carbon values are input into the DfT model, which reduces baseline demand for flying through passing costs onto consumers. We use carbon values to proxy SAF and engineered removals costs because they are uncertain, and the high values to account for non-CO_2 effects.[7] We assessed literature on policy to manage aviation demand, held an expert evidence

		roundtable, tested the level of demand in the Balanced Pathway with the CCC's citizens' panel, and analysed data on flying to verify that the level of aviation demand is achievable and could have acceptable distributional outcomes.
Efficiency improvements and new aircraft	Efficiency improvements relating to fuel, air transport movements, operations and aircraft technology, including hybrid electric and battery electric aircraft, reduce the carbon intensity of flying through reducing jet fuel consumption.	Assumes a central case for efficiency assumptions based on historical efficiency improvement trends. We assessed when new aircraft concepts are likely to enter the market to 2050. Hybrid electric and battery electric aircraft are included in CCC analysis and hydrogen aircraft are excluded (see Section 1.5.1 for further information on technology readiness levels).
SAF	Switching from kerosene-based jet fuel to HEFA, biomass, waste-based, and synthetic fuel reduces the lifecycle emissions of jet fuel.	Level of SAF determined by a variety of assumptions and evidence, such as future fuel supply availability and the cost effectiveness of synthetic fuels and engineered removals. The share of each SAF type is determined by fuel supply analysis.
Source: DESNZ (2023) *Traded carbon values used for modelling purposes;* CCC analysis.		

11.2.2 Aviation demand management

Given present aviation technology limitations, the sector is expected to have significant residual emissions by 2050. The options to address these emissions are ambitious levels of SAF, engineered removals, and managing the forecasted increase in aviation demand.

Our Balanced Pathway analysis considers the most feasible and cost-effective way to reach Net Zero based on current evidence. Given SAF and direct air capture and carbon storage (DACCS) are currently uncertain and expensive technologies, managing the increase in projected aviation demand will be important for ensuring the sector reaches Net Zero.

CCC aviation demand forecasting is modelled by DfT's aviation modelling suite. Our analysis adopts the following assumptions:

- **Polluter pays principle:** We assume the aviation industry pays to decarbonise the aviation sector. In CCC analysis, technology costs are represented by applying DESNZ's high carbon values to ticket prices in the DfT model, which passes costs onto those who choose to fly.[8] This results in demand being lower than in the baseline.
  - Our citizens' panel were clear that industry and those who fly should pay rather than the taxpayer. Each year, half of the population does not fly abroad. We estimate less than 10% of UK residents fly abroad more than three times a year and account for almost half of passenger flights abroad (see Box 11.1).[9]
  - The DfT model uses price and income elasticities to calculate the impact of increased ticket prices on aviation demand. Elasticities are uncertain and evidence is limited on the demand response to large changes in price or by different income groups.[10;11]
- **Carbon values:** Carbon values are used to proxy future technology costs instead of estimated costs. This is because future costs of synthetic SAF and DACCS (the expected marginal units of SAF and permanent engineered removals respectively), and the exact volume of SAF and DACCS, are highly uncertain. We use the high carbon value to account for non-CO_2 effects, which have likely contributed significantly to the UK's total warming effects from flying and are currently projected to increase to 2050 (see Box 11.2 on non-CO_2 effects).

- Carbon values are deflated to 2015 prices in line with the DfT's aviation modelling approach.[12] In 2025, the 2023 DESNZ ETS price forecast is used, which is linearly scaled up to the Government's 2035 high carbon value by 2035. From 2035 to 2050, the full high carbon value is applied (see Figure 11.4).

- This also avoids the need to model demand for aviation and supply of SAF and DACCS simultaneously, which is not possible within DfT's aviation model.

- **Technology costs:** CCC analysis generally considers technologies for inclusion in the pathway only once they become cost-effective compared to the UK Government's central 'target-consistent' carbon values (see Sections 1.5 and 1.7.2 for more detail). In 2040, the central carbon value is £352/tCO_2e (in £2023). In 2040, the new unit abatement cost of DACCS is estimated to be around £349/tCO_2e and £630/tCO_2e for synthetic fuel. See Chapter 2 for more information on CCC abatement cost methodology.

  - Our cost estimates find that DACCS is cheaper than synthetic fuels in the Seventh Carbon Budget period due to the multiple expensive inputs (low-carbon hydrogen and captured carbon) and energy conversion losses incurred during synthetic fuel production process, compared to the costs of capturing and storing carbon. Despite this, we include some synthetic fuels in the Balanced Pathway to reflect the uncertainty in costs and the need to maintain technology optionality.

- **Modal shift:** There is a small demand reduction effect from assuming modal shift from flying to rail for some flights. We reviewed Civil Aviation Authority data on domestic flights to identify which flights could be replaced by a rail alternative to validate this assumption. We also discussed this measure with our citizens' panel, who had mixed views on its effectiveness.

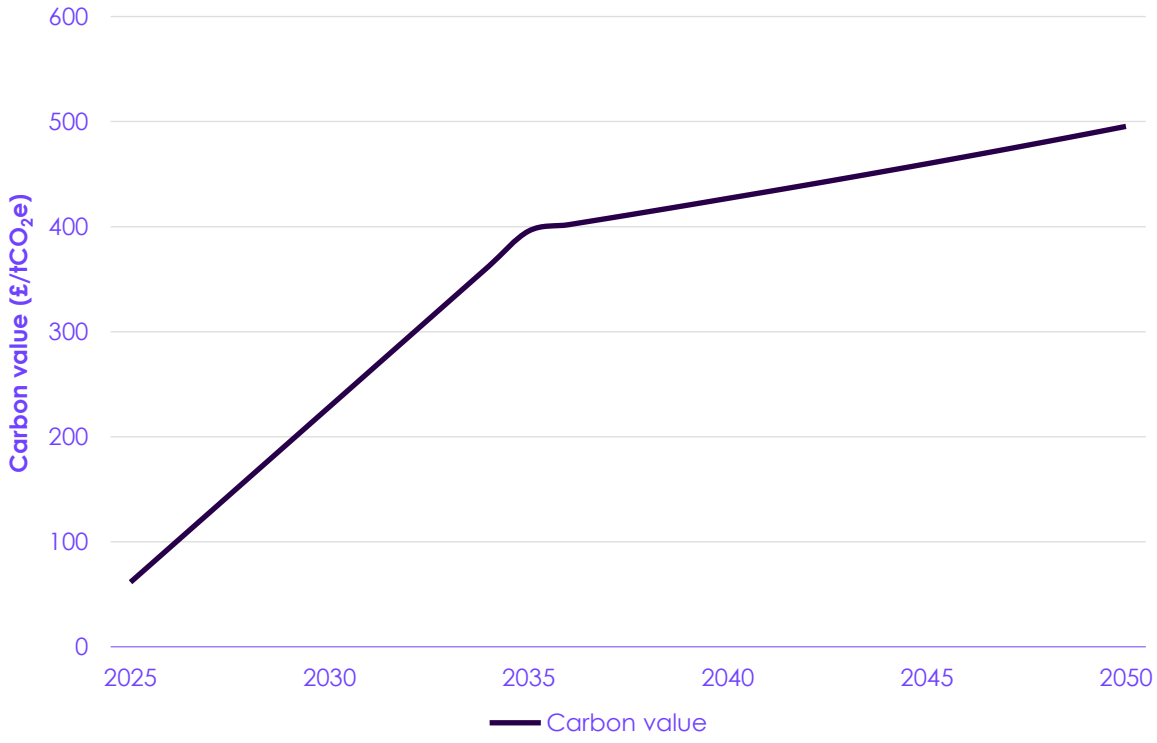
- **Business flight demand:** The rate of business flight demand growth increases in line with recent historical data, where the demand growth rate has reduced. Without this assumption applied, between 2025 and 2050 domestic business flight demand increases by 54%. In the Balanced Pathway, it grows by 35%. This adjustment is applied to these markets after aviation demand has been forecasted in the model using economic input assumptions, including carbon values.

- **Exclusions:** To protect essential connectivity flights, we do not assume any demand management for domestic flights to or from Northern Ireland or the Scottish Highlands and Islands. Military flights are excluded from the demand measure.

- **Wider evidence:** We reviewed evidence on the different policy options for managing demand to understand the feasibility of achieving the Balanced Pathway's demand levels. This included price-based mechanisms such as VAT and Air Passenger Duty, market-based mechanisms such as Emissions Trading Schemes, and more centralised policies such as airport expansion limitations. See Box 7.6.2 of the Seventh Carbon Budget advice report for more information. We also held a stakeholder evidence roundtable on demand management policy and conducted a citizens' panel to expand our evidence base on household choices for aviation demand.[13] With the citizens' panel, we tested the acceptability of illustrative ticket price rises. See Box 11.3 for more information.

- **Costs:** For the demand measure, we consider the reduced cost to aviation due to reduction in demand for flying relative to the baseline. This is in the form of fewer planes and reduced maintenance costs. To calculate capital (purchase of new aircraft) and operational (such as airframe maintenance and fuel) costs associated with aviation demand, we use costs from joint DfT- and CCC-commissioned research and CCC fuel supply costs.[14]

Figure 11.4 Carbon value assumptions used as a proxy for the cost of SAF and engineered removals in aviation modelling



Description: Carbon values inputted into the DfT model between 2025 and 2050 increase over time.
Source: UK Government (2023) traded carbon values used for modelling purposes; UK Government (2023) Green Book carbon values.
Notes: 2015 is the starting year of the DfT's modelling framework. In the DfT model, prices are rebased to a common reference year to allow for comparison. The base year selection does not influence demand projections, as demand is affected by relative price changes rather than absolute values. In CCC analysis, carbon values are deflated to 2015 prices. In 2025, the 2023 Government's ETS price forecast is used, which is linearly scaled up to the high carbon value by 2035. From 2035 to 2050, the full high carbon value is applied.

Box 11.1
Estimation of the proportion of international flights taken by frequent fliers

In our Seventh Carbon Budget advice report, we estimate the proportion of international flights taken by different shares of the population. Our approach is as follows:

- Use data from the National Travel Survey on the percentage of people that took a given number of flights abroad in the last year, for the years 2019 and 2023.[15] For 1–10 flights, the survey gives data for each number. For 11–100 flights, data increases in bands of 10. There is then one band for 101+ flights.
- Estimate the total number of international flights taken by UK residents and the proportion of flights that different groups of the population account for, by combining this data with ONS population estimates.[16] For bands over 11, we assume the mid-point number of flights in that band is taken, and for the 101+ band we assume 150 flights are taken.
- The survey is for residents of England, and we assume the number of flights each group takes is representative of the rest of the UK.

The total number of flights that this implies broadly aligns with data from the Civil Aviation Authority and ONS on terminal passenger demand.[17;18] Some small differences in the data sets can be explained by the methodology of the National Travel Survey, which considers domestic travel to be that which occurs in the boundary of Great Britain, which means that flights to Northern Ireland and the Channel Islands are counted as international flights.

A sensitivity analysis, assuming that the lowest number of flights was taken for the banded estimates rather than the mid-point, finds that for both the central and sensitivity assumptions, between 7–8% of the population fly abroad four or more times a year and take between 40–47% of international flights. The distribution of flights across groups is broadly consistent across both years.

Box 11.2
Estimating temperature change from non-CO_2 warming effects from aviation

This box outlines the methodology for producing Figure 7.6.4 in the Seventh Carbon Budget advice report. Non-CO_2 effects include the impact on the climate from nitrogen oxides, water vapour, black carbon (soot), and sulphur dioxide emissions. In addition to these pollutants, contrail formation, which can occur when aircraft fly through supersaturated air, also contributes to the non-CO_2 effects from aviation. The impact of non-CO_2 effects is very uncertain, though they are likely to have a high warming effect. Non-CO_2 effects are estimated to contribute around two-thirds of aviation's total effective radiative forcing globally.[19] We estimate temperature change from non-CO_2 warming effects in the UK for both our baseline and Balanced Pathway, based on fuel use and departing aircraft kilometres.

Our analysis uses the following methodology:

- Using Lee et al.'s (2020) approach, we calculate non-CO_2 warming effects from pollutants as an effective radiative forcing.[20]
- We convert fuel use into water vapour, black carbon, sulphur dioxide, and nitrogen oxides emissions using Lee et al.'s (2020) emission index in g/kg of fuel.
- We then calculate the effective radiative forcing of each pollutant using the relevant effective radiative forcing constant.[21]
- For contrails, aircraft kilometres are converted into contrail radiative forcing using the effective radiative forcing constant for contrail cirrus.
- The total warming equivalent for the pollutants and contrails is calculated using an average of the effective radiative forcing from the 20 years previous. A 20-year average is used to account for the warming from non-CO_2 effects lasting between 10 and 20 years, compared to warming from CO_2, which lasts for centuries into the future.
- To compare warming from non-CO_2 effects to warming from CO_2, the total warming equivalent (the sum of the warming equivalent from the pollutants and contrail formation) is converted into temperature change using the IPCC's (2021) central estimate of the transient climate response to cumulative CO_2 emissions.[22]

As noted above, calculating non-CO_2 warming effects for each pollutant requires an average of the radiative forcing for the preceding 20 years. For our Balanced Pathway we calculate non-CO_2 warming effects from 2025 to 2050, requiring effective radiative forcing values, and therefore fuel use and aircraft kilometre data, from 2005 to 2050. Between 2005 and 2023 GHG inventory data and the kerosene emission factor are used to establish historic fuel use data.[23] We then use historical aircraft kilometre data to calculate the effective radiative forcing of contrails between 2005 and 2023. Between 2024 and 2050, fuel use and departing aircraft kilometres are taken from our Balanced Pathway to calculate non-CO_2 warming effects. For this work we assume all fuels in our Balanced Pathway produce the same non-CO_2 impacts as kerosene. More research is required to establish whether alternative fuels to kerosene have different impacts on non-CO_2 effective radiative forcing.[24]

Box 11.3
Estimation of future ticket prices

We estimate the impact on airline ticket prices in 2050 if the Government's high carbon value is applied to tickets and airlines are assumed to pass on 100% of costs. To do this, we:

- Use two of the most common long and short haul flight routes to represent the range in emissions from long and short haul flights. For short haul, we show a return flight from London Gatwick to Alicante, Spain. For long haul, we show a flight from London Heathrow to New York.[25]
- Use the International Civil Aviation Organization (ICAO) carbon emissions calculator to estimate the emissions per passenger for a typical return long haul and short haul flight to these two destinations.[26] There are small variations over time in emissions data shown from the ICAO carbon calculator; we used emissions data at the time of analysis, which was July 2024.
- Remove the emissions expected to be delivered by efficiency improvements by 2050 in the Balanced Pathway.
- Apply the Government's high carbon value for 2050 to the residual emissions, to calculate the additional cost in 2050. The carbon value is converted from 2020 prices to 2023 prices.[27] The final numbers presented in the report have been rounded to the nearest £50.
- Forecast 2050 real household income per capita using 2023 household real disposable income per capita and OBR projections of growth in real GDP per capita. We take the absolute income change between 2023 and 2050 and compare this to the absolute change in ticket price.

We tested a preliminary version of this analysis with our citizens' panel, where the costs were similar but not exactly the same. We presented a range of future ticket prices, with the example of the cost of a return flight to Madrid in 2050 increasing by £50–£150, and the cost of a return flight to New York increasing by £160–£360.

11.2.3 Sustainable aviation fuel

Switching from kerosene jet fuel to HEFA, biomass, waste-based, and synthetic fuel reduces the lifecycle emissions of jet fuel. SAF is a developing technology with low levels of rollout internationally and in the UK. In 2023, SAF accounted for less than 1% of total UK jet fuel consumption.

In the Balanced Pathway, SAF meets 6% of total fuel demand in 2030, 17% in 2040, and 38% by 2050. This trajectory is lower than the Government's SAF mandate due to the short- and long-term uncertainties regarding the costs and supply of SAF, particularly synthetic fuels; projected cost effectiveness of DACCS compared to synthetic SAF; and Intergovernmental Panel on Climate Change guidelines for imported synthetic fuel accounting.

CCC fuel supply analysis determines the share of each SAF type in the Balanced Pathway. SAF types are categorised into HEFA, biomass, waste-based, and synthetic fuel. Assumptions for each SAF type are outlined in Chapter 12 on fuel supply.

The modelling approach and key assumptions for our aviation analysis are:

- **Modelling:** The overall SAF trajectory is determined by the Committee, informed by the latest evidence on technology development, SAF emissions accounting rules, UK and global SAF policy, SAF supply considerations, and the cost effectiveness of synthetic fuels in comparison to DACCS, among others. Fuel supply analysis inputs this level of SAF and determines the share of each SAF type (see Section 12 for more information on fuel supply assumptions and constraints). The aviation model then uses direct and indirect emissions intensities and LRVCs from CCC fuel supply analysis to calculate abatement and costs.

- **Synthetic fuel, DAC, and costs:** DAC can be used to either store carbon (a removal) or to produce CO_2 feedstock for synthetic fuel. CCC analysis finds that DACCS is likely to be cheaper than synthetic fuels. DACCS abatement costs in 2040 are forecasted to be £349/tCO_2e and synthetic fuel £630/tCO_2e. A cost-optimising approach would limit SAF to

non-synthetic SAF types and use captured carbon for storage. However, our analysis retains optionality given wider sector uncertainty and non-synthetic SAF feedstock supply considerations.

  - To estimate the future cost of synthetic SAF and DACCS, we reviewed the potential s-curves of technologies related to hydrogen, carbon capture and storage (CCS) and DAC, which affect the cost of synthetic fuel. See Section 1.7.3 for more information on how CCC analysis considers the potential for future technology cost reduction.

- **Emissions accounting rules and synthetic fuel imports:** Current international emissions reporting guidelines are unclear regarding reporting of emissions savings derived from imported synthetic fuels. Synthetic fuels, which combine hydrogen with a source of captured carbon, may only count towards reducing domestic emissions if also produced domestically. Due to this ambiguity, our analysis assumes synthetic fuels are produced in the UK.[*;28] In practice, future SAF production and supply is likely to operate in an international market and be produced in the most cost-effective location.

- **UK policy:** SAF policy has progressed over the past five years. The UK's SAF mandate has now come into force, which targets 10% SAF uptake by 2030 and 22% by 2040. Other economies have also set SAF targets, such as the European Union's ReFuelEU aviation mandate, which targets a 6% share by 2030, 34% by 2040, and 70% by 2050.[29]

- **SAF supply:** SAF is an emerging technology and market that faces various uncertainties. Our fuel supply analysis considered global datasets, evidence provided by the UK Government's SAF mandate consultation, and current SAF buildout rates to understand the potential for UK domestic SAF production and SAF imports.[30;31]

  - The previous UK Government's Jet Zero Strategy committed to having five SAF plants under construction by 2025.[32] To support this, the Advanced Fuel Fund has awarded £135 million to SAF projects around the UK.[33] As of 2024, no SAF plants were operational in the UK.[34;35]

  - CCC stakeholder engagement highlighted that globally and in the UK, SAF producers building first-of-a-kind plants are facing investment and technology challenges, which is delaying SAF production.

- **Costs:** SAF is counted as an operational cost in aviation analysis, using the LRVC of each fuel type to calculate the total cost of SAF in the pathway.

11.2.4 Efficiency improvements and low- and zero-emission aircraft

The efficiency measure in CCC analysis refers to fuel, air transport movements, and operational improvements, and the introduction of hybrid electric and battery electric aircraft. New aircraft are not treated as a separate measure due to modelling constraints. There are currently no hybrid or zero-emission aircraft in UK aircraft fleets.

The efficiency improvements assumption is based on the aviation industry's historical efficiency improvement rate. The assumptions on new aircraft technology are informed by the CCC's wider approach to assessing new low-carbon technology (see Chapter 1) and historical case studies of the time taken for new technologies to enter a market.

- **Modelling:** DfT's aviation modelling suite provided abatement inputs to the CCC's aviation model for efficiency improvements and new aircraft. For efficiency improvements and hybrid electric aircraft, the DfT model can choose between a 'pessimistic', 'likely', and

[*] See the UK's 1990–2021 Greenhouse Gas Inventory, Section 1.8.2.3, for the relevant guidelines.

'optimistic' assumption, which respectively increase seat-km per tonne of fuel by an average of 0.5%, 1.3%, and 2.0% between 2025 and 2050.[36] For battery electric and hydrogen aircraft, the input is an entry into service year.

- **Efficiency improvements:** CCC analysis adopted the 'likely' case for efficiency improvements and hybrid electric aircraft. This aligns with the historical improvement rate. The compound annual reduction rate of aircraft fuel intensity over the past 60 years is around 1.3%, with significant variation between different time periods.[37;38]

- **Hybrid electric aircraft:** Hybrid aircraft use more than one energy source during flight, either simultaneously or alternately. For electric propulsion, the electricity can come from batteries or hydrogen fuel cells. Test flights have taken place of battery concepts, such as EcoPulse, which has carried out 50 test flights.[39] Hybrid electric aircraft are considered an efficiency improvement in DfT's aviation model. Within the 'likely' efficiency improvement scenario, these aircraft enter the fleet in 2040. As the most developed new aircraft concept, it is likely that some hybrid electric aircraft concepts will enter the fleet in the 2030s.

- **Zero emission aircraft:** We reviewed evidence on zero emission aircraft concepts – battery electric, hydrogen fuel cell, and hydrogen gas turbine aircraft – to understand what aircraft may enter the UK fleet by 2050. For each aircraft, we considered technology readiness levels; compared the aircraft's stage of development with historic technology analogues; identified demand and supply side opportunities and challenges (such as specialist skills, infrastructure requirements, and manufacturing capability); and potential costs. Optimism bias is also incorporated into assumptions. See Chapter 1 for more on CCC low-carbon technology analysis.

  - In the pathway, battery electric aircraft enter the fleet in 2040 and begin to replace retiring aircraft that align with the battery electric aircraft specification. Concepts have undergone test flights, such as Rolls Royce's Spirit of Innovation.[40] Technology challenges remain, such as improving battery life span and energy density.

  - Hydrogen aircraft concepts are excluded from our analysis. Technology readiness levels of concepts are currently low and, as well as advancing hydrogen aircraft technology, will also need to address hydrogen infrastructure and cost challenges. Hydrogen aircraft concepts could be included in future carbon budget analysis if technology and industry plans progress.

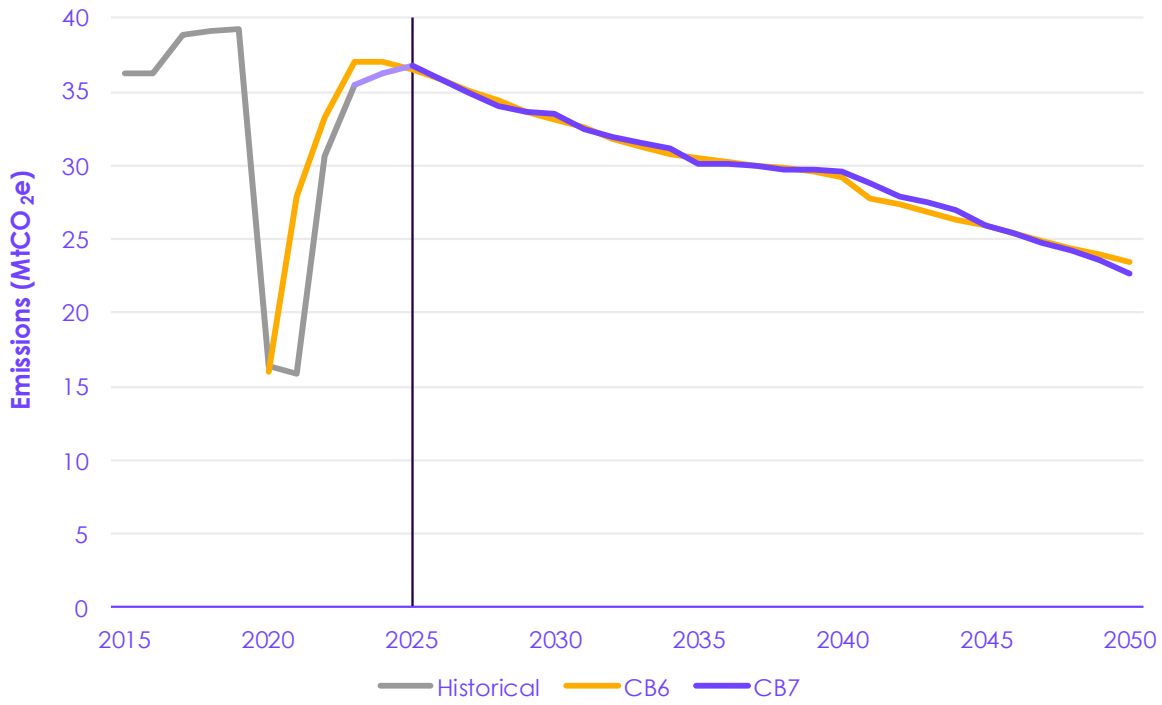
- **Costs:** Efficiency improvements and hybrid aircraft capital costs (such as the purchase of new aircraft) and operational costs (such as airframe maintenance) use data from joint DfT- and CCC-commissioned research.[41] The impact of reduced demand in the pathway compared to the baseline is separated from efficiency costs and accounted for in the demand measure. Due to a lack of evidence, we do not cost battery-electric aircraft.

11.3 Changes since our Sixth Carbon Budget advice

11.3.1 Comparison with our Sixth Carbon Budget pathway

Our Balanced Pathway for aviation is very similar to that in our Sixth Carbon Budget advice, despite some differences in baselines and measures to reduce emissions (Figure 11.5).*

Figure 11.5 The Balanced Pathway for aviation compared to our Sixth Carbon Budget advice



Description: The Sixth (CB6) and Seventh Carbon Budget (CB7) Balanced Pathways show similar rates of emissions reductions for the aviation sector.
Source: DESNZ (2024) *Provisional UK greenhouse gas emissions national statistics 2023*; DESNZ (2024) *Final UK greenhouse gas emissions national statistics: 1990 to 2022*; CCC (2020) *The Sixth Carbon Budget*; CCC analysis.

11.3.2 Emissions changes since our Sixth Carbon Budget advice

There was a sharp drop in flights during the COVID-19 pandemic, but aviation emissions have now almost rebounded to pre-pandemic levels.

- Aviation emissions in 2023 rebounded to 90% of 2019 levels. This is roughly in line with the rate of recovery that we projected in our Sixth Carbon Budget advice.

* All comparisons in this section compare the Balanced Pathway in this advice with the Balanced Net Zero Pathway in our Sixth Carbon Budget. Our Sixth Carbon Budget advice also included four other exploratory pathways, which are not discussed here. Data for those pathways can be found in our Sixth Carbon Budget advice.

11.3.3 Key pathway differences compared to our Sixth Carbon Budget advice

There are several key areas in which the deployment rates, measures included, or underlying assumptions in our updated Balanced Pathway have been revised since publication of our Sixth Carbon Budget advice in 2020. These include:

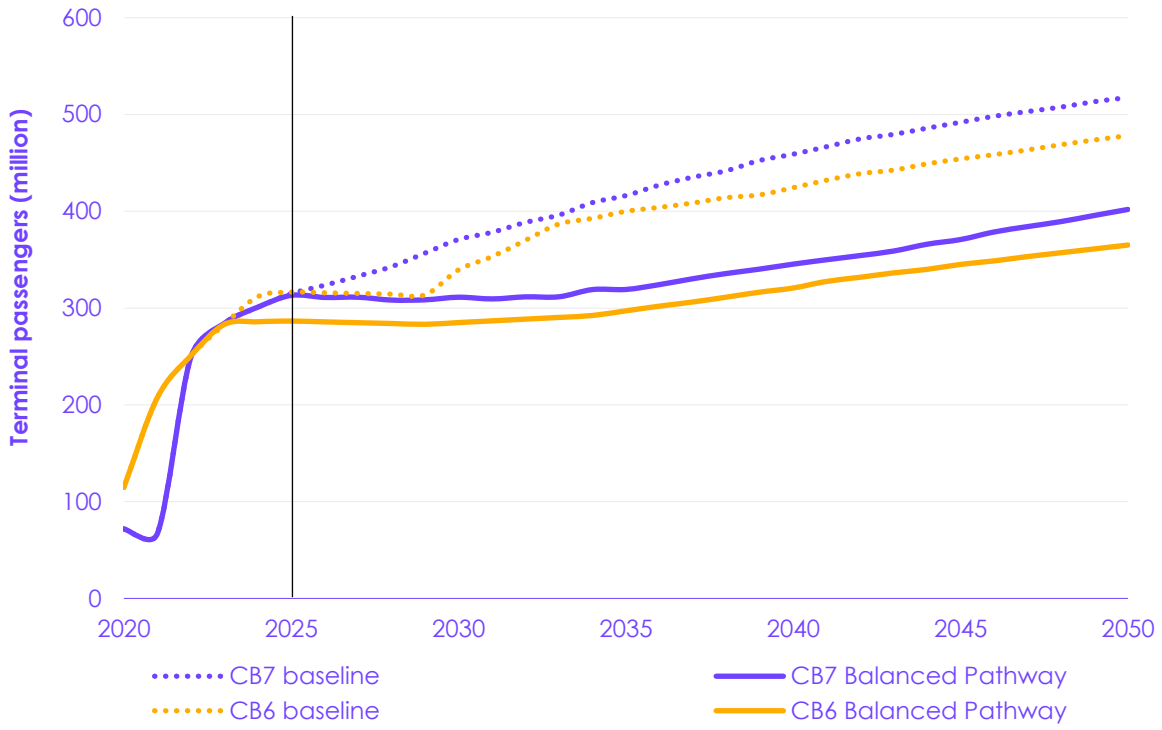
- **Baseline**: Sixth Carbon Budget advice on aviation made an adjustment to forecasted demand to account for delays to Heathrow expansion, which causes the small decrease in emissions before 2030 and the sharp increase in the early 2030s. The Seventh Carbon Budget baseline adopts the Government's 'best use policy,' which assumes all planned airport expansions proceed based on industry plans at the time the modelling was undertaken.

- **Aviation demand:** Our updated analysis assumes a slightly higher level of aviation demand in 2025 due to the rebound in demand seen since the COVID-19 pandemic. This means that demand is slightly higher than in our Sixth Carbon Budget advice (Figure 11.6a).

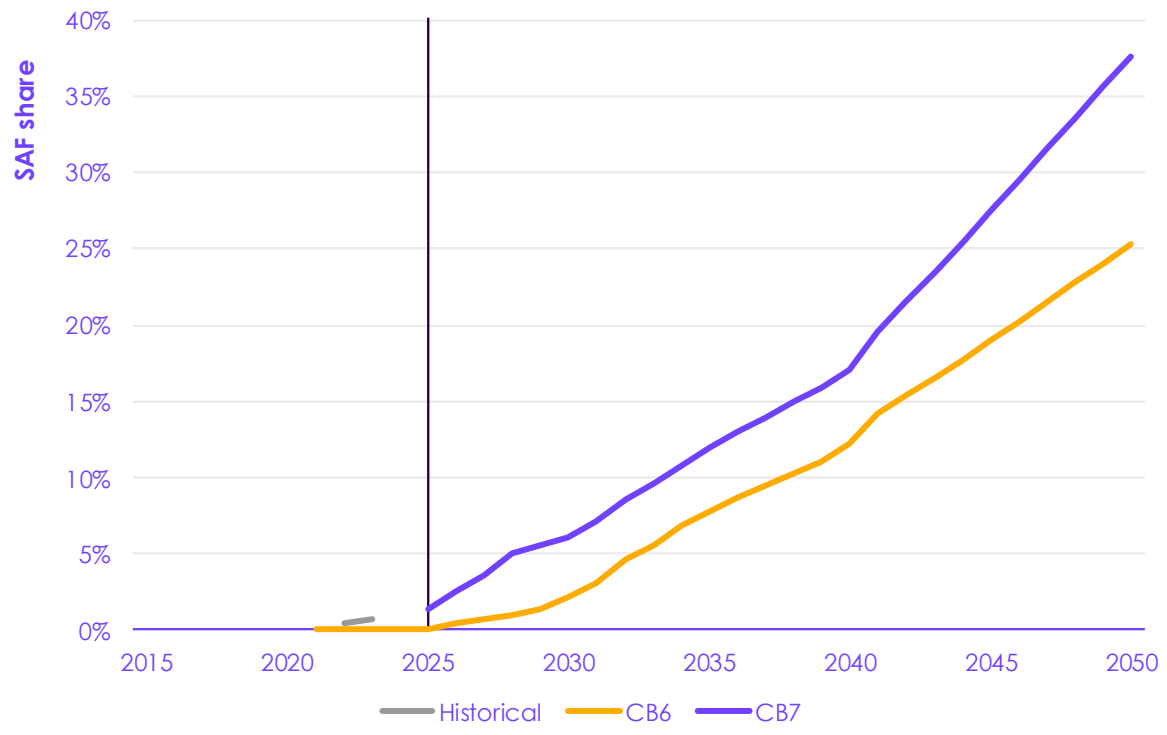
- **SAF:** We have increased our projected share of SAF in recognition of the progress made through the implementation of the UK's SAF mandate and historic SAF share being slightly above Sixth Carbon Budget projections (Figure 11.6b). However, our Balanced Pathway SAF trajectory is lower than the Government's, as discussed in the previous section.

Figure 11.6 Key differences in deployment trajectories in the Balanced Pathway for aviation compared to our Sixth Carbon Budget advice

(a) Total UK terminal passenger numbers



(b) SAF share of UK jet fuel



Description: Our Seventh Carbon Budget (CB7) analysis has higher terminal passenger demand in the aviation sector and higher SAF uptake compared to our Sixth Carbon Budget (CB6) analysis.
Source: CCC analysis.

11.4 Uncertainties and sensitivity analysis

Aviation emission forecasts are uncertain and sensitive to economic inputs. As aviation has significant residual emissions in 2050, these sensitivities have economy-wide implications for the Balanced Pathway to Net Zero.

Aviation emissions sensitivity analysis considers uncertainties that influence Balanced Pathway aviation demand: UK GDP, foreign GDP, oil price, and price elasticity of demand input assumptions (Table 11.2 and Figure 11.7). UK GDP and oil price sensitivities use central CCC assumptions (see Chapter 5); the price elasticity of demand sensitivity uses a CCC aviation analysis assumption; and the foreign GDP sensitivity uses DfT assumptions (see below).

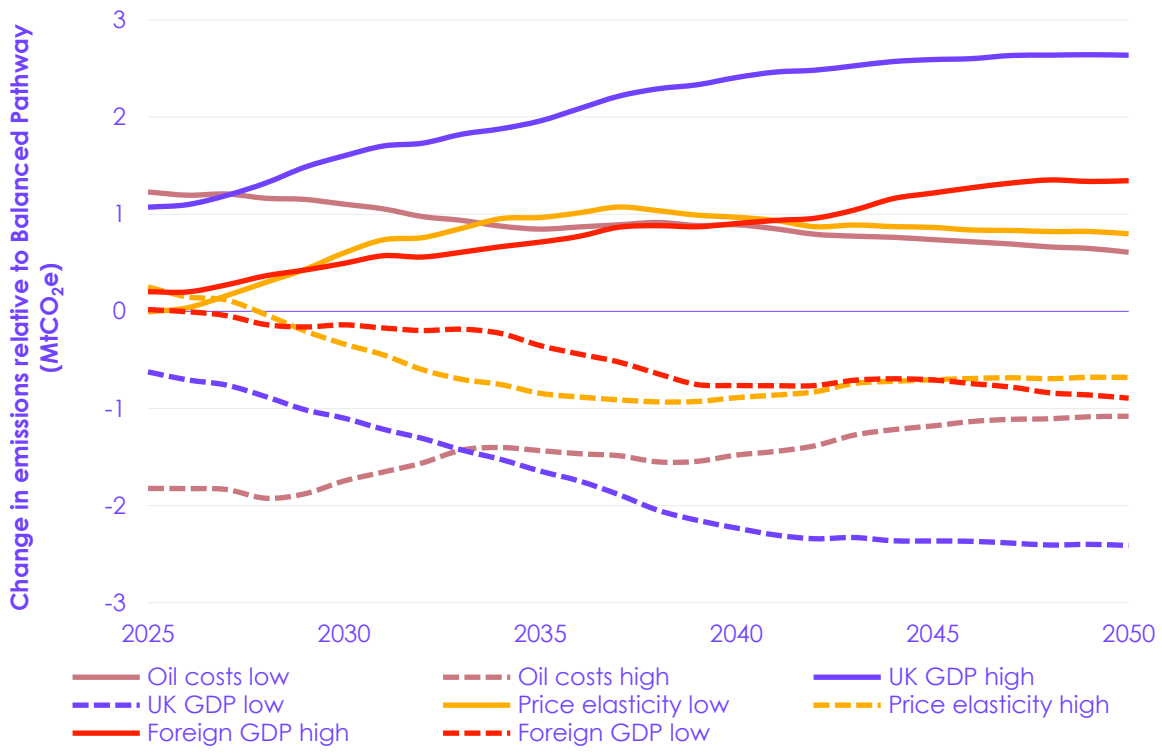
If certain uncertainties materialise and cause emissions to rise significantly beyond the Balanced Pathway projections, contingency measures to course correct emissions will likely be needed (see Section 11.6). See Chapter 5 for our general approach to uncertainty and contingency analysis, including descriptions of the methodology behind sensitivity tests that apply across multiple sectors.

Table 11.2
Key sensitivity tests for aviation

Sensitivity test	Description	Impact on emissions in 2040		
		$MtCO_2e$	% of sector emissions	% of total emissions
UK GDP	Assumes low UK GDP growth	-2.4	-8%	-2%
	Assumes high UK GDP growth	+2.4	+8%	+2%
Foreign GDP	Assumes low foreign GDP growth	-0.9	-3%	-1%
	Assumes high foreign GDP growth	+0.8	+3%	+1%
Oil prices	Assumes low oil price growth	+0.9	+3%	+1%
	Assumes high oil price growth	-1.6	-5%	-1%
Ticket price elasticity	Assumes low ticket price demand elasticity	+0.9	+3%	+1%
	Assumes high ticket price demand elasticity	-1.0	-3%	-1%

Source: DfT aviation modelling suite; CCC analysis.

Figure 11.7 Emissions impact of key sensitivity tests for aviation



Description: Sensitivity assumptions regarding UK GDP, foreign GDP, ticket price demand elasticity, and oil costs impact the projected level of aviation emissions in the Balanced Pathway.
Source: DfT aviation modelling suite; CCC analysis.
Notes: This chart uses a five-year rolling average between 2025-2050 to smooth each sensitivity.

11.4.1 UK GDP

Economic growth is a key driver of future aviation demand and therefore emissions in the DfT model. Variation in UK GDP growth has the largest impact on aviation emissions, whereby high UK GDP growth forecasts increase aviation emissions as household income increases. GDP sensitivity assumptions use central CCC assumptions (see Chapter 5).

11.4.2 Foreign GDP

London Heathrow Airport is an international hub airport that provides international flights to non-UK citizens. Foreign GDP forecasts have the same effect in the model on aviation emissions as UK GDP, but the impact is smaller as UK citizens take the majority of departing flights from the UK. The foreign GDP sensitivity assumption adopts DfT assumptions, which varies annual growth across all regions by ±0.5%.

11.4.3 Oil price

Kerosene prices are closely correlated with oil prices as kerosene jet fuel is a derivative of crude oil. In the model, low oil prices decrease ticket prices, causing aviation demand and emissions to increase. Oil price sensitivity assumptions use central CCC assumptions (see Chapter 5).

11.4.4 Price elasticity of demand

The price elasticity of demand measures the change in demand for a good in response to a change in price. A low price elasticity of demand means that a price change creates a small change in demand, also known as inelastic demand. High price elasticity of demand, or elastic demand, describes a good that is more responsive to price changes. For aviation, this analysis explores people's willingness to pay to fly at different prices.

The sensitivity analysis adopts a ±25% deviation from the central case. The low price elasticity of demand assumption results in aviation emissions increasing relative to the Balanced Pathway; the high price elasticity of demand assumption results in aviation emissions decreasing relative to the Balanced Pathway.

11.5 Contingencies in aviation

The contingency that we have modelled in the aviation sector is shown in Table 11.3. See Chapter 5 for our general approach to contingency analysis.

Table 11.3
Contingency option in aviation

Contingency	Description	Potential average annual emissions savings ($MtCO_2e$, % of sector emissions)			
		2030	CB6	CB7	2050
Additional aviation demand management	Carbon value used as ticket price proxy in the model increased from high carbon value to double the central carbon value	1.4 4%	1.7 6%	2.1 7%	1.7 8%

Source: DfT aviation modelling suite; CCC analysis; 2023 DESNZ carbon values.

11.5.1 Aviation demand management

As aviation will be one of the UK's highest-emitting sectors by the Seventh Carbon Budget period, measures to manage demand could offer sizeable additional emissions savings. To calculate this contingency, we increased the carbon value inputted into the DfT aviation model to double the DESNZ central carbon value, deflated to 2015 prices. This results in 2.1 $MtCO_2e$ average annual additional emissions savings for the Seventh Carbon Budget period.

There are a range of options for managing the forecasted increase in aviation demand, which is discussed in Box 7.6.2 of the Seventh Carbon Budget advice report.

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Chapter 12: Fuel supply

Introduction

The pathway for fuel supply covers decarbonisation of existing fossil fuel supply (oil and gas) and the production of low-carbon fuels, including hydrogen, bioenergy, and synthetic aviation and shipping fuels. This chapter is set out in two sections: decarbonising fossil fuel supply, then producing low-carbon fuels. For each fuel, the methodology and assumptions underpinning the Balanced Pathway are described.

- Options for decarbonising fossil fuel extraction and refining are modelled using an in-house Net Zero Industry Pathways model, developed by Element Energy and updated since our Sixth Carbon Budget advice. The model uses a cost-optimising approach to estimate the abatement potential and decarbonisation options at individual point sources of emissions, over the period to 2050.

- For the analysis underpinning hydrogen production, we commissioned the consultancy AFRY to undertake modelling using their BID3 model. This has an hourly representation of electricity demand and generation, co-optimising the power and hydrogen production and storage systems simultaneously.

- Bioenergy and waste supply estimates bring together latest land use, agriculture and waste sector analysis using an in-house model. Resources are allocated to end-use sectors from known 2022 positions, transitioning to best use (maximal GHG savings) by 2050.

- Synthetic shipping fuels are modelled using the Department for Transport's maritime emissions model which cost-optimises fuel switching across a range of low-carbon fuels and electricity. Synthetic aviation fuels make up the residual supply to meet total Sustainable Aviation Fuel (SAF) demand, after biogenic based resources have been allocated to produce SAF. Both synthetic shipping and aviation fuels are assumed to be produced domestically and become available in the mid-2030s as direct air capture becomes available.

12.1 The baseline for fossil fuel supply

Our baseline for fuel supply represents a scenario in which there is no further decarbonisation action by either the Government or the market in the fuel supply sector. See Chapter 1 for our general approach to baselines.

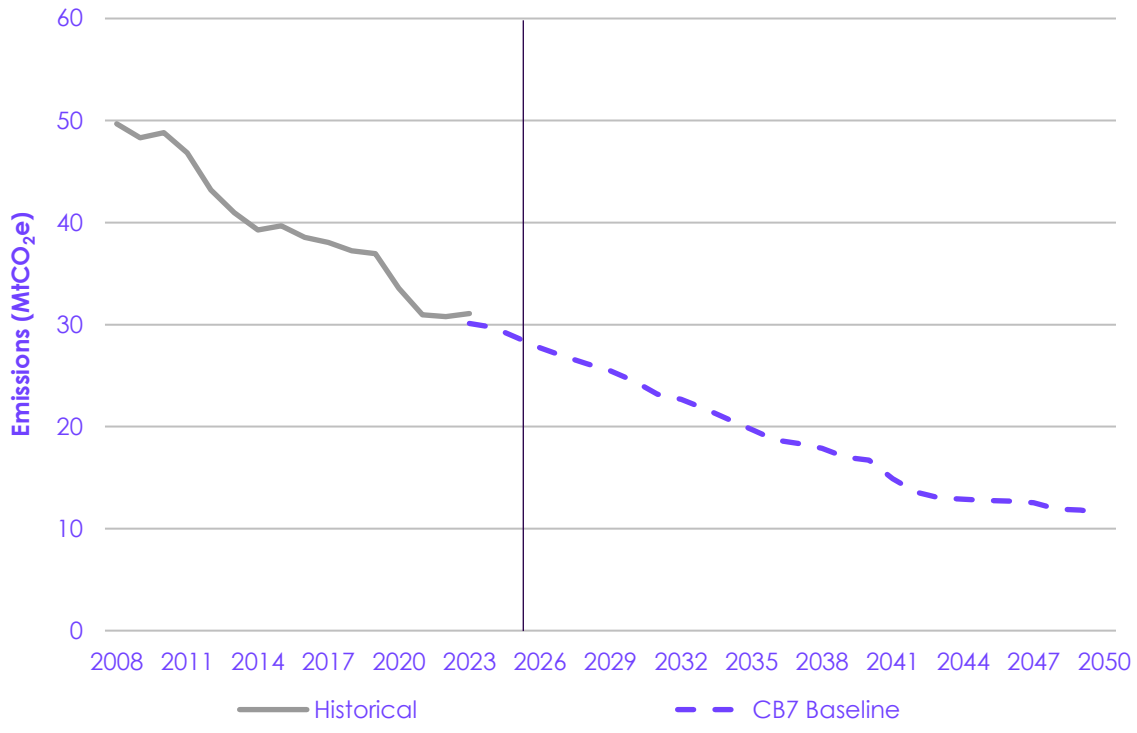
Our baseline for fossil fuel supply emissions is based on the following assumptions:

- The baseline is made up of specific projections for fossil fuel subsectors, which include oil refining, oil and gas platforms and processing terminals, gas distribution, and coal mines (open and closed). Emissions are largely associated with operating oil and gas platforms, as well as leakage, flaring, and venting of methane.

- The emissions baseline starts aligned to historical emissions for 2023, based on the National Atmospheric Emissions Inventory (NAEI).[1] Energy starting points are calibrated to the NAEI Energy Background Dataset, which underpins the UK's GHG inventory.

- The source of our baseline is the Government's Energy and Emission Projections (EEP) reference scenario, as published in October 2023.[2] As the EEP projections stop in 2040, the baseline is extended to 2050 based on specific assumptions by subsector. In the baseline, emissions fall by 44% to 2040 and by 62% by 2050, compared to 2023 levels (Figure 12.1).
  - The reduction in emissions largely reflects that the North Sea is a mature and declining basin. North Sea oil and gas production declined by 72% between 2000 and 2023 and is projected by the North Sea Transition Authority (NSTA) to fall a further three-quarters to 2040 (the last year of the EEP).[3] Production data used in the EEP reference scenario includes production from new oil and gas fields. We have also smoothed a kink in the EEP reference scenario that occurs in the mid-2030s.
  - From 2040 to 2050, a subsector specific approach is taken to extend the baseline.
    - Emissions from most subsectors extrapolate the existing trend within the EEP reference scenario, either held flat or declining.
    - Emissions from oil and gas platforms and terminals are aligned to NSTA business-as-usual emissions projections.[4] The NSTA projections show a reduction in baseline emissions in the early-2040s which reflects assets ceasing production.
- In addition, the baseline:
  - Includes no carbon capture and storage (CCS), hydrogen, or newer electric heating technologies (such as heat pumps).
  - Assumes no specific energy efficiency measures, but includes some energy efficiency improvements as end-of-life equipment is replaced with newer, more efficient kit.
  - Assumes no abatement from resource efficiency.

Figure 12.1 Baseline emissions in fuel supply



Description: Emissions from fossil fuel supply have been falling historically, and continue to reduce in the baseline out to 2050.
Source: DESNZ (2024) *Provisional UK greenhouse gas emissions national statistics 2023*; DESNZ (2024) *Final UK greenhouse gas emissions national statistics: 1990 to 2022*; DESNZ (2023) *Energy and emissions projections 2022 to 2040*; NSTA (2024) *Emissions Monitoring Report 2024*; CCC analysis.
Notes: Emissions starting point is lower than historical because we account for abatement from biomethane injection into the gas grid in the fuel supply sector, rather than spreading across all gas users; total economy-wide emissions are unaffected. Almost all the remaining emissions in the baseline are from the oil and gas subsector.

12.2 Pathway assumptions and modelling for fossil fuel supply

12.2.1 Modelling the Balanced Pathway for fossil fuel supply

Overall modelling approach

The approach for modelling the Balanced Pathway for fossil fuel supply is based on assessing the reduction in demand for fossil fuels across the economy and options for decarbonising remaining fossil fuel production processes. See Chapter 1 for our general approach to pathway analysis.

The following are the key steps:

- Determines a baseline (detailed in Section 12.1), based on the current stock of low- and high-carbon technologies.
- From this emissions baseline, deducts abatement resulting from:

- **Economy-wide reductions in fossil fuel demand ('fuel switching').** This reflects demand reductions in oil-based products in surface transport, buildings, and industry as they switch to non-fossil fuel technologies, which has the effect of reducing emissions via lower need for refining. We classify abatement achieved via this measure as 'fuel switching', which only affects the oil refining subsector.

- **Resource (material) and energy efficiency.** More efficient use of resources, materials, and energy in production and refining processes.

- **Switching to low-carbon processes** involved in fossil fuel extraction and refining, based on modelling of cost-optimised decarbonisation measures for these subsectors (e.g. CCS).

Figure 12.2 sets out how these are incorporated in our analysis.

- Fossil fuel demand to 2050 is summed from demand in end-use sectors (e.g. for surface transport, industrial uses, buildings heating, electricity generation). This falls over time and we assume leads to a reduction in UK refining activity. We do not model international trade flows in fossil fuel markets.

- Options for decarbonising remaining fossil fuel extraction and refining are modelled using the NZIP1 (Net Zero Industry Pathways) model.[5] The model uses a cost-optimising approach to estimate the abatement potential and decarbonisation options at individual point sources of emissions, over the period to 2050.

  - The model determines how and when to decarbonise each site by comparing the net present values (NPV) of the incumbent baseline technologies with the range of low-carbon alternative options, subject to suitability. Therefore, technology choice and pace of deployment are based on:

    - Capital costs of equipment and infrastructure, such as offshore electric cabling, hydrogen and CCS pipeline connections. Cost reductions of equipment over time are factored into the analysis.

    - The value of carbon for abated emissions, based on Government Green Book values.

    - Fuel costs for the decarbonisation option compared to the baseline and other operating costs, such as transport and storage of CO_2.*

    - A 3.5% social discount rate.

  - The model then selects the technology with the highest NPV. As the carbon value increases year-on-year, all else equal the likelihood of switching to low-carbon technologies grows.

  - NZIP1 outputs include emissions, energy demands, capital and operating costs, abatement costs, CO_2 transport and storage costs, and the distance to a CO_2 injection point and source of hydrogen (if piped). It provides these outputs at site, cluster, and subsector levels.

- Emissions reductions from resource and energy efficiency improvements are included in NZIP as inputs. Decarbonisation measures are deployed after resource (material) and energy efficiency measures.

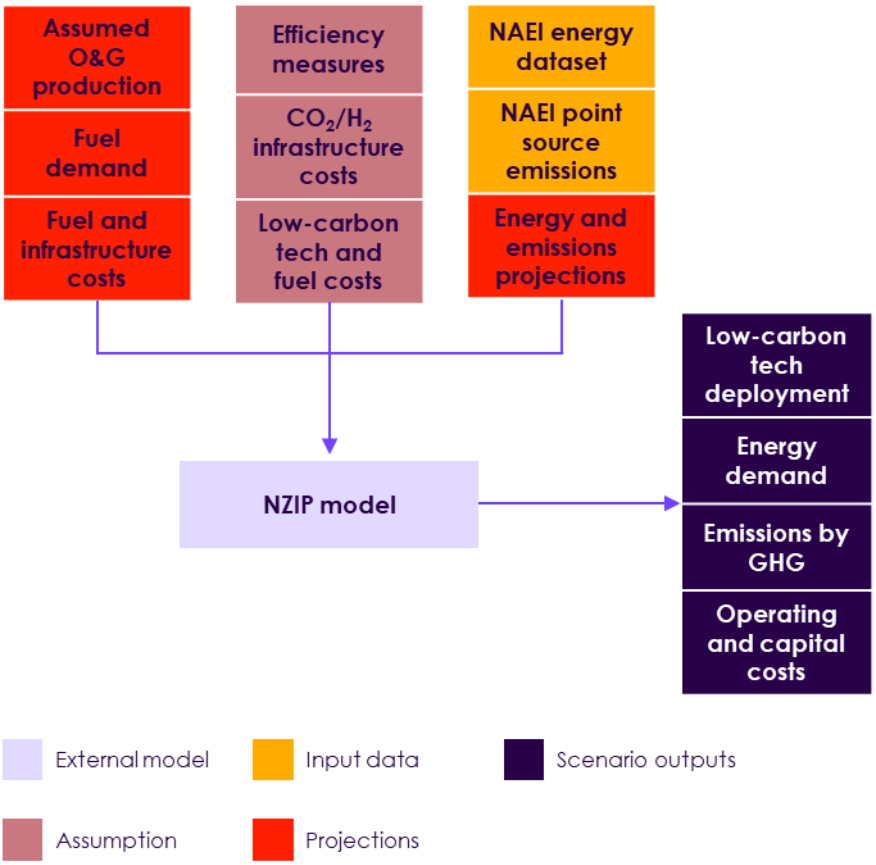
* Fuel costs are based on long-run variable costs rather than retail prices, see Chapter 1.

- The measures then applied to decarbonise the extraction and refining of fossil fuels fall under one of four categories: electrification, CCS, hydrogen (fuel switching from gas in generators), and reduced methane leakage, flaring, and venting.

- Within the NZIP model, effects from economy-wide reduction in fossil fuel demand – and implied reduction in activity and fuel output – are modelled as leading to closures of oil refinery sites, rather than reductions in the sizes of sites. This is captured within the measure 'fuel switching'. In practice, decisions will be taken by site owners.

There are similarities with how industry sector emissions are modelled, using a least-cost optimisation model developed by DESNZ (NZIP2, see Chapter 8). The NZIP2 model is an iteration of NZIP1, specifically modelling 17 manufacturing subsectors. However, it does not include all fossil fuel supply subsectors, only refining. For internal consistency we therefore used NZIP1 for fuel supply analysis.

Figure 12.2 Modelling schematic for fossil fuel supply



Description: Our fuel supply modelling is based on the demand for fossil fuels from our sectoral models of the rest of the economy, together with analysis of the deployment of measures to reduce emissions in fossil fuel production using the NZIP model.
Source: CCC analysis.
Notes: This diagram is illustrative and does not detail all model inputs and outputs.

The Balanced Pathway for fuel supply

In the Balanced Pathway, fuel supply emissions are projected to fall by 83% to 5.4 $MtCO_2e$ by 2040 (the mid-point of the Seventh Carbon Budget period) and to 1.6 $MtCO_2e$ by 2050 (Figure 12.3). The key decarbonisation measures are summarised in Table 12.1, and the main measures applied are:

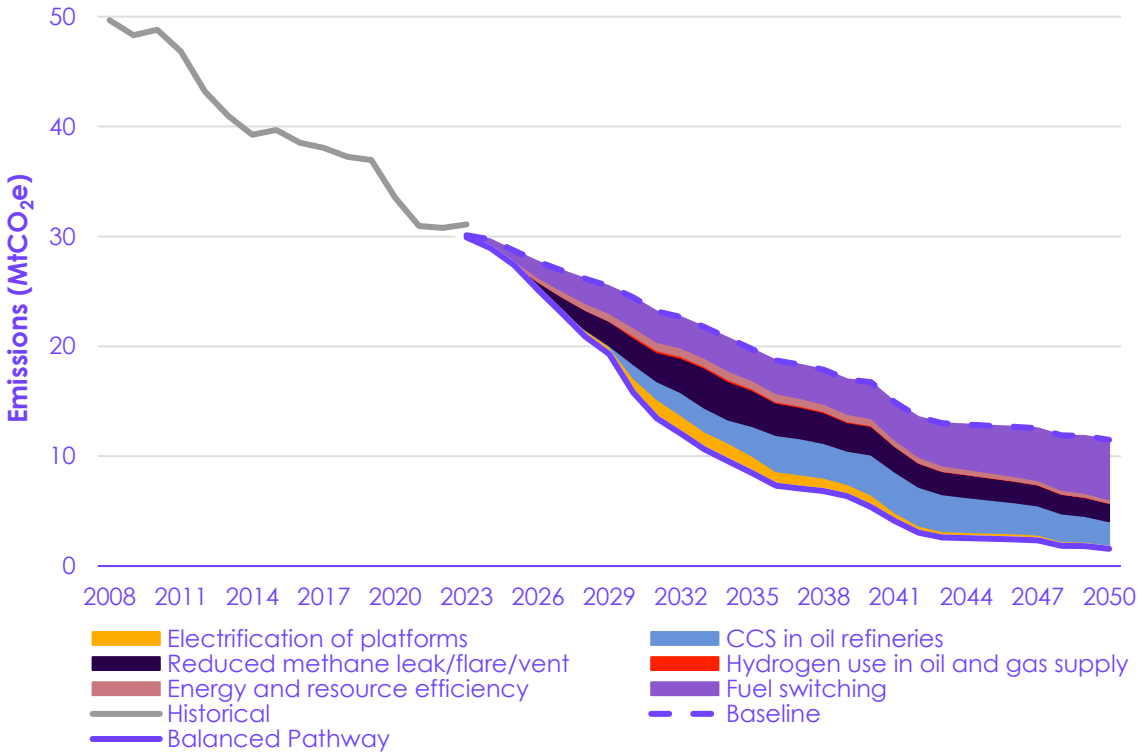
- Emissions from offshore oil and gas platforms and from onshore processing terminals are decarbonised mainly by electrification and then from reducing flaring and venting on platforms.

- Oil refineries are decarbonised through CCS. Demand for oil-based products across the economy determines the level of refinery capacity required.

- Methane leaks from the gas distribution and transmission networks are reduced using a combination of Leakage Detection and Repair (LDAR) and continuous monitoring technologies.

The largest share of emissions reduction in the pathway is due to economy-wide fuel switching away from fossil fuels (leading to lower output from refineries) and the second largest source is CCS processes adopted in remaining oil refineries. Smaller contributions come from reducing flaring and venting on offshore platforms, and methane leakage reduction in distributing gas (Figure 12.3).

Figure 12.3 Sources of abatement in the Balanced Pathway for fuel supply



Source: DESNZ (2024) *Provisional UK greenhouse gas emissions national statistics 2023;* DESNZ (2024) *Final UK greenhouse gas emissions national statistics: 1990 to 2022;* CCC analysis.
Notes: (1) Emissions starting point is lower than historical because we account for abatement from biomethane injection into the gas grid in the fuel supply sector, rather than spreading across all gas users; total economy-wide emissions are unaffected. (2) The increased emissions from production of low-carbon fuels are included as a reduction in the size of the 'Fuel switching' wedge.
Description: The largest source of abatement in fuel supply is fuel switching, and the second largest source is CCS in oil refineries. Smaller contributions also come from reduced flaring and venting on offshore platforms, and methane leakage from gas distribution.

The measures in our pathway

Table 12.1 summarises the measures for reducing emissions in the fossil fuel supply sector that are considered in our modelling, how these lead to emissions reductions, and the key factors that influence their uptake. The methodology used to develop the assumptions and analysis underpinning these is described in the rest of this section.

Table 12.1
Measures considered within our modelling for fossil fuel supply

Decarbonisation measure	How does this measure influence emissions in our modelling?	What are the key factors that affect uptake in our modelling?
Electrification on offshore oil and gas platforms and onshore processing terminals	These are electrical alternatives for powering offshore operations, moving away from diesel or gas generators and compressors. Heat pumps also replace most types of fossil fuel-fired boilers, used for heating and cooling processes offshore.	The rate of deployment is determined by the cost-effectiveness of electrification. The maturity and technology readiness of electrification is generally higher than hydrogen for low temperature heat. First power is available from 2029. The cost of connecting to a source of electricity was included in the NPV calculation (where a process has an electric abatement option).
Hydrogen generators	Hydrogen can replace gas-fired generators on oil and gas platforms. Given timing constraints on the availability and location of hydrogen production, only available in offshore settings from 2030.	Hydrogen was typically selected where alternative options were limited. The high cost of hydrogen fuel, its limited geographic availability and hydrogen supply infrastructure access restricts the selection of hydrogen options.
Reduced methane flaring and venting on offshore oil and gas platforms	Measures such as capturing the gas and switching from venting to flaring (where safety requires at least one or the other).	This measure was assessed by the NPV calculation and implemented if cost effective. It broadly aligns with regulatory guidance that mandated zero routine venting and flaring for all offshore activities by 2030.[6]
Reduced methane leakage in gas distribution	Methane leaks from the gas distribution and transmission networks are reduced using a combination of leakage detection and repair (LDAR) technologies and continuous monitoring.	This measure was selected if cost-effective. Leakage is also affected by the fall in economy-wide gas demand, though emissions reduction from lower consumption is captured in end-use sectors.
CCS at oil refineries	Applying CCS (modelled as retrofits) abates significant process emissions which have few viable alternative decarbonisation options.	CCS was selected by sites close to CO_2 pipeline infrastructure and access to a CO_2 terminal. These tend to be in clusters, such as Merseyside and Humberside. Availability of CCS starts from 2028.
Economy-wide fuel switching, and resource and energy efficiency improvements	Reducing demand for fossil fuels (primarily via economy-wide electrification of transport, heating, and industry) reduces the need for refining activity and hence emissions.	Demand for fossil fuels is based on sector-level modelling of the transition to Net Zero. In addition, small improvements from resource (material) and energy efficiency were assumed for each subsector.

12.2.2 Measures to decarbonise oil and gas platforms and terminals

Electrification

Electrification is now recognised as a principal component in attaining the most significant decreases in emissions across the UK offshore industry. Our Balanced Pathway adopts the earlier modelled date (2029) for first power published by the NSTA.[7]

Electrification using electricity supplied either from the UK mainland national grid or from offshore wind turbines is a primary route for emissions reductions. There are limited other routes to

decarbonise this subsector. The maturity and technology readiness level (TRL) of electrification technologies is generally higher than other measures to decarbonise offshore low temperature heat (i.e. hydrogen or biomass for boilers, generators, and compressors). Therefore, the majority of abatement results from electrification on offshore oil and gas platforms. Electrification of assets such as generators and compressors delivers 1.2 $MtCO_2e$ of abatement in 2040, which is at the upper bound of scenarios developed by the NSTA.[8]

Hydrogen

Hydrogen supply to decarbonise offshore processes is reliant on pipeline and storage infrastructure being in place, both from repurposing and decommissioning existing oil and gas infrastructure.[9] From 2030 hydrogen is assumed available in boilers and generators on offshore platforms, based on electrolytic hydrogen production scaling up from 2030. Low uptake in our modelling is driven by high fuel and infrastructure costs (see Chapter 1). Therefore, hydrogen adoption for heat demand on platforms achieves 0.1 $MtCO_2e$ abatement in 2040 across platforms and terminals.

Reduced venting and flaring

In 2022, one-seventh of emissions from offshore oil and gas production came from venting and flaring. The total volume of gas flared and vented reached its lowest level recorded in 2023 and represented a decrease of 63% since 2001.[10]

Our modelling assumes the amount of methane flared from offshore platforms and onshore processing terminals can be reduced by recovering the gas then sending it for onsite utilisation or sales. For venting occurring offshore, vapour recovery units are installed. By 2040, 0.4 $MtCO_2e$ of methane emissions are abated. The recent industry regulatory target to achieve zero routine flaring and venting by 2030 would further mitigate residual emissions from this process in oil and gas production.[11]

12.2.3 Measures to decarbonise oil refineries

Carbon capture and storage (CCS)

CCS is the main emissions reduction measure for remaining refinery production (after fuel switching from reduced economy-wide demand for oil), abating 3.6 $MtCO_2e$ in 2040. Refineries also serve the chemicals industry; abatement of these processes is covered in the industry sector (see Chapter 8).

- In the UK the future deployment of CCS for both industrial and refining processes is reliant on the development of CCS infrastructure, focused in industrial clusters. We have assumed CO_2 injection starts to become available in the most advanced clusters from 2028, with earliest modelled conversion seen in the early-2030s.

- We have assumed that CCS technologies in fossil fuel supply capture 90% of emissions until 2040, and 95% thereafter (see Chapter 18).

- Refineries convert to CCS where this is cost-effective to do so. Within the NZIP modelling three oil refineries modelled convert to CCS in England-based industrial clusters.

12.2.4 Other decarbonisation measures

Economy-wide fuel switching, and resource and energy efficiency

Decreasing demand for fossil fuels reduces the need for refining activity and hence emissions. Demand for oil falls by 84% between 2025 and 2050 in the Balanced Pathway, due to the electrification of transport, heating, industry, and other sectors. In addition, we assume a limited potential for resource (material) and energy efficiency improvements.

- This demand reduction equates to 4.5 $MtCO_2e$ emissions reduction in the fuel supply sector in 2040. We incorporate the closure of Grangemouth refinery in Scotland in 2025, and in the modelled pathway Pembroke refinery in Wales closes in 2040.

- Using energy more efficiently reduces operating costs while cutting emissions. Our modelling makes assumptions about the annual abatement that can be achieved through resource (material) and energy efficiency in each fossil fuel subsector, using a study from the University of Leeds and University of Manchester.[12] Energy efficiency abatement is applied in the modelling after resource efficiency measures, but before the model selects low-carbon technologies.

Reduced methane leakage in the gas grid

The Balanced Pathway applies monitoring, leakage and detection measures to identify and reduce leakage of methane. This is achieved currently by the iron mains risk reduction programme, replacing 'at risk' iron mains pipes with new plastic pipes, as leakage rates for plastic pipes are around 99% lower than for metallic pipes.[13] Uptake is modelled using cost-effective NPV decision-making within NZIP for gas transmission and distribution activities.

- Leak detection and repair (LDAR) is a measure that captures operational and maintenance (O&M) strategies to identify and repair/reduce fugitive leaks, alongside O&M continuous inspection.

- Continuous monitoring is assumed to capture 90% of fugitive methane emissions, whilst LDAR captures 40% to 80%.

Application of these measures abates 2.1 $MtCO_2e$ of methane emissions in the gas transmission and distribution networks in 2040.

Gas grid decommissioning

In the Balanced Pathway gas demand falls from 720 TWh in 2025 to 168 TWh by 2050, including a move to electrify home heating. This reduces the need for operating and maintaining the full extent of the existing gas distribution network.

While this is not a decarbonisation measure, we have incorporated costs for beginning the process of decommissioning the gas distribution network:

- Timing of the decommissioning process is uncertain as it depends on a range of factors including the rate of uptake in natural gas alternatives (e.g. electricity) and associated energy costs, the cost of transition (network and customers), liabilities and the regulatory framework, and scale of technical requirements.

- Based on an Arup study for the National Infrastructure Commission and Ofgem, we adopt the assumption that works to decommission 60% of the National Transmission System (NTS) and 100% of the Local Transmission System (LTS) (not used for gas or repurposed for hydrogen) start from 2045, and costs gradually start to be incurred.[14]

- We assumed decommissioning could occur once sufficient switching to low-carbon alternatives (e.g. heat pumps in buildings) has occurred.

12.3 The baseline for low-carbon fuels

Our baseline represents a scenario in which there is no further decarbonisation action by either the Government or the market in the low-carbon fuels subsector. See Chapter 1 for our general approach to baselines.

Our baseline for low-carbon fuel emissions is based on the following assumptions:

- Sustainable aviation fuel (SAF) is projected forward at a constant level to 2050 from 2023 historic data at 1 TWh/year of HEFA in the aviation sector baseline. The 1 TWh/year was calculated using provisional 2023 UK Government fuel supply statistics.[15] All other SAF types are assumed to be zero to 2050 in the baseline.

- There is no use of low-carbon hydrogen (produced for direct consumption or use in synthetic fuel production), synthetic aviation and shipping fuels, or other low-carbon fuels (e.g. ammonia).

- Existing use of bioenergy in the fuel supply sector is currently primarily captured in the emissions inventory via biomethane injected into the gas grid. We reflect this use in our fuel supply baseline. Existing use of bioenergy in electricity supply is covered in the electricity supply Chapter 10.

  – The GHG inventory accounts for biomethane in the gas grid using data from the Digest of UK Energy Statistics on the quantity of biogas injected into the grid. The fossil CO_2 factor of all downstream gas use is reduced to reflect the proportion of gas in the grid that is biogenic.

  – We assume gas supplied via the gas grid is fossil gas, and separately account in the fuel supply sector for emission savings from biomethane injection.

12.4 Pathway assumptions and modelling for low-carbon fuel supply

12.4.1 Modelling the Balanced Pathway for low-carbon fuel supply

The modelling approach for low-carbon fuels covers hydrogen, the supply and best-use allocation of bioenergy, and the production of synthetic fuels used in aviation and shipping. See Chapter 1 for our general approach to pathway analysis.

12.4.2 Hydrogen

For the analysis underpinning low-carbon hydrogen production, we commissioned the consultancy AFRY to undertake modelling using their BID3 model. The model co-optimises the electricity and hydrogen production and storage systems simultaneously, at an hourly resolution for electricity supply and a 6-hourly resolution for hydrogen supply. Further details on the modelling approach are set out in the electricity supply Chapter 10.

- **Demand.** Hydrogen demand, including hydrogen required to produce synthetic fuels used in aviation and shipping, is summed from other sectors. Hydrogen use for electricity

generation was determined within the optimisation of the BID3 model. In the Balanced Pathway total economy-wide hydrogen demand increases to nearly 60 TWh in 2040.

- **Supply.** Production of low-carbon hydrogen is available through electrolysis ('green hydrogen'), methane reformation with CCS ('blue hydrogen'), and biomass gasification with CCS (a form of greenhouse gas removals). Both blue and green hydrogen technologies are dispatched on a least-cost basis. This broadly means that electrolysers will operate when the cost of power is lower than the variable cost of blue hydrogen production. We assume hydrogen is produced via electrolysis using surplus renewable generation, which is consistent with our previous published analysis.[16] Biomass gasification is allocated available resource from best-use cross-economy analysis.

Our modelling assumes hydrogen is produced domestically, optimising it with use in the electricity supply sector and production linked to the availability of renewable capacity. However, there is potential for imports of electricity, fossil gas, and potentially biomass to be used to produce hydrogen.* Direct imports of hydrogen are not assumed given likely challenges and costs involved in transportation.

Electrolysis

Electrolytic hydrogen, produced using zero-carbon electricity from renewable sources, is the main production route in 2040, providing over half of supply (54%).

- In the Balanced Pathway there is 10 GW of installed electrolyser capacity in 2040, doubling by 2050. This produces 33 TWh of hydrogen in 2040, rising to 72 TWh in 2050. This level of hydrogen production is not sufficient to meet all hydrogen demand, so other sources of low-carbon hydrogen will be needed.

- This is due to constraints on the roll-out of renewables (see electricity supply Chapter 10 for deployment rate assumptions), hydrogen storage, and the rate of electrification of the wider economy, for which use of zero-carbon electricity from renewables should be prioritised over hydrogen production given the much higher emissions saving potential.

- We project how costs would develop in our pathway based on observed learning rates and expectations about how these may continue. Table 12.2 shows the electrolyser cost assumptions used in the Balanced Pathway. We use long-run variable costs (LRVCs) to value changes in energy consumption (Chapter 1).

  - Learning rates represent the rate of cost reduction per doubling of deployment. We applied a learning rate of 18% to electrolysers, based on a global capacity deployment pathway from International Energy Agency scenarios.[17] This is combined with UK government capex estimates.[18;19] Chapter 10 sets out more detail on our approach to learning rates.

Methane reformation with CCS

This method splits methane gas molecules into CO_2 and hydrogen, with CCS to capture 95% of the resulting emissions. In 2040 this blue hydrogen makes up 44% of hydrogen supply and falls to around 30% in a more supporting role by 2050.

- This process is capable of producing low-carbon hydrogen at scale. However, it is not zero-carbon, with lifecycle emissions savings of up to 85% relative to unabated fossil gas. The

* See Section 6.4.2 of our Seventh Carbon Budget advice report on contingency action for less reduction in bioenergy imports allowing more BECCS hydrogen production.

emissions impact of blue hydrogen production is limited (i.e. less than 0.5 $MtCO_2e$ in all years to 2050 in the Balanced Pathway), and these emissions are offset by removals.

- The main constraint on blue hydrogen production is the availability of CCS. Our modelling assumes blue hydrogen production is sited at industrial clusters and becomes available as CCS is deployed from 2028.

- In the Balanced Pathway there is 4 GW of blue hydrogen production capacity in 2040, rising to 7 GW in 2050. This produces 27 TWh of hydrogen in 2040. This level of capacity is capable of meeting hydrogen demand even when there is less electrolytic hydrogen produced in a low wind year.

Biomass gasification with CCS

Gasification is a mature technology that heats a solid feedstock, such as biomass wood pellets, in a reduced concentration atmosphere (to avoid combustion) comprising air, oxygen or steam to produce a synthetic gas (syngas). Hydrogen is then separated out of the syngas.

Hydrogen production via this process is not expected to comprise a major proportion of future hydrogen supply, forming 2% of hydrogen supply in 2040 and 4% in 2050. This is due to constraints on sustainable biomass feedstock availability, and alternative uses in other forms of bioenergy with CCS (BECCS). However, keeping open the option of deploying bio-hydrogen will be important given the value of the removals it provides; 2.5 $MtCO_2$ in 2050, assuming a 90% capture rate.

Table 12.2 sets out key technology assumptions included in our modelling.

Table 12.2
Key assumptions in the Balanced Pathway - Hydrogen

Capital cost (£/kW)		**2030**	**2035**	**2040**	**2050**
Hydrogen production	Electrolyser (PEM)	264	196	185	185
	Methane reformation with CCS	520	488	458	403
	Hydrogen salt cavern storage	132	132	132	132
	Hydrogen medium-pressure storage tank	80	80	80	80
Efficiency (%)		**2030**	**2035**	**2040**	**2050**
Hydrogen	Electrolyser	75%	77%	78%	81%
	Methane reformation with CCS	80%	80%	80%	80%
	Biomass gasification with CCS	54%	55%	56%	60%

Source: BEIS (2021) *Hydrogen Production Costs 2021*; CCC (2023) *Delivering a reliable decarbonised power system*; IEA (2023) *World Energy Outlook 2023*; Schmidt et al (2019) *Projecting the Future Levelized Cost of Electricity Storage Technologies*, Joule, 3(1), 81-100.
Notes: All costs are real £2023.

Networks and storage

A new infrastructure for transportation and storage of hydrogen will be required for the delivery of the Balanced Pathway, to connect supply and demand both geographically and over time.

- **Hydrogen transportation.** A hydrogen transmission network will be needed to connect production with sources of storage and demand, and to provide system resilience and encourage competition between hydrogen producers.

  - We have modelled a transmission network that begins operation in the early-2030s to join up initial industrial clusters in the north-east of England, first connecting Teesside and Humberside, followed by regional expansion to the west of England and Scotland – facilitating flows of green hydrogen produced from offshore renewables and meeting industrial demand in northern clusters.[20] Around 2040 the network extends to Wales and the south of England.

  - Network capacity and build was not optimised within the modelling but broadly aligned with phases identified in Project Union, and on modelling undertaken for our 2023 report on *Delivering a reliable decarbonised power system*. Given lower levels of hydrogen demand in the Seventh Carbon Budget compared to previous modelling, it is possible a less extensive transmission network could be required in practice.

  - We only model a hydrogen distribution network for some localised industrial applications (see Chapter 8). Given the declining role of natural gas, in the longer-term the gas distribution network will likely need to be decommissioned.

- **Hydrogen storage.** Long-term storage of hydrogen will play an important role in the future energy system. This will help provide a low-carbon source of generation for balancing the electricity system and managing low wind periods, through use in hydrogen-fired power stations.

  - Storage will help balance the electricity system by providing a source of fuel as and when dispatchable low-carbon electricity generation is required.

  - Our previous analysis showed that the role of long-term storage will be more likely for managing periods of low wind availability rather than seasonal variations in demand.[21] Offshore wind will be the backbone of the future energy system, and its generation will be well correlated with the seasonal pattern of demand (i.e. both are higher in winter).

  - Hydrogen storage via pressurised tanks and/or salt caverns helps to bridge mismatches between electrolytic hydrogen production and hydrogen demand. To provide a flexible solution to meet variable demand from low-carbon dispatchable electricity generation, BID3 builds out salt cavern capacity to cost-effectively store green hydrogen produced during periods of surplus renewable energy. Blue hydrogen is primarily run baseload to produce hydrogen where demand is relatively constant over the year, for example for use in industry. It is also used to top-up supply and stores when insufficient green hydrogen is available to meet demand.

  - Our Balanced Pathway has 3 TWh of hydrogen storage capacity in 2040 and increases to 5-9 TWh in 2050.

Scotland, Wales and Northern Ireland

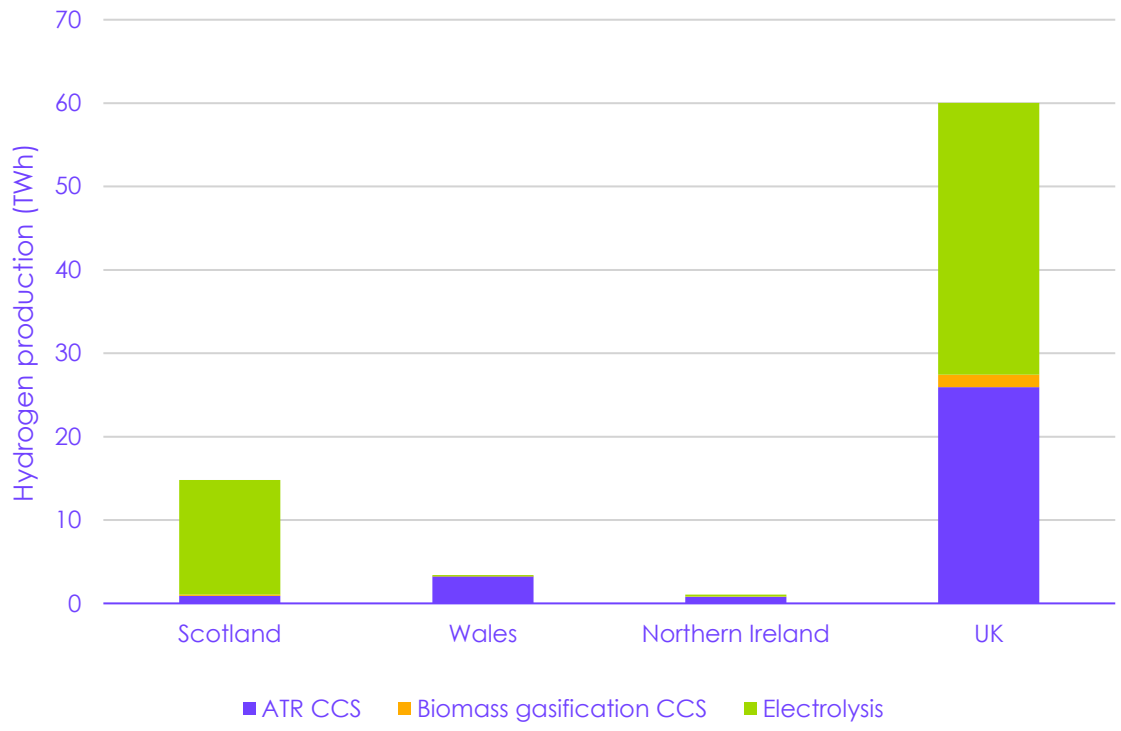
BID3 models the electricity and hydrogen systems on a zonal basis. Renewable capacity is allocated to energy zones, using existing capacity information and pipeline projects for planned capacity (see electricity supply Chapter 10). This therefore affects the regional balance of green and blue hydrogen production across the UK (Figure 12.4):

- **Scotland.** Electrolysis is the dominant production route for hydrogen in Scotland, providing 14 TWh in 2040. This is produced via surplus low-carbon electricity as wind and solar generation is proportionally higher than Scotland's regional demand requirements. The region supplies hydrogen to demand in industrial clusters in North East England via a

pipeline network from the early-mid-2030s. This drives the UK balance to be slightly in favour of production via electrolysis in 2040.

- **Wales and Northern Ireland.** Blue hydrogen is the main route for hydrogen supply in Wales and Northern Ireland - 4 TWh in total in 2040 - based on location of renewables and availability of CCS in industrial clusters in South Wales and Derry/Londonderry. Of the 0.5 $MtCO_2e$ of UK-wide GHG emissions from this production process, Wales and Northern Ireland production combined make up less than one-sixth of these emissions.

Figure 12.4 Hydrogen supply in 2040 in Scotland, Wales, Northern Ireland and the UK, by production route



Description: In 2040 hydrogen supply in the UK is a roughly even balance between green and blue hydrogen, with a small contribution from biomass with CCS. In Scotland, most hydrogen supply is from green hydrogen. In Wales and Northern Ireland most hydrogen supply is from blue hydrogen.
Source: CCC and AFRY analysis.

12.4.3 Bioenergy

Bioenergy and waste supply estimates are provided by land use, agriculture and waste sector analysis. Resources are allocated to end-use sectors starting from known 2022 positions, transitioning to best use (maximal GHG savings) by 2050. This analysis supports the need for bioenergy to maximise sequestered CO_2 and displace high-carbon fossil fuels, especially in sectors with few low-carbon alternatives which can't electrify. The availability of CCS from the late-2020s causes convergence between all routes in terms of GHG abatement, towards CCS applications.

The approach identifies the sustainable supply of biomass and bioenergy and then allocates these to best uses. Figure 12.5 sets out how these elements are incorporated in our analysis.

- Bioenergy and waste supply are determined by land, agriculture and waste sector modelling assumptions and projections (see Chapters 17, 9, and 13 respectively).

- Given bioenergy and waste are scarce resources, best-use analysis identifies the highest value applications and transitions resource to those uses over time.

  - We identify the subset of biomass applications that are considered 'best use', based on total CO_2 sequestered and displaced, costs, and efficiencies of production methods. The best uses of biomass are with CCS (where it provides a source of greenhouse gas removals), and in sectors where there are limited other options for reducing emissions (e.g. in aviation as SAF, with CCS applied to the production process). Other uses of biomass are phased out as far as possible in the longer-term. By 2050, almost all the bio-resource used in our pathway is with CCS (BECCS).

  - We include all potential best-uses of biomass in our modelling, to ensure the optionality of these abatement routes is preserved. These routes have similar emissions saving potential, and there is uncertainty over which uses will be most competitive in the long-term.

  - Allocation of biomass resource to best-use sectors is based on constraints at the sector level, taking into account abatement costs, timings, and alternative options for reducing emissions (see sector chapters for further details).

- 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). Costs of production with CCS (BECCS) are captured in the removals sector (see Chapter 18).

Bioenergy supply

Sustainable bioenergy plays an important role in providing low-carbon alternative fuels for many sectors. Overall domestic bioenergy supply grows to around 100 TWh in 2040 in the Balanced Pathway and 125 TWh in 2050. We assume a declining role for imported biomass given global governance and sustainability challenges.

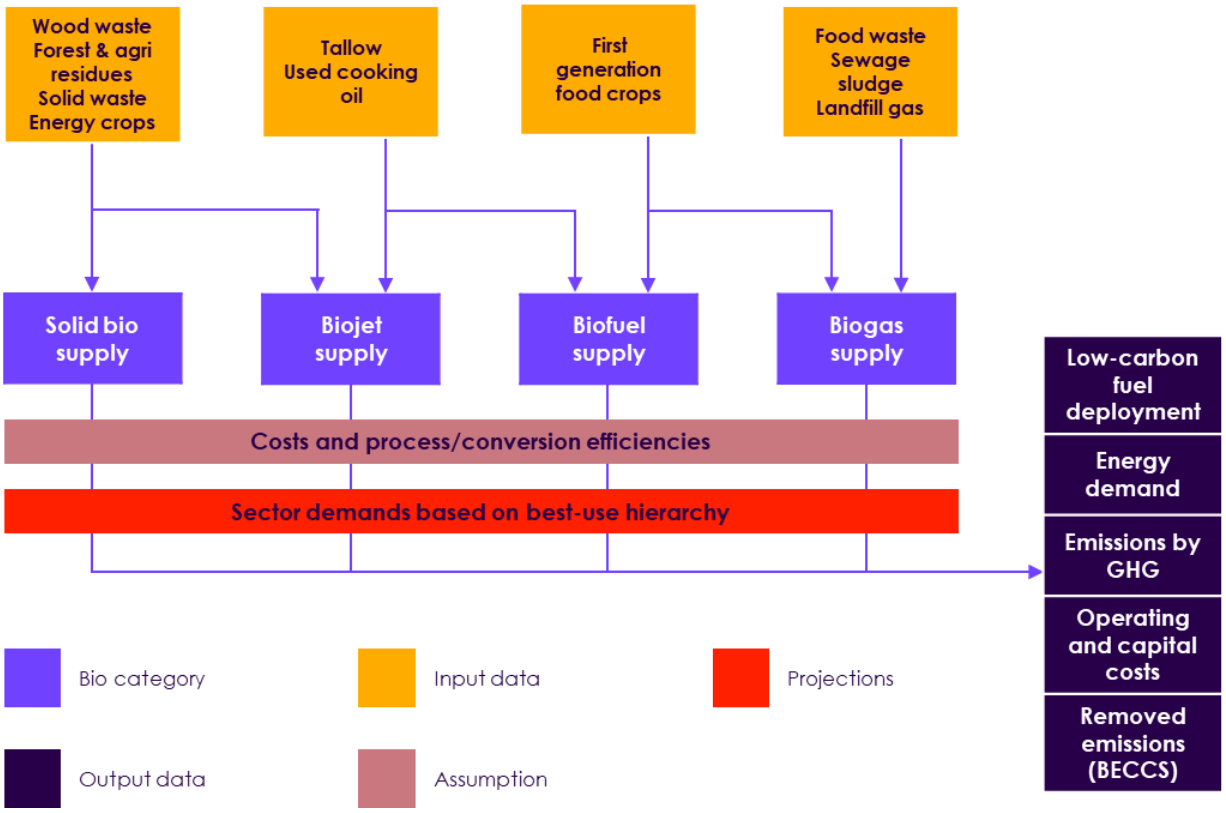
- Most growth in domestic bioenergy supply comes from increasing production of energy crops (i.e. miscanthus, short rotation coppice, short rotation forestry), with smaller contributions from forestry and agriculture residues, and diversion of waste materials.

- Domestic feedstocks are expected to play a larger role than biomass imports. The share of domestic bioenergy supply grows from around 75% in 2030 to 85% in 2040 and by 2050 meets almost all demands modelled in the Balanced Pathway.

- In 2040 biomass imports are 14 TWh whilst biofuel imports supply 3 TWh to meet falling demands in surface transport and industrial and agricultural machinery.

Several different bioenergy production routes are included in our analysis, along with the use of biogenic wastes (Figure 12.5). Feedstock costs were held fixed over time, whereas conversion processes have been assumed to become cheaper and more efficient over time. Plant lifetimes are assumed to be between 25 to 30 years for all plants converting biomass, and 25 years for those converting wastes. 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, and carbon capture rates increase over time. The added costs of CCS include costs of downstream transport and storage of CO_2.

Figure 12.5 Sources of bioenergy



Description: Our modelling of bioenergy supply is based on assessments of the availability of various feedstocks, the costs and efficiencies of production processes, and the demands by sector based on our assessment of the best use of this limited resource.
Source: CCC analysis.
Notes: Solid waste includes municipal solid, commercial, and industrial waste. Biofuels are biodiesel and bioethanol.

Solid biomass

Domestic feedstocks (forestry and agricultural residues, perennial energy crops, and wastes) and imported biomass feedstocks are supplied directly (without conversion) to the power, industry, buildings and agriculture sectors. These end-uses increasingly transition to CCS or phase out over time.

- **Energy crops.** Domestic energy crop production is a mix of miscanthus and short rotation coppice, with short rotation forestry available longer term, beyond 2050. Current rates of delivery are negligible, and use of energy crops is currently low. The annual rate of deployment is based on the rate of land transitioning from agriculture and the availability of land-types (see land use Chapter 17). Land allocated to energy crop planting reaches 710,000 hectares of the UK by 2050, which equates to 3% of UK land area.

- **Forest residues.** Both broadleaf (hardwood) and conifer (softwood) residues from cleaning, thinning or felling woodlands are included in our analysis. The softwood and hardwood production forecasts from Forest Research were used to estimate the timber and wood fuel production from existing UK forests.[22;23] These are underpinned by the CARBINE Forest model and detailed harvesting assumptions (see land use Chapter 17).[24]

- **Agricultural residues.** Dry straw resources are agricultural residues based on projections of crop areas for wheat, barley, oat, and oilseed rape. Poultry litter resource is driven by falling poultry livestock numbers, which reduce 26% between 2022 and 2050.

- **Waste wood**. Waste modelling outputs determine that the supply of waste wood remains steady at around 13 TWh from 2028 onwards. Current informal supplies of waste wood for building heating of around 7 TWh are assumed to phase down from 2035 to 6 TWh in 2050.

- **Biogenic waste**. In 2040, 27 TWh of the biogenic component of municipal solid waste and waste from commercial and industrial processes are made available as biogenic resource for fuel production. There is assumed a near-elimination of biodegradable waste sent to landfill from 2028, and a near-elimination of all other waste to landfill from 2045.

- **Biomass imports.** Our pathway has a transition away from imports towards domestically produced biomass, assuming imports decline at the rate of expansion of the domestic supply to meet demand. This acts as a constraint on total supply available to allocate to end-use sectors.

Biofuels and biojet fuels

- **Biodiesel**. UK supplies are assumed to vary with used cooking oil (increases as population increases, based on ONS reported population forecasts) and tallow (declines with agriculture sector livestock numbers), based on waste sector modelling.[25] These are combined with a process efficiency to convert to biodiesel/biojet fuel. Conventional routes to biodiesel involve transesterification or hydrotreatment of waste fats/oils (biodiesel FAME) or solid biomass feedstocks can be gasified then undergo Fischer-Tropsch (FT) catalysis for conversion into biodiesel, with CCS (biodiesel FT).

- **Bioethanol.** Unleaded petrol used in light duty vehicles since 2021 contains a 10% blend of bioethanol by volume, equivalent to 7% by energy.[26] Domestic bioethanol is produced by fermenting arable crops in existing facilities. As petrol demand falls over time, bioethanol imports are assumed to phase out first before domestic bioethanol production.

- **Biojet.** As biodiesel demands from transport fall through the 2030s, waste fats and oils (HVO or HEFA) are converted into biojet. Solid biomass is also used to produce biojet.

- **Biofuel imports** are phased out by 2040.

Biogas

In the Balanced Pathway biogas supply is considered from a range of routes including food waste, sewage sludge, livestock manures, landfill gas, and crops based on inputs from waste and agriculture sector analysis:

- **Food waste.** The amount of biogas available from anaerobic digestion of food waste is determined by food waste collection rates (which increase in our pathway), and the level of food waste available for collection (which decreases in our pathway) (see waste Chapter 13). Overall, this provides 5 TWh of biogas supply in 2040.

- **Sewage sludge.** Supply scales with increasing population based on ONS reported population forecasts, and the increasing use of advanced AD which produces more biogas per tonne of sewage sludge treated. This route provides 6 TWh of biogas in 2040.

- **Livestock manures.** Assumed to be used on-farm (e.g. for fertiliser) as these uses are assessed to be more cost-effective than AD, and so none are available as biogas or upgraded to biomethane supply produced via AD. If all animal waste were to be used for AD, then additional dry feedstocks would be required with potential land use implications.

- **Landfill gas**. Biogas available from landfill is determined by the amount of biogenic waste sent to landfill (which is largely phased out by 2028) and the level of capture rates (assumed

to increase). The net impact of these is that landfill gas declines, from 9 TWh currently to 4 TWh biogas supply in 2040.

- **Crops.** The difference between waste sector biogas supply and DUKES UK biogas production is assumed to be maize silage AD. We model a transition away from first generation crops that compete with food production, and maize AD is therefore assumed to phase out by 2035 from 8 TWh/year in 2025. No additional energy crops are grown for biogas supply due to other competing land use and carbon savings from other uses.

Overall, in 2040 15 TWh of biogas supply is available from anaerobic digestion of food waste and sewage sludge, and from landfill gas. While increased supply of biogas could be available by diverting biomass from other uses, this would represent a re-distribution of emission savings rather than additional savings. Furthermore, the scope for this may be limited by the availability of alternative abatement options to compensate for lower biomass allocation to end-use sectors. If this were to be the case, it is possible that transfer of biomass resource to biogas/biomethane production could increase economy-wide emissions.

Bioenergy demand

Supply is allocated to sector uses in our modelling, using sector analysis on demands for each bioenergy supply route (biomass, biofuel, biogas and bio-waste), alongside maximising the CO_2 sequestered across the economy from using scarce bioenergy resources.

Electricity supply, buildings, and industry

Continued use of unabated solid biomass is not a best use of biomass in either electricity supply or industry. We therefore assume a transition to uses with CCS.

- Power BECCS is assumed to start substantively in 2032, with a small scale up in 2031 (see removals Chapter 18). This is the largest sector using biomass in 2040 (48% of supply).

- The next largest sector demand is from industry (16% of supply), prioritised in cement and chemicals subsectors that deploy CCS (see industry Chapter 8).

In the Balanced Pathway, biogas is predominantly upgraded and blended into the gas grid as biomethane, displacing natural gas, with this role declining from 2030 at the rate that gas demand falls as heating is electrified. From this point, the biogas freed up becomes increasingly available for use in combined heat and power (CHP) processes in power (7 TWh in 2040) and industry (3 TWh in 2040) sectors, reducing the need for gas imports. Based on CCS network infrastructure rollout and availability (Chapter 1) we assume that from 2030 biomethane upgrading facilities feed their CO_2 into a CCS network.

Surface transport and off-road machinery

Transitional use of biofuels such as FT and FAME biodiesel and bioethanol can help reduce emissions in surface transport and off-road machinery (including in industry and agricultural equipment).

- Using biofuels to decarbonise the surface transport fleet (particularly in heavy goods vehicles) has a declining role over time – falling to 2 TWh in 2040 and 0.1 TWh in 2050 – as other low-carbon options such as EVs become increasingly available, reducing the potential emissions savings below those offered by other uses.

- Use of biofuels in off-road machinery declines over time. In agriculture, its use is phased out by 2040. In industry, usage peaks in the early-2030s at 1.3 TWh and falls to 0.1 TWh in 2050.

- As use of biofuels declines in these sectors, their resource increasingly becomes available for other applications including in aviation.

Waste

After re-use and recycling, residual waste not exported or landfilled is predominantly incinerated in energy-from-waste plants, all of which fit CCS by 2045 to capture the fossil and biogenic CO_2 emissions resulting from the mixed fossil/biogenic waste fractions (see waste Chapter 13). From 2028, where a near elimination of biodegradable waste to landfill increases the volume of residual biogenic waste, biogenic waste-based aviation fuel produced with CCS makes up a growing share of demand (see below).

Aviation and shipping

Supply of low-carbon aviation and shipping fuels is split between bio-derived routes (19 TWh in 2040), and synthetic fuels (3 TWh). Allocation to aviation and shipping uses is based on availability of biogenic resources, demand in other sectors, and GHG savings achieved for each end-use of bioenergy, compared to the next best decarbonisation alternative (e.g. electrification, other low-carbon fuels).

Biofuels

- **Aviation biojet** is modelled through three production routes utilising domestic sources of biomass, municipal waste, and waste fats and oils, plus imports (Figure 12.6).
  - **Biomass-to-liquid.** Solid biomass feedstocks are gasified then converted into an FT aviation fuel, with CCS applied to the production process from 2033. Starting from 2029, FT biojet ramps up to meet 8% of aviation fuel demand in 2040.
  - **Waste-to-liquid.** The biogenic fraction of waste is converted to FT biojet with CCS. Given similar GHG savings, residual biogenic wastes are assumed to be increasingly diverted from energy-from-waste plants, providing 4 TWh of biojet in 2040 and contributing to 3% of aviation fuel demand.
  - **Waste fats and oils (HEFA).** Biogenic waste fats and oils are converted to Hydroprocessed Esters and Fatty Acids (HEFA) biojet. As biodiesel demands from surface transport reduce through the 2030s, waste fats and oils are instead converted into biojet. This fuel route peaks in 2035 to meet 6% of aviation fuel demand, falling to 1% in 2040 when HEFA imports are phased out.
  - **Imported aviation biofuel (HEFA).** A proportion of SAF production is assumed to be based on imported HEFA. This peaks at 7 TWh imported in 2035 and phases out by 2040. This helps manage the sector's transition away from fossil fuels and increases diversity of SAF production routes (across biomass, waste, and synthetic fuels).
- **Shipping biofuel.** Waste-based biodiesel plays a small role in reducing emissions from half of existing inland waterways and leisure vessels by 2050.[27] Demand reaches 1.5 TWh in 2040. Biofuels are not adopted in other segments of the shipping sector based on limited resource achieving greater emissions savings in other sector applications.

Synthetic fuels

Synthetic fuels combine low-carbon hydrogen with a source of carbon recovered from the atmosphere, for example via direct air capture, to make carbon-neutral fuels for use in aviation and shipping.

- The supply of synthetic jet fuel meets the residual demand for SAF after biogenic based resources have been allocated to produce SAF. This accounts for technological and best-use constraints in the fuel supply and removals sectors, as well as the expected high cost of synthetic fuels (see aviation Chapter 11).

- Demand for synthetic methanol in shipping is determined by cost-optimisation in DfT's maritime emissions model for fuel switching from a range of low-carbon fuels and electricity.

- Since IPCC inventory guidelines are unclear regarding reporting of emissions savings from such fuels, we assume that all synthetic fuels are produced domestically and are available from the same year direct air capture becomes available, 2035.*

In the Balanced Pathway, 13 TWh of synthetic fuels are produced in 2040, which requires 18 TWh of low-carbon hydrogen and 3 $MtCO_2$ via direct air capture.

- 6 TWh of synthetic aviation fuel is assumed to contribute to the mix of SAF in 2040, representing 4% of total aviation fuel demand.

- We assume that 1.33 TWh of hydrogen is required per 1 TWh of synthetic SAF produced using direct air capture, and 1.25 TWh of hydrogen per 1 TWh of synthetic methanol produced.[28;29;30]

The production of synthetic fuels in the Balanced Pathway is influenced by the current international emissions accounting framework:

- Aviation and shipping fuels are presently supplied from global markets.

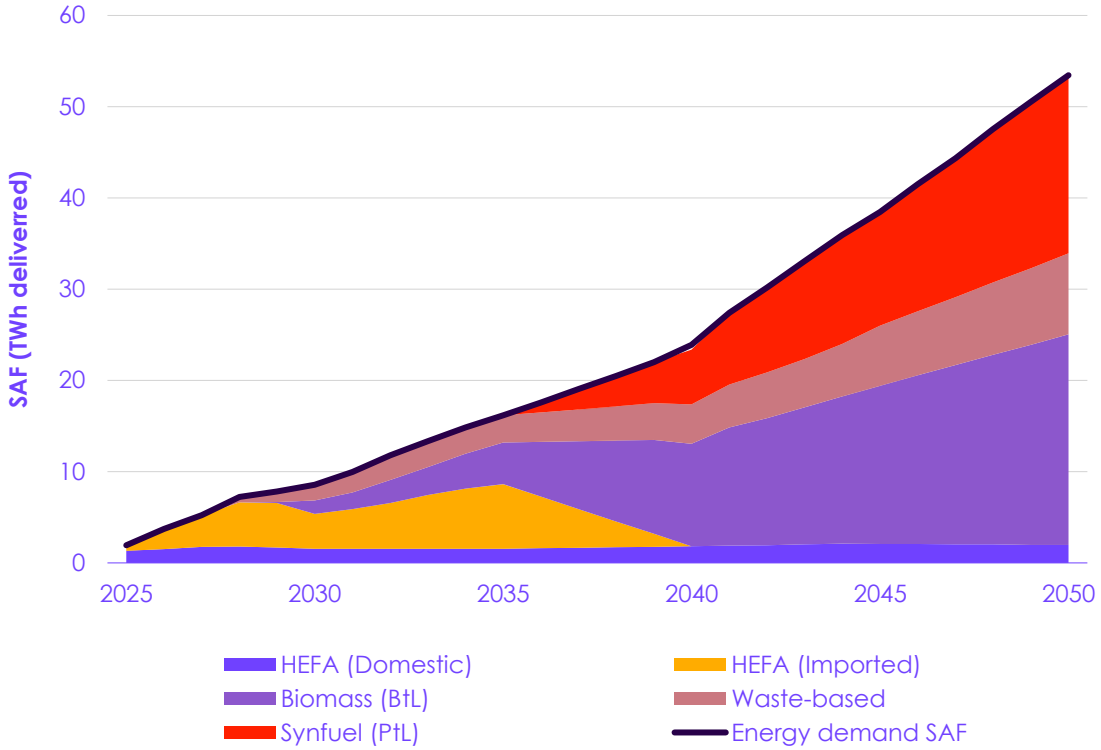
- It is likely that the most competitive locations to produce synthetic fuels in the future will be where there is access to abundant low-cost renewable energy and large-scale fuel production supply chains, supplying global markets including import to the UK.

- However, international emission accounting rules for synthetic fuels are currently unclear. They could require emissions savings for captured carbon to be counted in the country where the capture takes place. This would mean emissions savings from synthetic fuels are counted in the producing country not the place of fuel combustion (this does not apply to other low-carbon fuels that are not based on captured carbon, including biofuels, hydrogen, and ammonia).

- In the Balanced Pathway, we have assumed that all synthetic fuel used in the UK is produced domestically, enabling the emissions savings to contribute to UK emissions reduction.

* Although DAC becomes substantively available in 2035, synthetic fuels in the shipping sector begin to be used in 2033 due to the model smoothing results over five years.

Figure 12.6 Sustainable aviation fuel (SAF) feedstock mix in the Balanced Pathway



Source: CCC analysis.
Description: Supply of sustainable aviation fuel (SAF) increases over time. By 2050 the largest source of SAF is biomass based, the next largest source is synthetic fuel, and a smaller contribution comes from waste-based fuels.

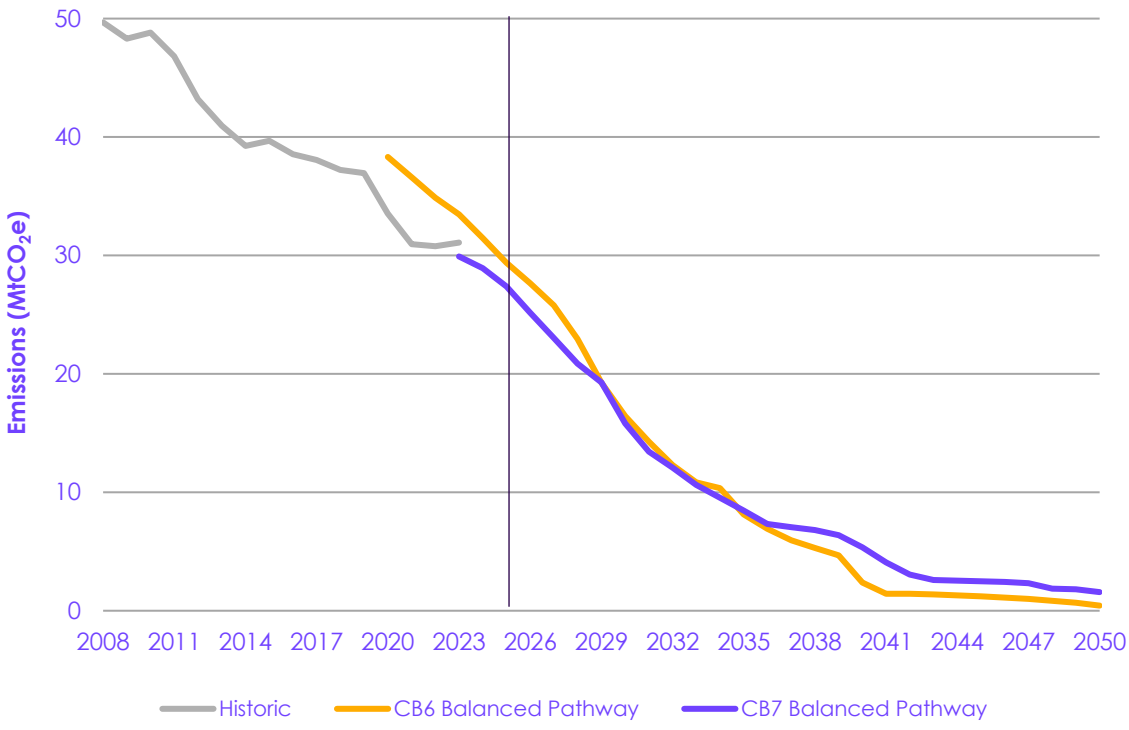
12.5 Changes since our Sixth Carbon Budget advice

12.5.1 Comparison with our Sixth Carbon Budget pathway

Emissions have fallen more quickly than expected in our Sixth Carbon Budget pathway, resulting in our Balanced Pathway starting slightly below the level that had been expected. * Going forward, emissions in both pathways fall similarly, with a slightly higher level of residual emissions remaining in 2050 in our Balanced Pathway than in our previous advice (Figure 12.7).

* All comparisons in this section compare the Balanced Pathway in this advice with the Balanced Net Zero Pathway in our Sixth Carbon Budget. Our Sixth Carbon Budget advice also included four other exploratory pathways, which are not discussed here. Data for those pathways can be found in our Sixth Carbon Budget advice.

Figure 12.7 The Balanced Pathway for fuel supply compared to our Sixth Carbon Budget advice



Description: Emissions from fuel supply have been falling historically, and continue to reduce in both the Sixth Carbon Budget (CB6) and Seventh Carbon Budget (CB7) pathways out to 2050. The CB7 pathway finishes at a slightly higher level of emissions in 2050 than the CB6 pathway.
Source: DESNZ (2024) *Provisional UK greenhouse gas emissions national statistics 2023*; DESNZ (2024) *Final UK greenhouse gas emissions national statistics: 1990 to 2022*; CCC analysis.
Notes: Emissions starting point is lower than historical because we account for abatement from biomethane injection into the gas grid in the fuel supply sector, rather than spreading across all gas users; total economy-wide emissions are unaffected.

12.5.2 Emissions changes since our Sixth Carbon Budget advice

Several developments in UK fossil fuel extraction and refining since 2020 mean emissions have diverged from our Sixth Carbon Budget pathway.

- Over the period 2019 to 2023, emissions in fossil fuel supply have fallen faster than envisaged in the Sixth Carbon Budget pathway.
- The largest reduction in emissions occurred in 2020 and 2021. This is likely to reflect the impact of the COVID-19 pandemic, which was not fully captured in the CB6 analysis.
- Petroineos announced that refinery operations would cease at Grangemouth in the second quarter of 2025. This closure decision has been incorporated into modelling of pathway emissions. In 2022 the refinery emitted around 1 $MtCO_2e$.

12.5.3 Key pathway differences compared to our Sixth Carbon Budget advice

There are several key areas in which the deployment rates, measures included, or underlying assumptions in our updated Balanced Pathway have been revised since publication of our Sixth Carbon Budget advice in 2020. These include:

- **Hydrogen demand.** Hydrogen demand in 2050 (96 TWh) is lower than presented in our Sixth Carbon Budget pathway (225 TWh). This reflects lower demand from industry, no hydrogen demand for heating buildings, and no domestic hydrogen used to produce ammonia for shipping.

- **Biomass supply.** Total supply in 2050 is under half the level modelled in our Sixth Carbon Budget advice. This reflects lower supply of both domestic and imported biomass.

  – Domestic supply is one-third (37 TWh) lower in the Balanced Pathway in 2050, compared to the Sixth Carbon Budget pathway in 2050. This is due to limited progress in tree planting, and lower estimates of forest residue availability (especially from hardwood).

  – Imported biomass was 52 TWh in 2050 in the Sixth Carbon Budget pathway, but is phased out by 2050 in the present advice. This reflects a Committee decision to minimise imports, given a lower overall requirement for removals (see Chapter 18) and governance and sustainability challenges around imports.

- **Delays to delivery.** The previous UK Government committed to having 1 GW of low carbon hydrogen capacity by 2025.[31] However, significantly less capacity (125 MW) has been procured through the first Hydrogen Allocation Round (HAR1).

- **Sustainable aviation fuel.** We have increased our projected share of aviation fuel that is SAF, in recognition of the progress that has been made (notably the implementation of the UK's SAF mandate) since our previous advice. However, our Seventh Carbon Budget SAF trajectory is lower than the Government's (see Chapter 11).

- **Fossil fuel supply.** In the Sixth Carbon Budget pathway, the emissions reduction potential for offshore oil and gas platforms was based on the then Oil and Gas Authority's highest electrification scenario, which accelerated electrification in the 2020s and 2030s. In this report the emissions baseline is aligned to the NSTA's business-as-usual pathway, and the decarbonisation pathway for offshore platforms is determined by the cost-effectiveness of electrification measures. The overall impact of this change is that emissions are now 0.5 $MtCO_2e$ lower in 2050 in the Balanced Pathway compared to our Sixth Carbon Budget advice.

12.6 Uncertainties and sensitivity analysis

There are inevitably uncertainties around how the key drivers of the Balanced Pathway will develop over the next 25 years. See Chapter 5 for our general approach to uncertainty and contingency analysis, including descriptions of the methodology behind sensitivity tests that apply across multiple sectors.

Some of the key uncertainties in our analysis of the fossil fuel sector include:

- **Timing of first power to offshore production.** Published NSTA scenario analysis suggests first power dates range between 2029 and 2032, which will affect the level of abatement that could be achieved from electrifying offshore facilities.[32]

- **Hydrogen use in electricity supply.** There is uncertainty around the balance of technologies for providing low-carbon dispatchable generation (e.g. between hydrogen and gas CCS). The resultant technology mix has knock on implications for the development of associated pipeline and storage infrastructure.

- **Imported biomass.** Cost competitiveness of domestic biomass production compared to biomass imports and developments in the global bioenergy market remain key uncertainties, alongside ensuring sustainability standards are met.

We have undertaken a sensitivity test to explore the impact of a different balance of low-carbon dispatchable electricity generation, and the implications for hydrogen supply. This sensitivity test has no overall effect on emissions, but instead affects the balance of technologies deployed in the energy system.

12.6.1 Different balance of low-carbon dispatchable electricity generation

This sensitivity tested the impact of deploying mostly hydrogen-fired turbines, instead of gas with CCS, to provide low-carbon dispatchable electricity. The sensitivity deployed a higher balance of hydrogen-fired turbines (72% of low-carbon dispatchable capacity in 2050), in contrast to gas with CCS making up 76% of capacity in the Balanced Pathway (see electricity supply Chapter 10 for further details).

The impacts on subsequent hydrogen infrastructure and production are most pronounced by 2050 as hydrogen demand for electricity generation increases through the 2040s.

- Total hydrogen production capacity increased 43% (12.1 GW) compared to the Balanced Pathway in 2050. Most (10.5 GW) of the additional capacity is provided by blue hydrogen.

- Hydrogen production increased 39% compared to the Balanced Pathway in 2050, with the increase coming from blue hydrogen production. This reflects a more even balance of blue and green hydrogen production, with blue hydrogen comprising 53% of production compared to 28% in the Balanced Pathway.

- Storage requirements increased to 9 TWh in 2050 compared to 5 TWh in the Balanced Pathway, primarily provided by salt caverns.

The impact on emissions is zero in 2040 and 0.6 $MtCO_2e$ more than the Balanced Pathway in 2050, given the greater production of blue hydrogen to meet demand. The emissions impact in electricity supply in 2050 is -0.6 $MtCO_2e$, so this represents a shift from post- to pre-combustion CCS in the energy system. While overall emissions are unchanged, the main implications are for hydrogen and CCS infrastructure.

12.7 Contingencies in fuel supply

We have explored one contingency action in fuel supply – namely around the level of imported biomass. The approach to this is described in Chapter 18, as the impact of this contingency on emissions is primarily accounted in the engineered removals sector.

Endnotes

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[2] Department for Energy Security and Net Zero (2023) *Energy and emissions projections.* https://www.gov.uk/government/collections/energy-and-emissions-projections.

[3] North Sea Transition Authority (2023) *Oil and gas production projections.* https://www.nstauthority.co.uk/data-and-insights/insights-and-analysis/production-and-expenditure-projections/

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[5] Element Energy for the Climate Change Committee (2020) *N-ZIP model.* https://www.theccc.org.uk/publication/deep-decarbonisation-pathways-for-uk-industry-element-energy/.

[6] North Sea Transition Authority (2024) *OGA Plan to reduce UKCS greenhouse gas emissions.* https://www.nstauthority.co.uk/media/laidjfqb/oga-plan-to-reduce-ukcs-greenhouse-gas-emissions.pdf.

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Chapter 13: Waste

Introduction

The waste sector covers emissions from landfill, energy from waste (EfW), composting, wastewater and other waste, which includes anaerobic digestion, incineration and mechanical biological treatment.

The Balanced Pathway for waste was determined by assessing the extent and pace of various measures available to reduce emissions from today to 2050, against a counterfactual baseline in which there is no further decarbonisation across the UK economy. Generally, this is done by considering what is feasible alongside Government ambition and targets. Emissions reductions from the following contributed to the pathway:

- **Solid waste**. We model the amount of waste produced through to 2050 before applying feasible reductions from resource efficiency, food waste avoidance and improved recycling rates to limit residual waste treatment. We then apply measures to decarbonise residual waste treatment, including stopping the landfilling of waste (in two stages) and capturing emissions from landfill and energy from waste plants. Modelling is done at a UK level from which pathways for Scotland, Wales and Northern Ireland are derived.

- **Wastewater**. Our pathway is established by deploying technologies which improve performance and reduce emissions, based on an assessment of cost, timing and feasibility of roll out. Each UK nation is modelled separately, and the UK pathway is the sum of these.

Our pathways were developed using a combination of in-house and external models. We model waste arisings and potential reductions, as well as deployment of CCS to energy from waste plants. Landfill methane emissions are calculated using MELMod (Methane Emissions from Landfill Model), a model developed by Ricardo and provided by Defra. We commissioned Arup to develop our wastewater emissions pathways.

13.1 Baseline emissions in waste

13.1.1 The baseline for waste

The baseline represents a scenario in which there is no further decarbonisation action by either the Government or the market in the waste sector. In this baseline scenario, emissions would rise by 5% from 2022 levels by 2040 (the middle of the Seventh Carbon Budget period) and by 10% by 2050 (Figure 13.1). See Chapter 1 for our general approach to baselines.

Our baseline for waste is based the following assumptions:

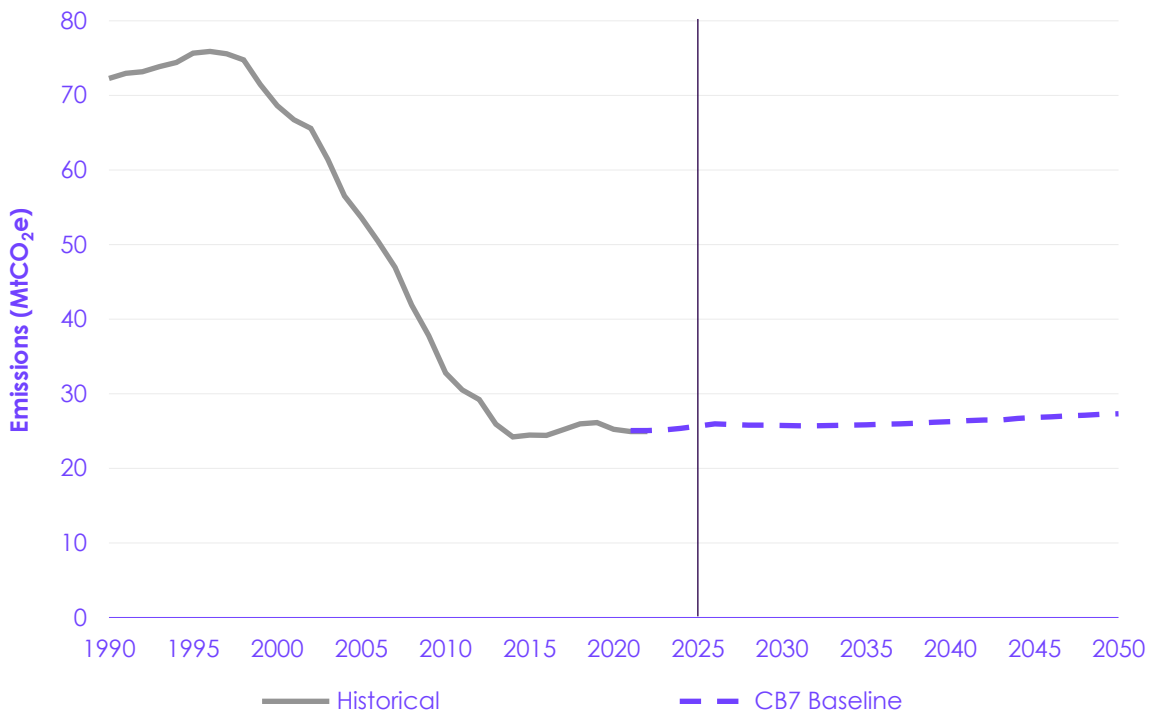
- Our emissions baseline uses DESNZ EEP 2022 'Reference Scenario' for emissions from landfill, wastewater, composting, mechanical biological treatment, anaerobic digestion and incineration (excluding energy from waste (EfW)) to 2040.[1] Between 2041 and 2050 emissions are held at 2040 levels.

- The UK's latest final national GHG emissions statistics, the final 2022 inventory of emissions, are used as the starting point in the waste sector as the 2023 provisional estimate of emissions used in other sectors only include CO_2, whereas non-CO_2 emissions are significant in the waste sector.[2]

- The EEP does not disaggregate emissions from EfW from power emissions therefore our EfW emissions baseline is determined from our own estimate of baseline residual waste arisings.
  - Baseline waste arisings increase between 2025 and 2050, roughly in line with population and GDP. This leads to an increase in residual waste sent to both landfill and EfW for disposal.
  - Waste sent to EfW increases by 8.8 Mt between 2025 and 2050 and causes a 35% increase in CO_2 emissions in the baseline. This reflects a recent trend of increased emissions from incineration, mostly EfW. This is partially compensated by a slight decrease in landfill emissions between 2022 and 2040, despite an increase in residual waste going to landfill over this period, resulting in a baseline that increases slightly between 2022 and 2050.

Baseline capital and operational costs for recycling, landfilling and energy from waste plants are calculated on a £/tonne of waste treated via each method, based on estimates from Ricardo Energy & Environment for the National Infrastructure Commission's second National Infrastructure Assessment.[3] The increase in waste arisings in the baseline lead to costs for energy from waste and landfill to increase as more capacity for disposal is needed. Costs in our pathway are calculated as additional costs compared to this baseline.

Figure 13.1 Baseline emissions in waste



Source: DESNZ (2024) *Final UK greenhouse gas emissions national statistics 1990-2022*; CCC analysis.
Notes: Historical emissions are shown only to 2022 because provisional 2023 emissions data are not published for GHGs other than CO_2, which make up the majority of emissions in this sector.
Description: Baseline emissions in waste gradually increase from 2025 to 2050.

13.2 Pathway assumptions and modelling for waste

13.2.1 Modelling the Balanced Pathway for waste

Overall modelling approach

Our pathway for waste is determined by assessing the potential of different options to reduce emissions, applying feasible improvements in waste reduction and deploying technologies where appropriate. Our analysis encompasses both fossil-based and biogenic waste (Box 13.1). See Chapter 1 for our general approach to pathway analysis.

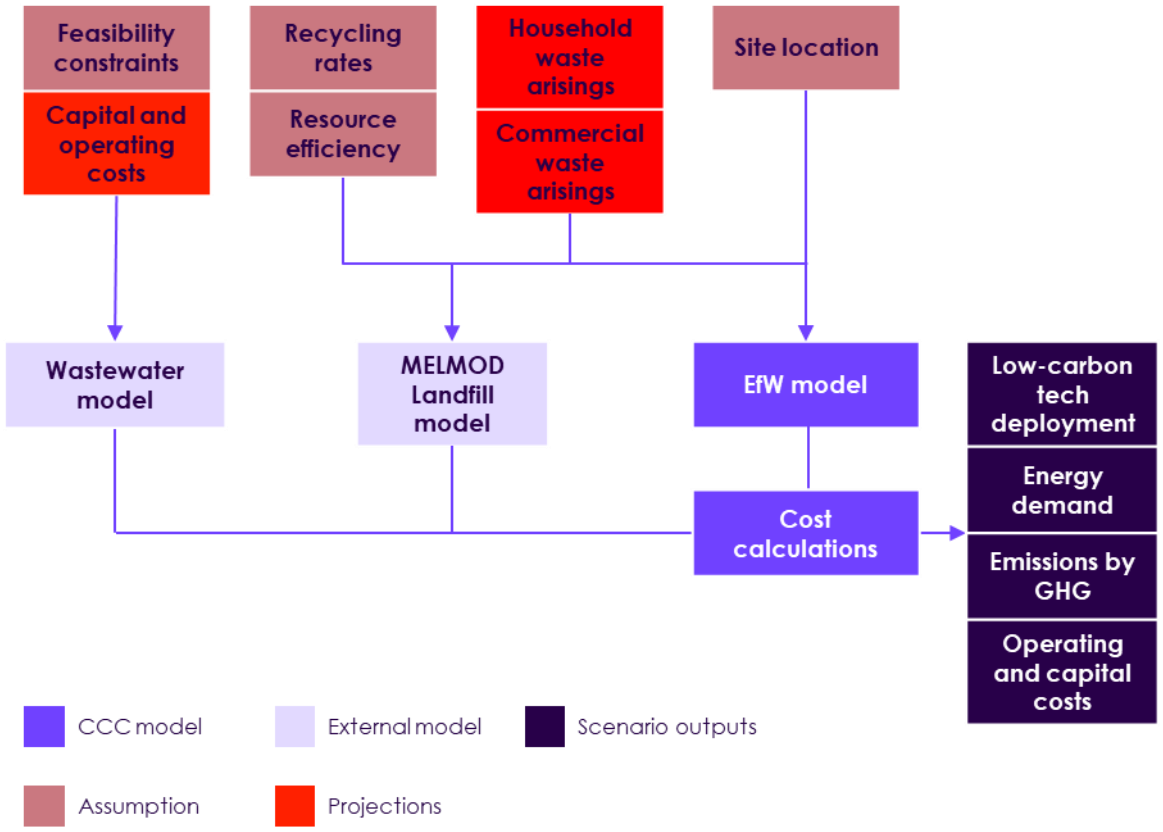
For solid waste, we broadly follow the principle of the waste hierarchy by first applying measures to reduce waste arisings and improve recycling, before applying measures to capture emissions from landfill and EfW (see Table 13.1). Emissions reduction from composting improvements are calculated separately.

- A base year of 2021 is used as the latest year for which waste arisings data was available during analysis. The levels of waste reduction we've assumed in our pathway are based on a mix of internal and external research regarding feasible improvements that could be made, taking government targets into consideration at both a UK level and devolved administration level.
  - Waste reduction is modelled at a UK level, with a similar level of waste reduction assumed in each of the UK's nations, relative to their 2021 starting point. This implies higher ambition in our pathway for nations that currently achieve a higher level of waste reduction than the UK wide level – in particular Wales (see section on recycling below for more details).
- After waste reductions and waste exports are applied, we calculate the emissions from disposing of the residual waste in landfill (using MELMod) and energy from waste (calculated using an in-house model). To reduce these emissions, measures are applied to prevent waste being sent to landfill, capture methane from landfill sites and apply carbon capture and storage (CCS) at energy from waste facilities (for further information on CCS, see Section 1.7.2).
- The waste modelling interacts with several other sectors across the economy. Waste reduction from resource efficiency aligns with measures to reduce production emissions in the industry modelling (see Chapter 8). Several waste streams are feedstocks for our fuel supply analysis (Box 13.2). Applying CCS to EfW plants results in the capturing of biogenic waste which counts as GHG removals, see Chapter 18. These removals and their proportion of the costs are counted in the removals sector.

Our wastewater pathway was modelled by Arup, who assessed technologies to abate N_2O and CH_4 emissions based on an Ofwat study and water and sewage companies (WASC) technology reports and business plans, considering the cost, timing and feasibility of rollout.[4;5] The full methodology is detailed in the accompanying report.[6]

How these models fit together to produce our waste sector pathway is summarised in Figure 13.2.

Figure 13.2 Modelling schematic for waste



Source: CCC analysis.
Notes: This diagram is illustrative and does not detail all model inputs and outputs.
Description: The waste modelling is largely done in three parts; the wastewater model, the methane emissions from landfill model (MELMod) and the EfW model. These take assumption and projections and calculate deployment, energy demand and emissions. Operating and capital costs for the waste sector are calculated in a separate model.

Box 13.1
Accounting of emissions from fossil and biogenic waste

We categorise waste as either fossil-derived waste or biogenic-derived waste. Fossil-derived waste is comprised of fossil matter, such as oil-based products like plastics, which when burnt release CO_2 that has been stored for millions of years. Fossil derived CO_2 is therefore counted as additional when considering the balance of greenhouse gases in the atmosphere. Biogenic waste is comprised of biological matter, such as plant-based products like food or timber, which when burnt returns to the atmosphere the CO_2 that was recently absorbed when the biogenic material was alive. Biogenic derived CO_2 is therefore counted as having a neutral impact on the balance of greenhouse gases in the atmosphere.

However, biogenic waste produces methane emissions when it biodegrades, for example in landfills. These emissions are counted as being additional to the balance of greenhouse gases in the atmosphere (albeit with a 'shorter lived' effect than CO_2).

Box 13.2
Waste as an input to power and fuel supply analysis

Several discreet waste streams are feedstocks for power (energy from waste plants), biogas, BECCS and Sustainable Aviation Fuel (SAF). Waste inputs are used in our fuel and power supply analysis to determine the availability of these energy resources.

Power, SAF, and biomass from residual waste

After applying reductions (resource efficiency, recycling), waste exports and allocating a proportion of waste to landfill, residual waste is available as a resource in fuel and power supply. A share of biogenic residual waste is allocated to produce waste-derived SAF (19% in 2040) and as a BECCS feedstock for use in industry (5% in 2040). All other residual waste is allocated to EfW for disposal, which generates electricity.

Biomass from waste wood

Waste wood is allocated to biomass supply which is used in a number of sectors including power, buildings and industry. Waste wood data for 2021 and 2022 were updated based on a report from the Wood Recyclers' Association, then held flat until 2050.[7]

Biofuels from tallow and used cooking oil

Tallow and used cooking oil resources are allocated to biofuel supply, which is used in a number of sectors including aviation, surface transport and agriculture. Tallow resources reduce over time in line with changes in livestock numbers, consistent with the agriculture sector analysis. Used cooking oil increases as population increases, based on ONS reported population forecasts.[8]

Biogas from landfill, sewage sludge, and anaerobic digestion

Methane captured at landfill sites, sewage treatment, and anaerobic digestion (AD) facilities is allocated to biogas supply, which is used in the industry and power sectors, including in the gas grid as biomethane.

The amount of biogas available from landfill is determined by the amount of biogenic waste sent to landfill (which is largely phased out by 2028 in our pathway), and the level of capture rates (which increase in our pathway). The net impact of these is a decrease in landfill gas available from 2025 to 2050.

The amount of biogas available from sewage sludge increases in line with increasing population, from ONS reported population forecasts, and the switch to advanced AD which produces more biogas per tonne of sewage sludge treated.

The amount of biogas available from anaerobic digestion of food waste is determined by the food waste collection rates (which increase in our pathway), and the level of food waste available for collection (which decreases in our pathway). The net impact of these is a slight decrease in biogas available from AD from 2025 to 2050.

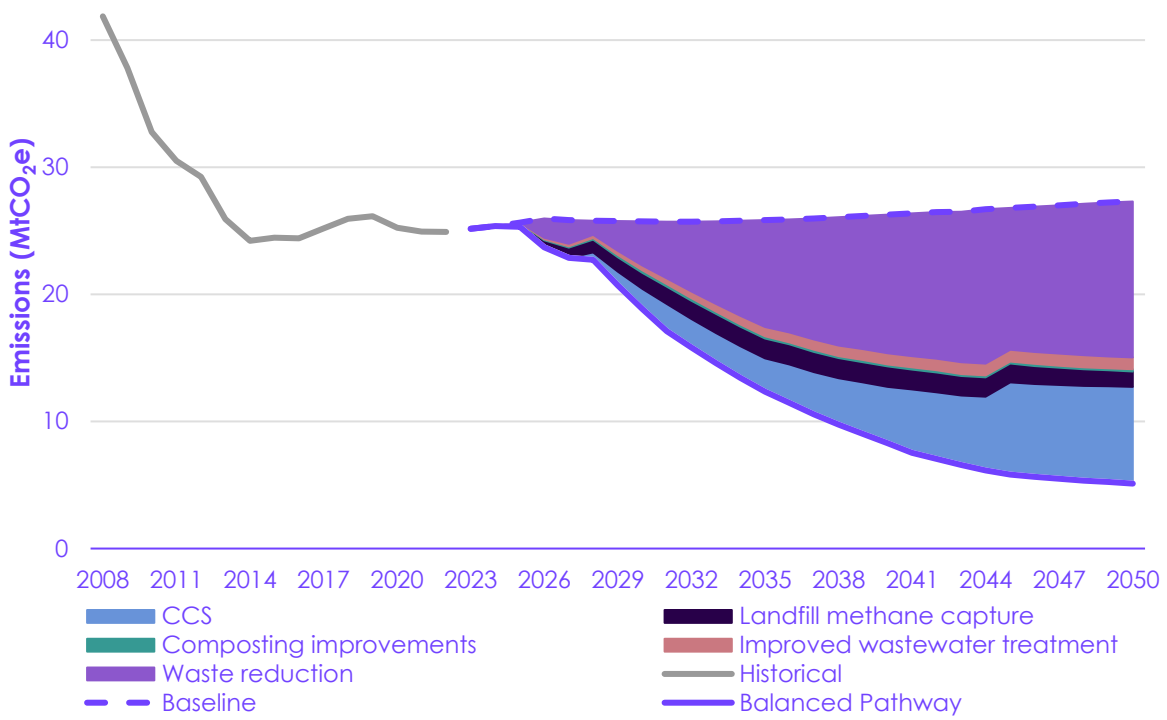
The amount of biogas available from livestock manures is assumed to be zero from 2025 to 2050, as all livestock manure that is collectable (from housed livestock) continues to be used for fertiliser applications.

The Balanced Pathway for waste

In our Balanced Pathway, waste emissions are projected to fall by 67% from 2022 levels, to 8.3 $MtCO_2e$ by 2040 (the middle of the Seventh Carbon Budget Period) and to 5.1 $MtCO_2e$ by 2050.

The largest share of emissions reduction in the Balanced Pathway for waste comes from reducing waste sent to landfill and to EfW. This is achieved by reducing waste through improved resource efficiency, increased recycling rates, and a reduction in food waste. CCS is installed to capture the majority of emissions from the disposal of residual waste by EfW (Figure 13.3).

Figure 13.3 Sources of abatement in the Balanced Pathway for waste



Source: DESNZ (2024) *Final UK greenhouse gas emissions national statistics 1990-2022*; CCC analysis.
Notes: Historical emissions are shown only to 2022 because provisional 2023 emissions data are not published for GHGs other than CO_2, which make up the majority of emissions in this sector. In 2028 abatement from waste reduction reduces in the short term due to the near elimination of biodegradable waste sent to landfill before action on resource efficiency and recycling is sufficient to counteract the shift of biodegradable waste from landfill to EfW. In 2045, the near elimination of all waste to landfill is introduced, which also increases waste to EfW, leading to further abatement from CCS.
Description: The largest share of emissions reduction in waste is from waste reduction. Contributions also come from CCS at EfW plants, improved landfill methane capture and wastewater treatment, with minor contributions from composting improvements.

The measures in our pathway

Table 13.1 summarises the measures for reducing emissions in the waste sector that are considered within our modelling, how these lead to emissions reductions in our modelling, as well as the key factors that influence their uptake. The methodology used to develop the assumptions and analysis underpinning these is described in the rest of this section.

Table 13.1
Measures considered within our modelling for waste

Decarbonisation measure	How does this measure influence emissions in our modelling?	What are the key factors that affect uptake in our modelling?
Waste reduction	Waste reduction leads to less waste going for disposal in either landfill or through incineration at EfW plants. Less waste going to landfill reduces methane emissions from the decomposition of biodegradable waste, less waste to EfW reduces CO_2 from burning fossil waste.	Waste reductions from resource efficiency are derived from measures applied in the industry sector to reduce material consumption. Food waste reductions increase linearly from today to meet the Courtauld Commitment 2030.[9] Recycling potential is based on our assessment of what is technically feasible, partly based on examples of comparable economies.

		Waste exports are assumed to stay at today's level across our pathway. The near-elimination of biodegradable waste is achieved by 2028 across the UK in order to avoid transfers of waste between nations. The near elimination of (almost) all other waste to landfill in 2045 aligns with when all EfW capacity is fitted with CCS.
Carbon capture and storage	Installing carbon capture and storage at EfW plants captures CO_2 emissions, helping to abate CO_2 emissions from fossil-derived residual waste and enabling carbon removals by capturing biogenic CO_2 from biogenic-derived residual waste (see Box 13.1). EfW plants which cannot install CCS are phased out, thereby eliminating their emissions.	We assume CCS is only cost-effective for EfW facilities which can connect to CO_2 and transport infrastructure within industrial clusters. EfW capacity with CCS increases over time as industrial clusters across the UK access CCS. EfW capacity without CCS is phased out while ensuring there is capacity to treat all waste sent for disposal at EfW sites in each year. All EfW capacity in the UK is assumed to be fitted with CCS by 2045.
Landfill methane capture	A dispersed network of pipes is inserted into landfill to capture landfill gas from biodegradable waste decomposing in landfill, converting methane to biogas to use in power or in the gas grid, while feasible.	We assume a feasible methane capture rate based on historical performance and some improvements.
Improved wastewater treatment	Installation of monitoring and new technologies to treat wastewater leads to operational improvements which reduce nitrous oxide and methane emissions from wastewater treatment.	Roll out of technologies to decarbonise wastewater treatment processes depends on current level, expected deployment, maximum potential, and cost. The technologies chosen in the Balanced Pathway are those which are most cost effective, relative to the DESNZ central carbon value, and at the highest level of technology readiness.[10;11]
Composting improvements	The use of pumped air to improve compost aeration can reduce emissions from suitable composting sites.	Aeration is rolled out to all suitable sites between 2025 and 2030 assuming a linear deployment profile.

13.2.2 Waste reduction

Resource efficiency

We apply a reduction in waste arisings from resource efficiency measures which are implemented in our industry pathway (see Chapter 8). These reductions are calculated first before other waste reduction measures are applied, leading to less waste disposed of in both landfill and EfW.

- The reduction in material use delivered by resource efficiency measures is assumed to pass through to the waste sector on a five-year delay, so a 2% decrease in material use in 2030 leads to a 2% decrease in waste arisings in 2035. Resource efficiency measures are adopted in industry between 2026 and 2035, so decreases in waste arisings due to resource efficiency ramp up from 2031 to 2040 and remain at a similar level between 2040 and 2050. The waste reduction from resource efficiency is applied to all non-food waste but we only

consider the impact on materials that produce emissions when disposed of, not inert materials such as concrete from construction waste.

- We have excluded consideration of the cost of resource efficiency measures as we lack reliable evidence.

Food waste reduction

The reduction in waste arisings from food waste avoidance is calculated based on food waste reduction targets according to the Courtauld Commitment 2030, which all governments of the UK have committed to.[12] These reductions were calculated separately for household food waste and commercial and industrial food waste.

- The reduction in household, commercial, and industrial food waste increase in line with the Courtauld Commitment to deliver a 50% per capita reduction in all food waste by 2030, with waste reductions implemented in our pathway in the same year the target reduction is achieved. This commitment is in line with the UK SDG 12.3 target.[13] We assume it is feasible to deliver a further improvement to a 60% reduction in food waste per capita against the same baseline (see below) by 2050.
  - The 50% reduction ambition is established against a 2007 baseline for household food waste and against a 2011 baseline for commercial and industrial food waste, based on data from Wrap.[14;15] Food waste per capita was assumed to reduce linearly between target years.
- There is no cost associated with food waste reduction for either household or commercial and industrial food waste.

Improving recycling rates

To determine feasible future recycling rates for our pathway, we reviewed impact assessments for UK policies and examples of leading recycling rates internationally. We used these to determine feasible future rates for different waste types and then assumed a linear improvement from today's levels, to estimate a combined recycling rate for the UK, which comprises household and non-household waste.

- **Combined recycling rate (made up of household and non-household waste).** We use a UK combined recycling rate of 47% as our starting point in 2025. We assume a rate of 68% by 2035 in the Balanced Pathway based on international examples and estimates of future municipal recycling rates.
  - The UK Government currently has a municipal recycling target of 65% by 2035 for England, which is deemed feasible through its planned reforms to packaging and recycling and further policy development.[16;17] Depending on the reporting methodology the country with currently the highest municipal recycling rate is Austria with 59% in 2021 or Germany with 68% in 2023.*;[18;19]
  - These municipal recycling rates do not include commercial and industrial waste, which tends to be purer and has a higher potential for recycling, so we assessed Germany's 68% rate to be a feasible combined recycling rate for the UK (including commercial and industrial waste).[20]

* In 2024, Eunomia published a country league table of 2021 municipal recycling rates. It used municipal recycling rates reported to e.g. the European Commission and adjusted these for reporting inconsistencies between countries. In this league table Austria is top with an adjusted recycling rate of 59% and Germany fourth with 52%. England's recycling rate was one of the few upwards adjustments to 44% (compared to 42% reported).

- **Household recycling rate**. The UK recycling rate for Waste from Households (WfH) was 45% in 2021, which we use as our starting point in 2025.[21] We assume a rate of 57% by 2035 in the Balanced Pathway, based on the household recycling rate already achieved by Wales.

  - Recycling rates vary across nations, with Wales (57%) outperforming the rest of the UK.[22] England, which accounts for 84% of all waste arising in the UK, had a WfH rate of 44% in 2021.[23]

  - While there are relevant differences between Wales and other UK nations (e.g. England has a higher percentage of people living in larger built-up areas and far more local authorities), we consider waste collection infrastructure and services and engagement approaches to be similar enough to justify matching this ambition across the UK (this implies a higher rate for Wales as outlined below). According to UK statistics on waste, the recycling rate in Wales increased 12 percentage points, from 44% to 56%, between 2010 and 2019, we assume each UK nation, including Wales, improves their recycling rate by 12 percentage points, compared to their 2021 levels, by 2035.[24]

- **Non-household recycling rate.** We use an estimated recycling rate of 49% as our 2025 starting point for non-household waste (which is made up of non-household municipal waste and commercial and industrial waste). We assume a rate of 74% by 2035 in the Balanced Pathway, based on calculating the contribution of non-household recycling required to deliver the combined recycling rate of 68% and comparing this against UK modelling estimates for non-household municipal waste.

  - There is significant uncertainty and a lack of data for non-household waste. To determine our 2025 starting point we extended an assessment of the non-household municipal rate for England to cover commercial and industrial waste across the UK.[25]

  - Estimated recycling rates for non-household municipal waste achievable through planned waste reforms in different parts of the UK vary greatly across impact assessments, from 58% to a theoretical potential of 87%, but consistently put the recycling potential for non-household waste higher than for household waste.[26;27;28;29] Estimated recycling rates for commercial and industrial waste are not readily available, but it is assumed to be purer and therefore more easily recyclable than non-household municipal waste.[30]

  - 74% lies towards the middle of the range of estimated recycling rates for non-household municipal waste.

Our Balanced Pathway considers recycling potential at a UK level; we assume the percentage point increase in recycling rates at a devolved nation level. It would be useful to look at the relative feasible contribution from each nation, but this hasn't been possible due to the lack of consistent, comparable and reliable data. A UK-wide measure isn't skewed by the potential for waste to be transferred across nations.

- Our Balanced Pathway assumes that household recycling rates in each UK nation increase by 12 percentage points between 2025 and 2035, while the recycling rate for commercial and industrial waste increases by 25 percentage points.

- Given recycling starting points in each nation, our simplification implies higher recycling rates in Northern Ireland and Wales compared to the UK level (and England and Scotland), which may be more difficult to achieve in practice – although Wales has set out an aim to achieve a 75% household, municipal and industrial waste recycling rate by 2030.[31]

Reducing waste to landfill

We model the effect of a near-elimination of biodegradable waste to landfill in 2028 and a near-elimination of all other waste to landfill in 2045 in MELMod (Methane Emissions from Landfill Model).

- MELMod splits municipal waste sent to landfill into 15 waste streams, with 16 for commercial and industrial waste, classified as either predominantly biogenic, predominantly non-biogenic or inert, and then calculates the methane produced by the degradation of bio-genic waste. For the waste streams that are predominantly biogenic and predominantly non-biogenic, the amount sent to landfill is assumed to reduce to zero from 2028 and 2045 onwards, respectively. Inert waste streams continue to be sent to landfill to 2050.
  - In 2023 the UK Government ran a call for evidence to seek evidence and data to support the development of policies to achieve the near elimination of biodegradable municipal waste being sent to landfill from 2028 in England.[32] Northern Ireland is understood to have a similar ambition, while Wales and Scotland are aiming to achieve that goal sooner.[33;34;35]
  - In order to ensure alignment across nations (to avoid waste transfers between nations) we adopt an ambition to achieve this outcome by 2028 across the UK, but we extend it to apply to non-household waste also.
  - From 2045 all EfW plants in our pathway will have CCS, allowing any non-biodegradable waste streams still entering landfill to be sent to EfW for disposal from 2045.
- Costs associated with the diversion of waste from landfill to alternative disposal (for example recycling or EfW) are included in waste infrastructure costs (see Section 13.2.3 below).

13.2.3 Installation of carbon capture and storage

Energy from waste capacity is determined by the volume of residual waste after applying measures to reduce waste (resource efficiency, food waste reduction, and recycling), take-offs for landfill, a small portion for waste exports, and waste used in the fuel supply sector (see Box 13.2).* We then apply the roll-out of CCS to EfW capacity based on when access to CCS clusters should become available (see Section 1.7.2).

- To determine the timing of CCS adoption, current and future EfW capacity is allocated to 11 regions, based on 2020 NAEI point sources data.[36] Prospective industrial CCS clusters are then matched to proximate regions (not all regions are matched with a cluster). As industrial CCS clusters come online (starting in 2028), an increasing proportion of EfW with CCS is allocated in associated regions, based on the regions' starting share of EfW capacity. In parallel, EfW capacity in regions with no associated CCS cluster decrease to zero by 2045 (Figure 13.4).
  - This represents a re-allocation of the UK's existing EfW capacity increasingly to locations which can install CCS. In practice this might be realised through the decommissioning of existing dispersed EfW sites at the end of their intended design lives, avoiding stranded assets, in addition some dispersed sites may still be able to access CCS infrastructure. The reallocation leads to a slightly different regional split of EfW in 2050 compared to the start of our pathway. However, capacity at a UK level remains

*Between 4% and 6% of residual waste, after recycling, is exported. The volume of waste exported is assumed to stay at 2023 levels.

broadly similar. The split by nation of EfW capacity at the start and end of our pathway is shown in Table 13.2.

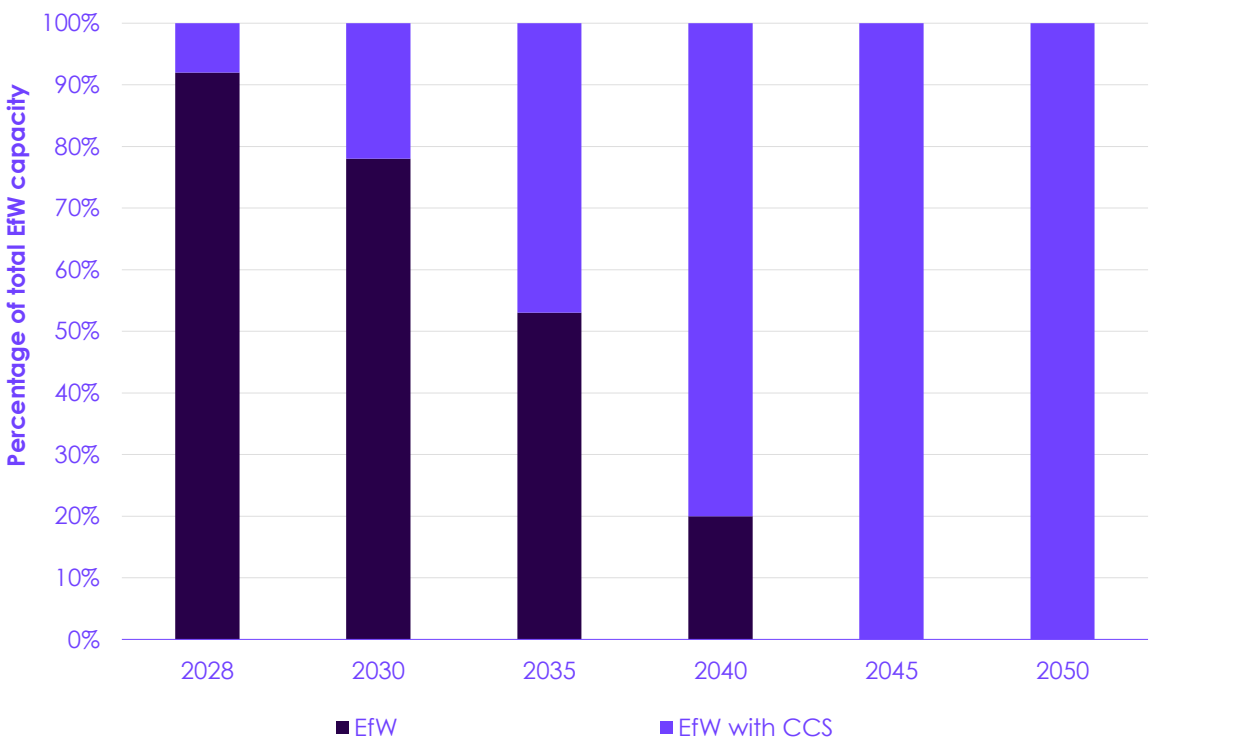
  - Roll out of CCS is limited to a maximum of 10% of EfW capacity in one year. Capture rates for CO_2 between 2028 and 2040 are assumed to be 90%, increasing to 95% from 2041 to 2050.

- In addition to capturing fossil CO_2, installation of CCS leads to carbon removals in the form of BECCS by capturing CO_2 from biogenic sources of residual waste. These emissions are accounted for in our removals sector (see Chapter 18).

  - Residual waste is split into biogenic and non-biogenic fractions. The biogenic fraction of residual waste is assumed to be 48% before 2028, based on DUKES 2022.[37] The near-elimination of biodegradable waste to landfill causes this fraction to increase in 2028 to 57%. The volumes of biogenic and non-biogenic waste are then used as feedstocks in the fuel supply analysis (see Box 13.2), with any residual waste not used by other sectors sent for disposal at EfW.

  - The proportion of biogenic waste sent to EfW decreases across our pathway due to improvements in recycling, food waste collection, and the use of biogenic waste as a feedstock for SAF (see Box 13.2), by 2050 38% of waste sent to EfW is biogenic.

Figure 13.4 Proportion of EfW with and without CCS capacity in the Balanced Pathway



Source: CCC analysis.
Description: The proportion of EfW decreases across our pathway as the proportion of EfW with CCS increases. From 2045 all EfW capacity is combined with CCS.

Table 13.2
EfW capacity split between the UK's nations

	2025	2050
England	90%	88%
Northern Ireland	0.2%	0.1%
Scotland	5%	5%
Wales	5%	7%

Waste infrastructure costs

The capital and operational costs of landfill, recycling, EfW, and EfW with CCS were calculated based on work done by Ricardo for the National Infrastructure Commission's second National Infrastructure Assessment.[38]

- As part of this work Ricardo established a £/tonne cost for both capital and operational expenditure for treating waste via a variety of methods. There is high uncertainty on these estimates, particularly with capital expenditure which is highly dependent on location and surrounding infrastructure.

- For capital expenditure, the £/tonne for each disposal method; landfill, recycling, EfW, or EfW with CCS, was applied to any new waste arisings being disposed of in that year, within our scenario, compared to the previous year. Where waste arisings for that disposal method decrease compared to the previous year, due to either a decrease in waste arisings or a shift of waste going from one disposal method to another, capital expenditure is assumed to be zero.

  - Our capital cost assumptions for EfW with CCS include the total cost of building new EfW with CCS as capacity grows. Given the current location of plants, some capacity will be in a suitable location to be able to build CCS onto an existing plant, but some new EfW with CCS capacity will be needed as well. Our modelling doesn't consider each plant on an individual basis, so we have adopted a conservative approach of costing EfW with CCS capacity as all newly built. This could lead to an overestimation of capital costs for EfW with CCS.

  - Costs for EfW with CCS include an optimism bias (See Chapter 2) of 66% to account for additional uncertainty surrounding this technology. In addition, transport and storage costs are calculated based on the volume of CO_2 captured.

- For operational expenditure, the £/tonne for each disposal method was applied to all additional waste arisings being treated by that disposal method compared to our baseline. For some disposal methods, for example recycling, the operational costs will increase compared to the baseline as more waste is recycled, for other disposal methods, for example landfill, less waste is sent for landfilling in our pathway compared to the baseline so there will be a cost saving.

- Costs for decommissioning waste facilities has not been included in the waste sector costs. Facilities built within the pathway were assumed to have a 33-year lifespan and therefore do not require replacement before 2050.

13.2.4 Landfill methane capture

Landfill methane can be captured via a dispersed network of pipes inserted into landfill to capture landfill gas and convert it for use in power or the gas grid. Capture helps reduce methane emissions produced from landfill sites that are in use and sites that have been decommissioned but are still producing methane, which can happen for decades after waste is sent for disposal.

- The percentage of landfill methane captured increases in our Balanced Pathway, from 49% in 2022, based on DUKES 2022, to 80% in 2050.[39] Capture rates of 74% were achieved in 2016, the 2050 target stretches this achieved rate slightly further.[40] The capture rate is applied to landfill methane emissions calculated by MELMod.

- Capital and operational expenditure for increased methane capture at landfill sites are calculated on a £/MWh of additional gas captured compared to the baseline, £308 MWh/year for capital expenditure and £7 MWh for operational expenditure.[41]

13.2.5 Improved wastewater treatment

The modelling for the wastewater emissions pathway was produced by Arup, and further detail can be found in the accompanying report.[42]

Arup conducted an appraisal of a long list of technologies to mitigate wastewater processing emissions, based on water company business plan proposals. Arup selected viable technologies which are used in our pathway based on an assessment of cost, feasibility of rollout, and data availability, and then tested this with stakeholders in the water industry. All technologies used in the pathway have a high level of technology readiness and have been demonstrated at site level.

- Technologies that mitigate methane emissions:
  - Advanced anaerobic digestion is an upgrade to traditional anaerobic digestion systems which produce more biogas and can be achieved through a variety of methods including thermal hydrolysis.

- Technologies that mitigate nitrous oxide emissions:
  - Covering and containment which cover activated sludge process or liquor treatment plants using forced aeration to contain, reduce and/or eliminate emissions.
  - Enhanced monitoring and real time control involves the installation of live nitrous oxide monitors which allow emissions to be monitored and treated (e.g. by extended aeration or allowing for complete nitrification).
  - Digital twins optimise activated sludge process parameters to reduce process emissions.
  - Membrane aerated biofilm reactor (MABR), in which oxygen is provided to sludge attached to the membrane which provides improved emissions abatement compared to conventional biofilm processes.

The same technologies are deployed across the municipal and industrial wastewater sectors.* Roll-out of technologies for the municipal wastewater sector begins at the start of the regulatory investment period following the earliest deployment year (identified based on cost and maturity, see Table 13.3). For the industrial sector the deployment start year was assumed to lag five years

*We align with the final national GHG emissions statistics for the split of municipal (5D1) and industrial (5D2) wastewater emissions. Industrial wastewater is wastewater from industries that discharge directly to the water environment (not to sewer).

behind the earliest deployment in the municipal sector to account for reduced regulatory pressure. Technologies were rolled out in three stages:

- In the first stage 20% of maximum site coverage is reached, representing technology deployment leaders.
- In the second stage an additional 60% of maximum site coverage is achieved, representing the majority of technology deployment.
- In the third stage the final 20% of maximum site coverage is achieved, representing the laggards in technology deployment.

Within each stage, maximum site potential increases linearly over the time period. For England and Wales stages are five years long starting in 2025, while for Northern Ireland and Scotland the stages are six years long starting in 2027.

Table 13.3
Start year for first stage of technology deployment - municipal

Technology	England and Wales	Scotland and Northern Ireland
Covering and containment	2025	2027
Enhanced monitoring and real time control	2025	2027
Digital twin	2025	2027
MABR	2030	2033
Advanced anaerobic digestion	2021	2021
High strength liquor treatment	2035	2033
Vacuum extraction of methane	2035	2033

Emissions reductions are based on annual abatement potential of each technology, leading to a 47% reduction in nitrous oxide and a 14% reduction in methane in the municipal wastewater sector between 2021 and 2050, and a 48% reduction in nitrous oxide and a 17% reduction in methane in the industrial wastewater sector between 2021 and 2050.

Capital and operational costs were based on the median asset cost (per unit of abatement £/$MtCO_2e$) from across the water companies' business plans. No capital or operational costs were available for advanced anaerobic digestion, so these costs have been omitted from analysis.

13.2.6 Composting improvements

We apply a simple emissions reduction factor to represent potential improvements to reduce emissions from composting processes.

- In line with our analysis for the Sixth Carbon Budget, we have assumed that aeration technology reduces emissions at composting sites by 70% but is only suitable at a third of composting sites. The technology is established and low cost and therefore we assume the technology is rolled out to all suitable sites between 2025 and 2030. Emission reduction from composting improvements gradually increases between 2025 to 2030 and remain at a 23% reduction in composting emissions against our baseline in each year between 2030 and 2050.

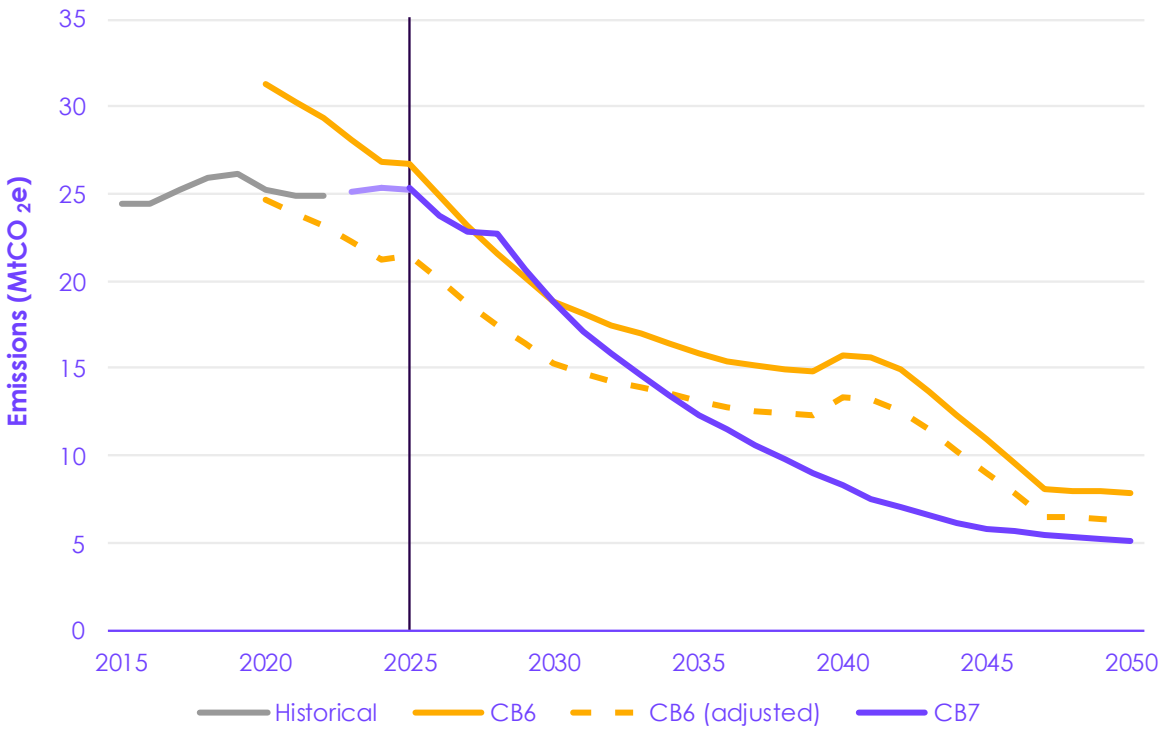
- Capital and operational costs for composting improvements are based on an industry estimate for installation and operating costs based on a volume of compost being treated. This was scaled up to the total volume of compost that would be treated across suitable sites. Costs estimates were based on costs used in our Sixth Carbon Budget advice, inflated to 2023 prices.

13.3 Changes since our Sixth Carbon Budget advice

13.3.1 Comparison with our Sixth Carbon Budget pathway

Changes in emissions accounting since our Sixth Carbon Budget advice have reduced estimated waste emissions. However, growth in energy from waste emissions, and the lack of progress in reducing residual waste arisings, mean that our pathway nonetheless begins close to our Sixth Carbon Budget pathway (Figure 13.5). Without adjusting for inventory changes, emissions remain similar to those projected in our Sixth Carbon Budget advice until 2030, before falling more steeply to a lower level than in our previous analysis. Earlier CCS roll-out in this sector and higher estimates of the potential for reducing emissions from wastewater are key drivers of this difference.

Figure 13.5 The Balanced pathway for waste compared to our Sixth Carbon Budget advice



Source: DESNZ (2024) *Final UK greenhouse gas emissions national statistics 1990-2022*; CCC analysis.
Notes: Estimates of emissions in this sector have been substantially affected by changes in emissions accounting methodologies in the inventory since our Sixth Carbon Budget (CB6) advice. Therefore, to enable easier comparison, we have included a 'CB6 (adjusted)' series estimating what the Sixth Carbon Budget pathway would look like if it had used the latest inventory accounting.
Description: Our Seventh Carbon Budget (CB7) Balanced Pathway begins close to our Sixth Carbon Budget (CB6) pathway. Emissions reduce faster in the 2030s in our pathway compared to our Sixth Carbon Budget pathway, and results in fewer residual emissions in 2050.

13.3.2 Emissions changes since our Sixth Carbon Budget advice

Our starting point for our Balanced Pathway is now lower than projected in our Sixth Carbon Budget advice, due to changes in emissions accounting reducing estimated waste emissions.

- For our Sixth Carbon Budget advice we used global warming potentials from the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Reports (AR5) with climate feedback.[43] When the global warming potentials from AR5 were implemented in the UK greenhouse gas emissions in 2021, AR5 without climate feedback was used, which have lower global warming potentials for both nitrous oxide and methane.[44] In our Balanced Pathway we use AR5 without climate feedbacks, in line with current methodology.

- Changes to the emissions accounting methodology for methane have caused a decrease in emissions from wastewater since our Sixth Carbon Budget advice.[45] There is significant uncertainty in wastewater emissions, and changes to nitrous oxide wastewater emission factors could cause emissions to increase again (see Section 13.4).

- Due to delays in implementing key waste reforms and a lack of progress in increasing recycling rates, emissions have not been falling during the period since our Sixth Carbon Budget advice was published, which is what we projected in that analysis.

13.3.3 Key pathway differences compared to our Sixth Carbon Budget advice

There are several key areas in which the deployment rates, measures included, or underlying assumptions in our updated Balanced Pathway have been revised since publication of our Sixth Carbon Budget advice in 2020. These include:

- **Recycling rate**. In our Sixth Carbon Budget advice, we assumed a combined recycling and reuse rate of 68% for the UK would be reached by 2030. For the Seventh Carbon Budget we have shifted the target year back to 2035, partly reflecting the lack of progress towards this target since our 2020 advice as well as improved evidence of feasible recycling rates.[46]

- **Resource efficiency**. In our Sixth Carbon Budget advice, we assumed resource efficiency measures in industry led to a 33% reduction in waste arisings by 2037, in our Balanced Pathway resource efficiency measures in industry lead to a 5% reduction in waste arisings by 2040. The evidence on emissions reduction from resource efficiency has been updated. Although emissions savings from resource efficiency in industry are similar to that in our previous advice, these are now predominantly in the construction industry which mostly reduces the amount of inert waste produced. Disposal of inert waste doesn't generate emissions so the emissions savings in the waste sector from resource efficiency measures are more limited.

- **Elimination of waste from landfill**. In our Sixth Carbon Budget advice, we assumed the near-elimination of biodegradable waste to landfill was from 2025 and the near-elimination of almost all other waste from 2040 (2025 in Wales). Due to delays in implementing reforms to waste collections and other policies to tackle waste arisings and reduce waste to landfill, these have been delayed to 2028 and 2045 respectively and aligned across the UK's nations to avoid waste transfers between nations. In 2045 EfW capacity has all converted to EfW with CCS. Therefore, diverting residual waste from landfill to EfW leads to the majority of emissions from disposing of the waste being captured.

- **CCS deployment**. In our Sixth Carbon Budget advice, we assumed the roll out of CCS in the waste sector would occur after the roll out of CCS for the industrial sector, and did not start until the 2040s. The start of the roll out has been brought forward in our Balanced Pathway to align to plans for establishing industrial CCS clusters (from 2028).

- **Wastewater improvements.** In our Sixth Carbon Budget advice, we assumed a 21% improvement in wastewater process emissions by 2030 from a combination of enhanced monitoring, operational measures and continued roll-out of advanced anaerobic digestion. For our Seventh Carbon Budget advice Arup completed a research project to update the emissions, energy and cost pathways for wastewater based on deploying a larger range of improvement technologies leading to further emissions reductions from wastewater improvements compared to the Sixth Carbon Budget advice.

- **Waste exports.** In our Sixth Carbon Budget advice, we assumed waste exports would be phased out by 2030 meaning the UK would treat all of the residual waste produced in the UK. For our Seventh Carbon Budget advice we have assumed the amount of waste exported remains at 2023 levels.

13.4 Uncertainties and sensitivity analysis

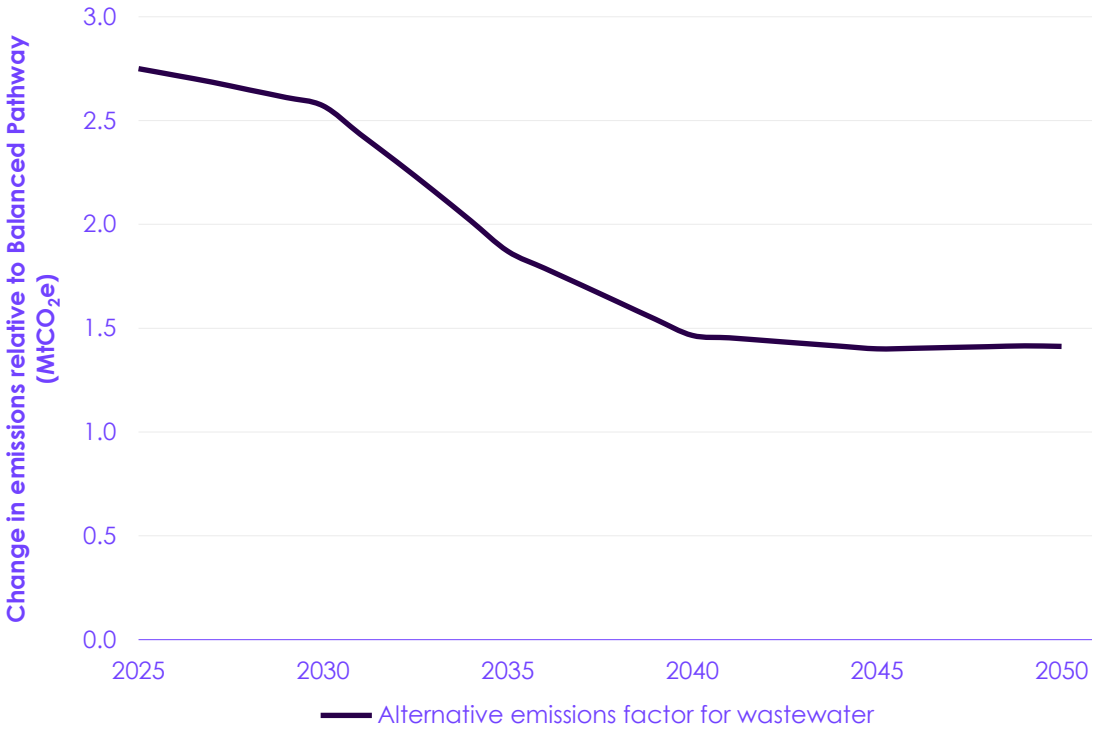
We have performed sensitivity analysis on the wastewater emissions factor as this could have a significant impact on emissions in the waste sector across our Balanced Pathway (Table 13.4 and Figure 13.6). See Chapter 5 for our general approach to uncertainty and contingency analysis, including descriptions of the methodology behind sensitivity tests that apply across multiple sectors.

Table 13.4
Key sensitivity test for waste

Sensitivity test	Description	Impact on emissions in 2040		
		$MtCO_2e$	% of sector emissions	% of total emissions
Wastewater emission factors	Assumes higher N_2O emission factor	+1.5	+18%	+1%

Source: Arup (2025) *Updating wastewater treatment pathways for the Seventh Carbon Budget*; CCC analysis.

Figure 13.6 Emissions impact of key sensitivity test for waste



Source: Arup (2025) *Updating wastewater treatment pathways for the Seventh Carbon Budget*; CCC analysis.
Description: The use of an alternative emissions factor for N_2O in wastewater causes an increase in emissions compared to the Balanced Pathway. This increase is highest in 2025, decreasing across the pathway to 2050.

13.4.1 Wastewater emissions factor

A key uncertainty in the waste sector is the wastewater emissions factor. Wastewater emissions have decreased since we published our Sixth Carbon Budget advice due to methodology changes for the greenhouse gas inventory (see Chapter 6 in the Seventh Carbon Budget advice report for more details).[47] However, N_2O emissions are currently based on an emissions factor which could be up to four times too low.[48]

- The N_2O emission factor used in the Balanced Pathway is the current value used within the Carbon Accounting Workbooks and the UK's national GHG emissions statistics.
- In 2019 the IPCC published updated guidelines containing an emissions factor four times higher, which was used for sensitivity tests. The sensitivity test was performed by Arup, and further detail can be found in the accompanying report.[49]

13.5 Contingencies in waste

The contingencies that we have modelled in the waste sector are shown in Table 13.5. See Chapter 5 for our general approach to contingency analysis.

Table 13.5
Contingency option in waste

Contingency	Description	Potential average annual emissions savings ($MtCO_2e$, % of sector emissions)			
		2030	CB6	CB7	2050
Additional investment in wastewater treatment	Investment in more expensive wastewater treatment and faster initial deployment.			0.3 4%	0.8 16%

Source: CCC analysis.
Notes: We have blanked out cells where the contingency measure in question is estimated to deliver less than 0.3 $MtCO_2e$ in potential emissions savings, to focus on high-yield options.

13.5.1 Further investment in wastewater technologies

Further emissions reduction in the wastewater sector can be achieved through a faster rate of deployment of technologies included in our Balanced Pathway along with the implementation of additional, more expensive technologies.

- Our contingency measure implemented a faster rate of deployment by increasing the percentage of maximum site coverage potential achieved in the first stage of technology roll out, from 20% to 30%. In addition, using DESNZ high carbon values resulted in two more technologies being selected to be deployed in our pathway; high strength liquor treatment to address nitrous oxide emissions and vacuum extraction of methane to address methane emissions.[50] Both technologies begin their roll out in 2033.
  - High strength liquor treatment treats nitrous oxide in liquors and side streams, involves upgrading the main treatment works (activated sludge process) to prevent nitrous oxide formation pathways. This technology has a lower technology readiness level than those included in the Balanced Pathway but is currently under investigation across Europe.
  - Vacuum extraction of methane can be used in addition to anaerobic digestion to collect methane from sludge exiting the digester rather than it being collected with the bulk of the biogas. This technology has a similar technology readiness level to those included in the Balanced Pathway but is more expensive.
- Higher levels of investment in wastewater treatment would be required to achieve this additional decarbonisation potential. This would enable more companies to be early adopters of these technologies and more expensive technologies to be included in the deployment mix.

13.5.2 Further action on resource efficiency

Additional action on resource efficiency could further reduce emissions from waste through increased waste reduction. We modelled this continency by adopting the maximum potential for the eight measures used in the Balanced Pathway. This contingency is discussed in our methodology chapter on the industry sector (see Chapter 8).

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[50] Department for Energy Security and Net Zero (2023) *Green Book supplementary guidance: valuation of energy use and greenhouse gas emissions for appraisal*. https://www.gov.uk/government/publications/valuation-of-energy-use-and-greenhouse-gas-emissions-for-appraisal#:~:text=This%20guidance%20provides%20government%20analysts,methodology%20for%20UK%20policy%20appraisal.

Chapter 14: Non-residential buildings

Introduction

The non-residential buildings sector includes emissions from commercial and public sector buildings. The largest emission source is the provision of space heat and hot water. We also consider minor emissions from catering, other fossil fuel uses and anaesthetics used in healthcare.

We developed the Balanced Pathway for non-residential buildings by assessing the extent, pace, and cost of deploying various low-carbon measures, against a counterfactual baseline in which these measures are not adopted. This was informed by testing the cost effectiveness of alternative options.

- In commercial buildings, this is considered against the UK Government's central carbon values, whilst in public sector buildings, this is considered against the Government's high carbon values reflecting the added value in going faster in this area to show Government leadership and help build supply chains to lower costs for commercial and domestic premises.

The non-residential buildings analysis is undertaken in an internal CCC model which is informed by a range of data sources, assumptions commissioned from PwC, the Government's National Comprehensive Assessment model of heat networks, international comparisons and stakeholder engagement.

14.1 Baseline emissions in non-residential buildings

14.1.1 The baseline for non-residential buildings

Our baseline for non-residential buildings represents a scenario in which there is no further decarbonisation action by either the Government or the market in the non-residential buildings sector. See Chapter 1 for our general approach to baselines.

Our baseline for non-residential buildings is based on the following assumptions:

- Energy demands for fossil fuels in public sector and commercial buildings in 2022 are taken from the National Atmospheric Emissions Inventory (NAEI) Energy Background Dataset, which underpins the UK's GHG inventory.[1] Energy demands for electricity and renewable energy are taken from the Digest of UK Energy Statistics (DUKES).[2]

- Bioenergy and heat pump energy use are assumed constant at 2023 levels in the baseline. Growth in demand for each other type of energy is projected using rates of growth from the Government's Energy and Emission Projections (EEP) existing policy scenario.[3] As the projections are up to 2040, our analysis applies the rate of growth from 2035-2040 up to 2050.

- The energy baseline is converted to an emissions baseline using the CCC's assumptions on emissions factors (see the accompanying data tables). This is calibrated to the UK's GHG inventory outturn emissions for 2023.[4]

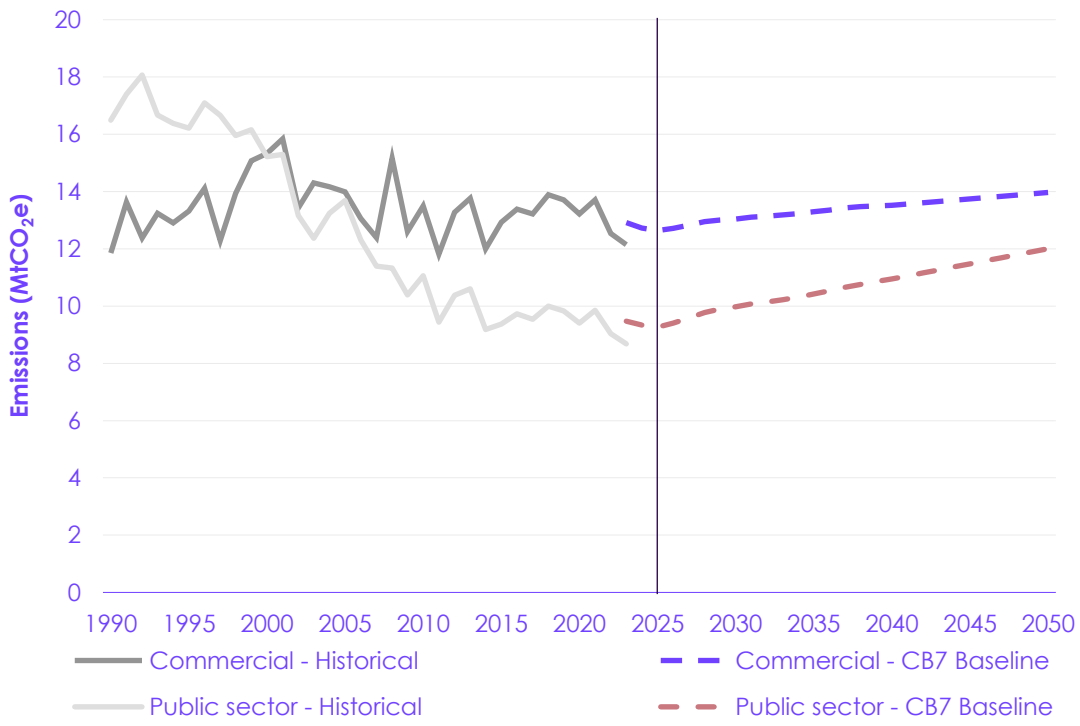
- The energy baseline and associated emissions baseline is broken down using data from Energy Consumption in the UK (ECUK) on the share of each type of energy that is used for different purposes (e.g. heating, catering) in public sector and commercial buildings.[5]

- Minor emissions sources that are not covered in the above analysis, such as emissions from anaesthetics and accidental fires, are assumed to grow with population growth.

In this baseline scenario, emissions would rise by 17% from 2023 levels by 2040 (the middle of the Seventh Carbon Budget period) and by 25% by 2050 (Figure 14.1). The majority of this growth is from the public sector where the Government expects growth to exceed energy efficiency gains, counter to recent trends.

- Baseline emissions and energy demands are inherently uncertain. They will depend, among other things, on the growth of the commercial and public sectors. New, more efficient buildings could add to the stock and in some cases replace existing buildings.

Figure 14.1 Baseline emissions in non-residential buildings



Description: Commercial emissions have fluctuated around a similar level over the last 30 years and have gradual growth in our baseline. Public sector emissions have fallen between 1990 and 2020 and grow in our baseline.
Source: DESNZ (2024) Provisional UK greenhouse gas emissions national statistics 2023, CCC analysis.
Notes: For this sector, we show the baselines for commercial and public sector buildings separately here, to highlight the different historical trends between the two subsectors.

14.2 Pathway assumptions and modelling for non-residential buildings

14.2.1 Modelling the Balanced Pathway for non-residential buildings

Overall modelling approach

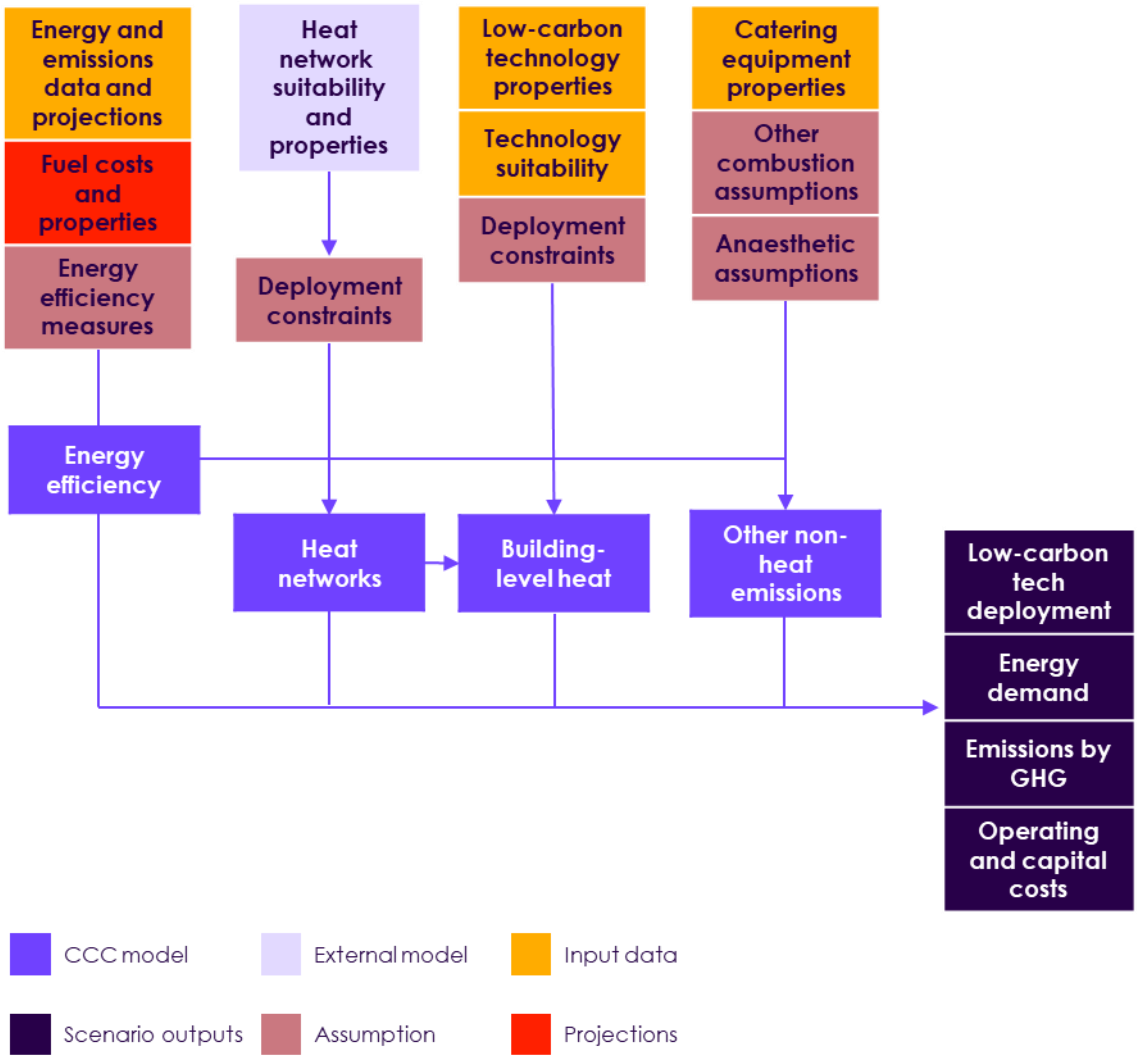
The non-residential buildings model uses a variety of inputs to assess the various sources of non-residential emissions. See Chapter 1 for our general approach to pathway analysis.

The analysis of heat decarbonisation works in a sequential way, first considering energy efficiency, then heat networks, and then building-level heat (Figure 14.2):

- Inputs inform the baseline, the technical suitability of abatement options, the technology properties, costs, and deployment constraints. Beyond the sector specific inputs indicated in Figure 14.2, the model uses the fuel cost, emission factor, and carbon value assumptions used across our Seventh Carbon Budget analysis in all sectors (see the accompanying data tables).

- The model assesses the cost effectiveness of options, which informs take up and the date from which these start to be deployed. In many sections of the model, the deployment is subject to constraints.

Figure 14.2 Modelling schematic for non-residential buildings

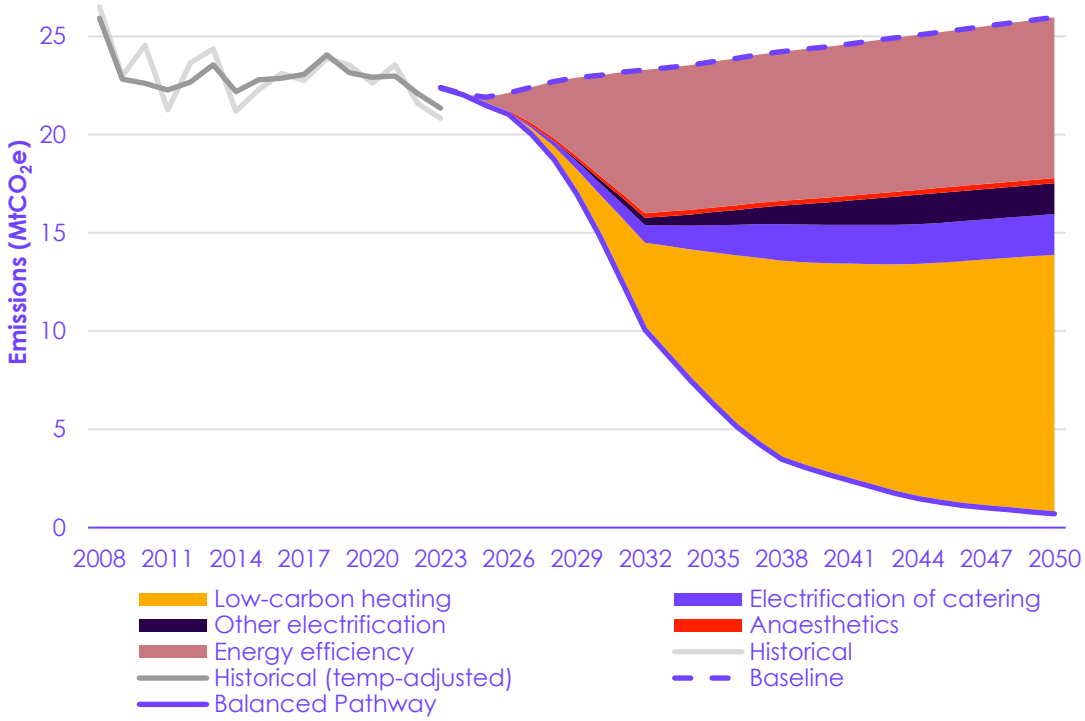


Description: Models for the uptake of low-carbon heating (both at building-level and for heat networks) and energy efficiency play key roles in producing our pathway outputs for non-residential buildings.
Source: CCC analysis.
Notes: This diagram is illustrative and does not detail all model inputs and outputs.

The Balanced Pathway for non-residential buildings

Emissions reduce rapidly during the late 2020s and early 2030s in the Balanced Pathway for non-residential buildings (Figure 14.3). The largest source of emissions reduction is the electrification of heating. There are also significant emissions reductions associated with deploying energy efficiency measures.

Figure 14.3 Sources of abatement in the Balanced Pathway for non-residential buildings



Description: The largest share of emissions reduction in non-residential buildings is from the switch to low-carbon electric heating, followed by energy efficiency improvements. Contributions also come from the electrification of catering and other fossil fuel equipment and reduced emissions from anaesthetics.
Source: DESNZ (2024) Provisional UK greenhouse gas emissions national statistics 2023; DESNZ (2024) Final UK greenhouse gas emissions national statistics 1990-2022; CCC analysis.
Notes: (1) The chart includes historical data both for actual emissions and temperature-adjusted emissions, which account for the impact of year-to-year fluctuations in temperature on heating demand. (2) Our analysis for this sector is based on commercial and public building energy demands in 2022, which is why there is a small gap between the starting point for our analysis and the latest actual emissions data. (3) We generally account for emissions reductions due to measures to reduce demand for high-carbon activities (including low-carbon choices and efficiencies) first, before the impact of low-carbon technologies. (4) Low-carbon heating is mostly electric, but also includes a small amount of low-carbon heat coming from waste heat used in heat networks.

The measures in our pathway

Table 14.1 summarises the measures for reducing emissions in the non-residential buildings sector that are considered within our modelling, how these lead to emissions reductions in our modelling, and the key factors that influence their uptake. The methodology used to develop the assumptions and analysis underpinning these is described in the rest of this section.

Table 14.1
Measures considered within our modelling for non-residential buildings

Decarbonisation measure	How does this measure influence emissions in our modelling?	What are the key factors that affect uptake in our modelling?
Energy efficiency	Reduced energy demand for heat and other uses.	Only measures that are cost effective relative to carbon values are included. There is a steady deployment up to 2032 when all potential is deployed.

Heat networks	Reduced direct emissions through replacing fossil fuel use with low-carbon heat.	Heat network deployment starts from when it is cost effective relative to carbon values and is subject to deployment constraints.
Building-level heat	Reduced direct emissions through replacing fossil fuel use with electrified heat.	Heating systems are replaced by low-carbon alternatives (primarily heat pumps) once this switch becomes cost effective relative to carbon values. The rate of deployment is affected by heating system lifetimes, scrappage rates, and supply chain constraints.
Electrification of catering	Reduced emissions from catering equipment by replacing fossil fuel use.	Catering equipment is electrified when it becomes cost effective relative to carbon values. Measures are deployed in line with natural replacement rates. We assume no supply chain constraints for these technologies.
Electrification of other fossil fuel uses	Reduced emissions from other fossil fuel uses (e.g. for swimming pools and in healthcare).	Equipment is electrified when it becomes cost effective relative to carbon values. Measures are deployed in line with natural replacement rates. We assume no supply chain constraints for these technologies.
Anaesthetic emission reduction	Reduced nitrous oxide emissions associated with anaesthetics.	Assumption taken from the NHS.
Hydrogen	Reduced direct emissions by replacement of gas heating if selected. This is not selected in our Balanced Pathway.	Hydrogen boilers are not taken up in our modelling because they are less cost effective than alternative options.

14.2.2 Energy efficiency

Evidence on the potential for energy efficiency savings and the cost of interventions is drawn from the Building Energy Efficiency Survey (BEES).[6] This covers a range of interventions including fabric efficiency, building systems and controls, and energy management practices.

- As BEES represents evidence for England and Wales, we scale the results up to reflect the UK. We use information at a BEES sector level (e.g. retail, health, education) and map these to commercial buildings and the public sector.
- We exclude several measures from the dataset, to take forward relevant and cost-effective measures.
  - We exclude the industrial buildings sector from BEES as that falls outside the scope of our non-residential buildings sector definition.
  - We exclude some measures that are likely to overlap with other parts of our analysis, for example, the upgrade of heating, cooling, and ventilation plants.

- We exclude some measures such as the replacement of lighting, refrigeration, and IT equipment. This is to reflect that the BEES data is from 2014-15 and many of these types of measures are now considered a default and are included within the baseline.

- The remaining measures were tested for cost effectiveness in sample years. Only measures remaining cost effective compared to central carbon values by 2045 were included in the Balanced Pathway.

- We estimate the energy savings potential from the measures taken forward and compare this to the baseline energy demand in BEES (Table 14.2). We apply these percentage savings to the relevant sections of our UK and devolved administration baselines. We acknowledge there are significant differences between the BEES baseline and our own and in following this method we are assuming that the energy saving potential is scalable to the new baseline. We are also assuming that the potential in England and Wales is representative of potential in Scotland and Northern Ireland for given purposes of energy use.

- We assume that all measures included in the Balanced Pathway are deployed by 2032, with a steady trajectory from 2025. This is based on all the measures being well established technologies or processes and accordingly there being limited supply chain constraints expected. We maintain the percentage energy savings from 2032 onwards.

Table 14.2
Reduction in energy use compared to the baseline from 2032 onwards

	Commercial		Public sector	
	Non-electric	Electric	Non-electric	Electric
Heat and hot water	35%	35%	39%	24%
Catering	10%	7%	14%	11%
Other purposes that include some fossil fuel use	6%	5%	5%	8%
Remaining electrical uses	-	9%	-	15%

Our cost analysis of energy efficiency measures uses the capital costs in BEES uprated to 2023 prices as its main input and operating cost savings are estimated using our fuel cost assumptions (see the accompanying data tables). The minor non-fuel opex impacts have not been accounted for.

- We assess capital costs at a measure category level, e.g. building instrumentation and control, or building fabric, for the main categories (see Table 14.3 for all categories).

- We assume that measures need renewal at the end of their lifetime and capital costs are incurred each time.

- We use lifetimes for each category based on the mix of lifetime assumptions for the measures it includes using the stated lifetimes in BEES. In two cases, we have revised the lifetime assumptions:

  - For building instrumentation and control and carbon and energy management categories we assume a 10-year average lifetime. This is based on Indicative Economic Life Expectancy from the CIBSE Guide M which includes measures akin to those in the building instrumentation and control category.[7]

- We assume that practices included in the carbon and energy management category would be updated at the same time.

- We use a simplified method for estimating capital costs for minor uses outside of our heat and hot water analysis.

Table 14.3 summarises the energy savings from each BEES category of measures deployed in 2032 (when we assume all potential measures are deployed). It also shows the lifetimes for each measure category and the capital cost for the initial deployment (not including any renewals).

Table 14.3
Energy efficiency deployment in the Balanced Pathway

Measure category	Annual non-electric savings in 2032 (GWh/year)	Annual electricity savings in 2032 (GWh/year)	Capex for initial deployment (£ million)	Lifetime (years)
Building instrumentation and control	13,140	1,850	3,530	10
Carbon and energy management	10,160	4,540	1,370	10
Building fabric	9,760	1,110	9,040	25
Space heating	5,180	440	1,420	7
Hot water	180	60	150	10
Swimming pools	110	10	10	5
Ventilation	-	1,480	190	8
Lighting	-	520	120	10
Small appliances	-	270	30	5
Air conditioning and cooling	-	270	40	6
Refrigeration	-	190	10	7
Total	38,530	10,730	15,910	

Source: CCC analysis, BEIS (2016) Building Energy Efficiency Survey.
Notes: Capex is presented in 2023 prices.

14.2.3 Low-carbon heating

Remaining heat demand, after the deployment of energy efficiency measures, is considered for decarbonisation options. We consider the relative cost effectiveness of heat networks and building-level technologies, before choosing a level of heat network deployment. Remaining heat demands are allocated to the most cost-effective suitable building-level technologies. The analytical approach to both types of heat provision involves:

- Applying projected changes in capital costs and technology efficiencies over time to our base assumptions. Using these with our fuel cost projections to assess the levelised cost of providing heat by different technologies in each year.

- Applying constraints to the deployment of heat technologies to reflect supply chain constraints and international evidence of feasible roll-out rates.

The following sections describe the data sources and approach to our building-level heat and heat networks analysis in more detail.

Building-level heat

Technology suitability

Our analysis of building-level heat technologies is based on an illustrative selection of technologies including air-to-air heat pumps, low temperature air-to-water heat pumps, electric resistive heating, and hydrogen boilers.

- Our energy and cost analysis uses air-to-air heat pumps and low temperature air-to-water heat pumps as they are among the most cost-effective technologies, but other types of heat pump may play a role in some circumstances, for example, ground source heat pumps or high temperature air-to-water heat pumps.

- We do not include biomass boilers as a replacement technology based on our view that biomass resources could be better used in sectors with fewer alternatives. Existing biomass boilers are phased out and replaced by heat pumps.

- We do include hydrogen boilers in our modelling and test their relative cost effectiveness, although we note reasons why these are not likely to be the most suitable option (see Box 7.2.2 of the Seventh Carbon Budget advice report). They are not selected, as more cost-effective options are available.

- Existing electric resistive heating is replaced by more efficient air source heat pumps. A small amount of new electric resistive heating is used in the instances where air source heat pumps are not considered suitable. For example, in replacing some localised gas heating systems in commercial buildings.

Our assumptions on heat technology technical potential, efficiencies, lifetimes, and costs are primarily drawn from research commissioned by the Government for non-residential buildings in England and Wales.[8] We apply the evidence drawn from this study to UK heat demand in our analysis.

- This indicates the heat demand that can be met by each potential technology for each BEES sector, split by whether the existing heating system is deemed ‘abated’, ‘wet’, ‘dry’, or ‘local gas’. We use the BEES sectors to map the technical potential against our public/commercial split of demand. A summary is provided in Table 14.4.

- Wet systems are dominant, especially in the public sector. Air-to-water heat pumps are considered suitable to replace all such systems, while air-to-air heat pumps are only modelled as suitable to replace wet systems that are using bulk fuels. Air-to-air heat pumps are considered suitable to replace all current electric resistive heating systems. Local gas systems in commercial buildings will need to be replaced by a mix of air-to-air heat pumps and resistive electric heating dependant on system type.

Table 14.4
Building-level heat technical potential

	Heat demand after deployment of energy efficiency and heat networks in 2040 (TWh)		Share of heat demand that can convert to each low-carbon heat option from the counterfactual technology category			
Counterfactual heating system category	**Commercial**	**Public sector**	**Air-to-water heat pump**	**Air-to-air heat pump**	**Electric resistive**	**Hydrogen boiler**
Dry (electric)	3.8	0.6	-	100%		-
Wet (gas, oil)	18.0	19.6	100%	4%	98%	96%
Local gas	2.6	-	-	70%	30%	-

Source: BEIS (2022) Evidence update of low carbon heating and cooling in non-domestic buildings; CCC analysis.
Notes: This shows technical potential before considering cost effectiveness. Hydrogen boilers are not selected in the Balanced Pathway as more cost-effective options are available. The share of heat demand that can convert to each technology is based on the stock in the source data excluding industrial buildings.

Key technology assumptions applied as the base of our analysis for 2023 are set out in Table 14.5.

Table 14.5
Heat technology assumptions for 2023 used in our analysis

	Efficiency*	Lifetime (years)	Capex (£/kW)	Non-fuel opex (£/kW)
Air-to-air heat pump	283%	20	910	11.7
Air-to-water heat pump (low temperature)	283%	20	1,760	7.2
Hydrogen boiler	86%	15	480	6.9
Electric resistive	100%	15	240	3.4
Biomass boiler	78%	20	770	14.8
Gas boiler	86%	15	270	6.8
Oil boiler	86%	20	330	7.0

Source: BEIS (2022) Evidence update of low carbon heating and cooling in non-domestic buildings; CCC analysis.
Notes: *In situ performance coefficient. Costs from the BEIS study are adjusted to reflect 2023 prices. Opex includes routine maintenance, but not fuel which is accounted for separately. Capex includes preparatory works, installation, completion and sundries. The capex figures and efficiencies stated are used for 2023 and changes over time are applied from this point for some technologies. Our capex assumption for biomass boilers is drawn from the renewal costs provided within the BEIS 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.

Technology costs

We consider changes in capital costs over time and changes in technology efficiency over time.

- We apportion capex into materials capex and labour capex using the shares of capex in Eunomia data.[9] We use data from PwC on how materials capex and labour capex are

expected to change over time, and apply these changes to our 2023 base values for each technology.[10]

- We assume there is a 1% annual increase in heat pump efficiency up to a maximum efficiency of 310%. The maximum value is based on the upper quartile value for air source heat pumps in the source data (where our base assumption uses the median value).[11] The maximum efficiency value is reached by 2035 and is held constant thereafter. Efficiency gains could come from improvements in performance, installation, and use.

- These assumptions, in conjunction with our projections of fuel costs, are used to estimate the levelised cost of delivering heat with different technologies (Table 14.6). We assess when a switch between a counterfactual technology and a replacement technology becomes cost effective relative to carbon values. For building-level technologies, we choose the lowest cost option where there are several suitable options. As air-to-water heat pumps are suitable for replacing all mains gas boilers and are more cost effective than replacing them with hydrogen boilers, no hydrogen boilers are included in our Balanced Pathway.

Table 14.6
Cost outputs for heat technologies

	Year from which the swap becomes cost effective relative to central carbon values	Additional levelised cost of the new technology relative to the counterfactual technology (£/MWh)				
		2025	2030	2035	2040	2050
Air-to-air heat pump – replacing gas boiler	Already	12.4	11.8	10.1	9.5	8.8
Air-to-air heat pump – replacing resistive electric	Already	-45.7	-40.2	-40.9	-40.3	-39.9
Air-to-water heat pump (low temperature) – replacing gas boiler	2029	63.2	59.1	54.7	52.0	47.6
Air-to-water heat pump (low temperature) – replacing oil boiler	Already	48.9	41.7	37.4	34.7	30.4
Hydrogen boiler – replacing gas boiler	2041	67.1	65.3	65.5	65.8	66.4
Electric resistive – replacing local gas heating	2029	58.1	52.0	51.0	49.8	48.7
Heat network – replacing gas boilers	Already	43.7	41.4	39.5	37.6	34.7
Heat network – replacing resistive electric	Already	-14.5	-10.6	-11.5	-12.2	-14.0

Source: CCC analysis.
Notes: Costs are in 2023 prices. The additional cost of heat technologies compared to the technology they replace is presented as a levelised cost per unit of heat delivered. This is over the lifetime of the technology and includes the up-front installation cost and ongoing fuel costs and maintenance costs.

Roll-out rates

Our pathway starts deployment of replacement technologies when they become cost effective, or from 2025 if they are already cost effective. The rate of deployment is determined by replacement rates and supply chain constraints.

- Technologies are generally assumed to be replaced at the end of their expected life based on the lifetimes in Table 14.5. The Balanced Pathway includes some limited early scrappage, meaning that some gas and oil boilers are replaced before the end of their expected lifetime. We assume that:
  - In commercial buildings gas boilers are replaced two years early from 2032 and oil boilers are replaced three years early from 2027.
  - In public sector buildings gas boilers are replaced four years early from 2028 and oil boilers are replaced five years early from 2027.
- The level and timing of scrappage is consistent with the measures remaining cost effective. In the commercial sector this has been tested using central carbon values. In the public sector we have used high carbon values to reflect the added value in going faster in this area to show Government leadership and help build supply chains to lower costs for commercial and domestic premises.
- The analysis of stock replacement gives us a maximum amount of demand for a replacement technology. For heat pumps, we assume that this demand is constrained by supply chain constraints. For other technologies that have well established supply chains, we assume there are no binding supply chain constraints.
  - We estimate limits on annual heat pump deployment by taking current deployment rates for the measure in the UK and applying a compound annual growth rate (CAGR). The CAGRs are estimated using evidence of deployment of large heat technologies internationally (Table 14.7). In commercial buildings the supply chain constraint uses a CAGR of 55% which is based on evidence from the top 10 international cases studied.
  - In public sector buildings the supply chain constraint uses a CAGR of 71% which is based on evidence from the top 5 international cases studied.
- A more ambitious assumption is used for public sector buildings, reflecting the added value in going faster in this area to show Government leadership and help build supply chains to lower costs for commercial and domestic premises.
- We use an average over a larger number of case studies than is used in the residential buildings analysis (see Chapter 7), as the data for non-residential buildings case studies contains smaller sample sizes than for residential buildings.
- We also constrain the level of heat delivered by each low-carbon heat technology so that its stock does not exceed the levels required by 2050 once taking consideration of the deployment of energy efficiency and heat network measures.

Table 14.7
Compound annual growth rates (CAGR) in large heat deployment, international comparisons

Scenario	Countries and technologies included	CAGR	Use in model
Average of top 10 case studies, highest five-year CAGR	Czech Republic – Sanitary hot water heat pumps Denmark – Combined Heat and Power (CHP) Portugal – Sanitary hot water heat pumps Denmark – Heat pumps: very large (>20kW) Spain – Industrial heat pumps (ground source) Belgium – Sanitary hot water heat pumps Slovakia - Sanitary hot water heat pumps Ireland - Sanitary hot water heat pumps Spain - Sanitary hot water heat pumps Denmark – Heat pumps: large (9-20kW)	55%	Balanced Pathway (commercial)
Average of top 5 case studies, highest five-year CAGR	Czech Republic – Sanitary hot water heat pumps Denmark – Combined Heat and Power (CHP) Portugal – Sanitary hot water heat pumps Denmark – Heat pumps: very large (>20kW) Spain – Industrial heat pumps (ground source)	71%	Balanced Pathway (public sector) and contingency (commercial)
Average of top 3 case studies, highest five-year CAGR	Czech Republic – Sanitary hot water heat pumps Denmark – Combined Heat and Power (CHP) Portugal – Sanitary hot water heat pumps	79%	Not used

Source: CCC analysis; European Heat Pump Association; The Danish Council on Climate Change; The Danish Energy Agency.

Heat networks

Our analysis of heat networks is based on research carried out by Arup using DESNZ's National Comprehensive Assessment (NCA) model. More details on this can be found in Box 7.2.

- Our non-residential buildings analysis uses outputs from the NCA model on potential for heat networks split by nation and by BEES sector which we use to map the potential to commercial and public sector buildings.

- The total level of non-residential heat demand analysed in the NCA model represents only around 60% of our non-residential heat baseline by 2040. To handle this discrepancy, and to reflect the uncertainty in technology mix, where the NCA results would allow up to 67% of UK non-residential heat demand to transfer to heat networks, we have taken forward a maximum of 40% overall for non-residential buildings. For commercial buildings this is 41% compared to take up of 42% in our Sixth Carbon Budget analysis and for public buildings this is 39% compared to take up of 44% in our Sixth Carbon Budget analysis.

- Assumptions on the technology mix used in heat networks, the efficiency of these, technology lifetimes, and the capital costs are all taken from the NCA model. Key technology assumptions for 2023 for the different elements of heat networks are summarised in Table 14.8. Our analysis assumes there are 20% distribution losses from the heat generated in heat networks, as in the NCA model.

Table 14.8
Heat network assumptions for 2023 used in our analysis

Energy generation source	Heating technology	Proportion of heat delivered	Efficiency	Lifetime (years)	Capex (£/kW)	Non-fuel opex (£/kW)
Location agnostic sources	Air source heat pump	54%	230%	20	700	2% of capex
Location agnostic sources	Ground source heat pump	13%	230%	20	1000	2% of capex
Water sources	Water source heat pump	14%	240%	20	850	2% of capex
Back up plant	Electric boiler	6%	98%	25	60	2% of capex
Energy from waste		5%	100%		0	2% of capex
Waste heat		8%	356%		0	2% of capex
Additional data						
Energy centre building				40	200	2% of capex
Pipework				60	2269 / m *	2% of capex
Ancillaries					100	2% of capex

Source: CCC analysis; Arup.
Notes: * Pipework costs are per metre of piping. Opex includes routine maintenance but not fuel which is accounted for separately. All costs are in 2023 prices. The capex figures and efficiencies stated are used for 2023 and changes over time are applied from this point for some technologies. Costs associated with energy from waste and waste heat are not accounted for in the buildings sector.

- To treat heat networks consistently with other heating technologies and reflect potential improvement over time, we apply the following changes over time:
  - Capital cost changes over time are based on PWC research.[12]
  - A 1% per annum improvement in efficiency is applied to heat pump components of heat networks. This is applied until a capping value is reached. The capping values are determined by applying the percentage increase (using the uplift from the median to the upper quartile value) for similar measures* in the building-level non-residential data (to the base values in Table 14.8.[13] This results in an increase in weighted average heat network efficiency (after distribution losses) from 182% in 2023 to 201% by 2039.
- We combine these assumptions with projections of fuel costs, to estimate the levelised cost of delivering heat by heat networks. This includes the capital and operational costs including fuel, spread over the lifetime of relevant components. We compare this against carbon values to estimate when heat networks become cost effective. With the assumptions described above and central carbon values, heat networks are estimated to

* Values for air source heat pumps have been used as a proxy for water source heat pumps due to data availability.

be cost effective for replacing gas heating from 2025 and are already cost effective for replacing electric resistive heating.

- We compared the levelised cost of delivering heat by heat networks with the levelised cost of delivering heat at an individual building level using a range of technologies (Table 14.6). On current assumptions, heat networks have lower costs as a replacement for gas heating with wet distribution systems than the main alternative individual technologies (e.g. air-to-water heat pumps), so the Balanced Pathway includes the maximum deployment described above. We have treated heat networks as replacing gas boilers and electric resistive heating based on their respective shares in the baseline in commercial buildings and public sector buildings, assuming that where a network is developed both types of buildings would be included.

The roll-out of heat networks is constrained by deployment constraints.

- The first deployment considered in the Balanced Pathway is from 2027, reflecting that there is a lag in how quickly these can be deployed.

- The long-term growth rate for heat networks assumed in our analysis is 7% average annual growth. This is based on experience in Sweden from 1970-2000 where heat networks are widespread.[14]

- Given the low current prevalence of heat networks in the UK, especially in the commercial sector, we have used a higher CAGR in early years before the 7% average annual growth rate is applied.

  - In the public sector the CAGR starts at 20% in 2027, before gradually reducing and taking up the 7% average annual growth rate from 2033.

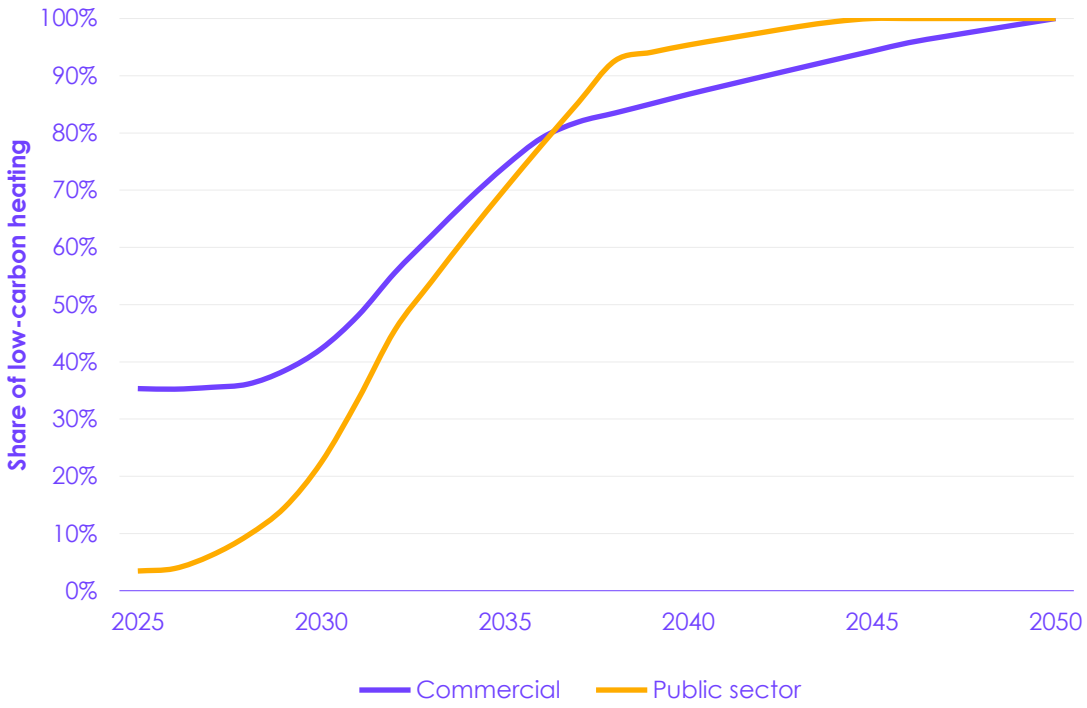
  - In the commercial sector the CAGR starts at 60% in 2027, before gradually reducing and taking up the 7% average annual growth rate from 2037.

- Evidence from the development of heat networks in Denmark shows CAGRs in excess of these levels for short periods in the roll-out of some types of heat networks.[15]

Overall low-carbon heating stock

The impact of deployment of low-carbon heating technologies on the overall share of heat demand being met by low-carbon heating in the Balanced Pathway is shown in Figure 14.4. The current reliance on gas heating in public sector buildings, coupled with our approach of the public sector leading the way, results in a faster conversion towards low-carbon heating in public sector buildings than in commercial buildings particularly through the 2030s.

Figure 14.4 Share of commercial and public sector heat delivered by low-carbon technologies in the Balanced Pathway

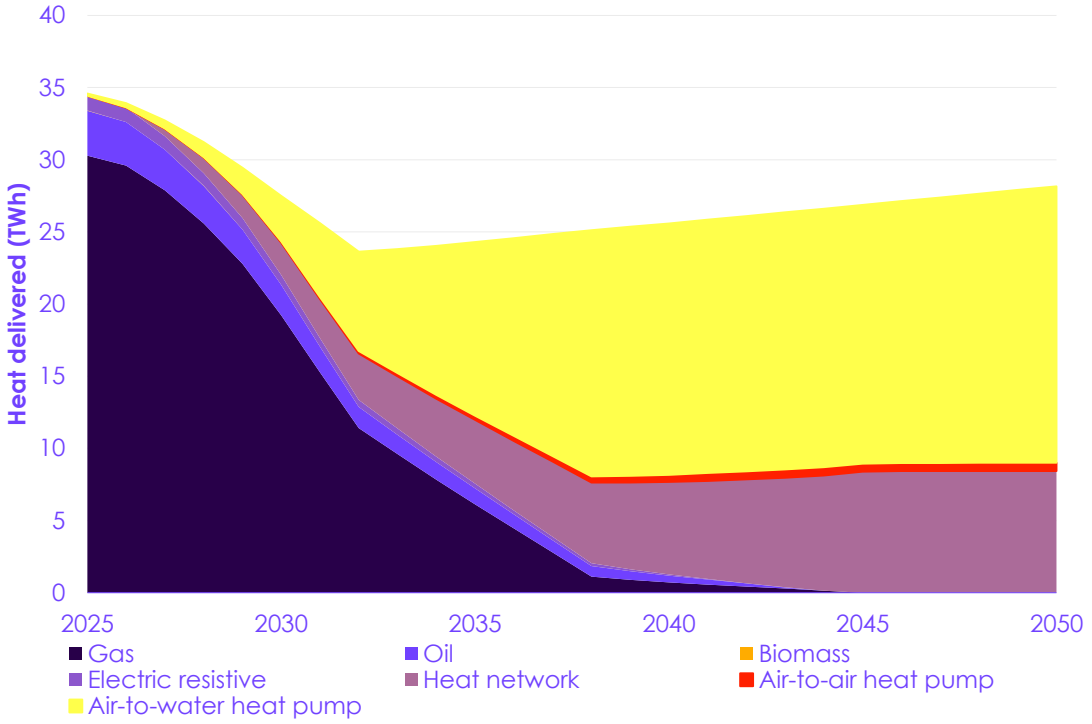


Description: The low-carbon share of heat in commercial buildings grows strongly through the early 2030, before reaching a more gradual rate of increase through to 2050. The public sector starts from a low share of low-carbon heating in 2025 before growing rapidly in the 2030s and reaching 100% before 2050.
Source: CCC analysis.
Notes: The share of heat delivered by low-carbon technology includes heat pumps, new district heating, direct electric heating, and biomass boilers.

Our Balanced Pathway represents an illustrative mix of heating technologies. The actual balance of individual heat pumps and heat networks will depend on a range of factors.

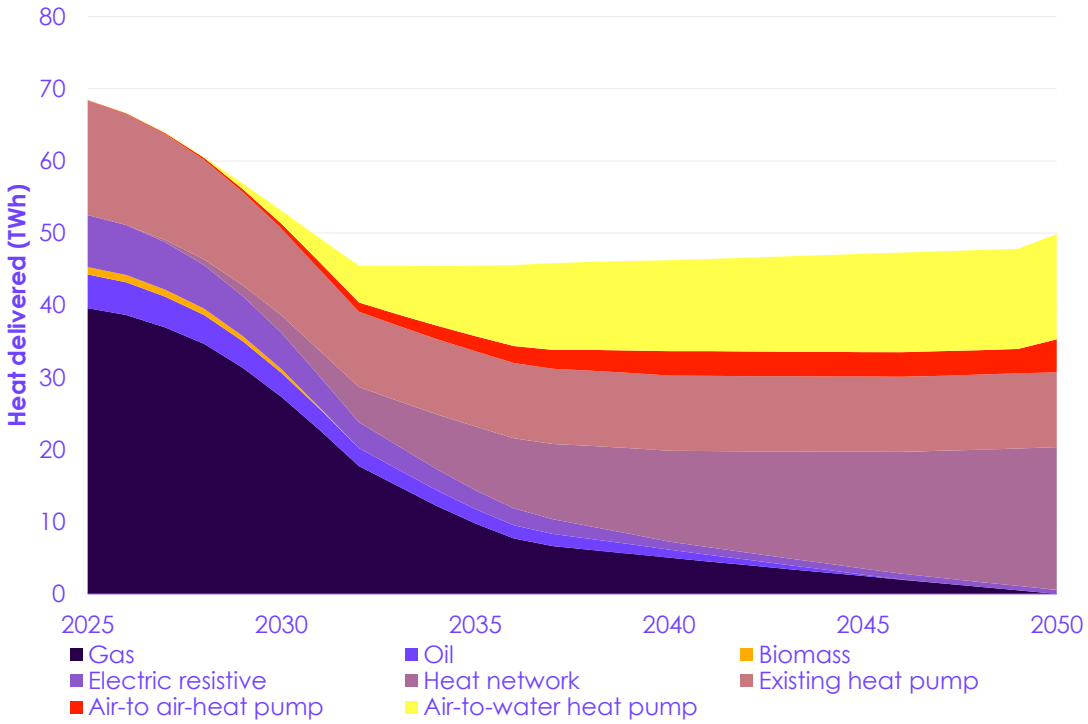
- Air-to-water heat pumps serve the majority of public sector heat demand in our Balanced Pathway (Figure 14.5) providing an efficient alternative to gas systems.
- Heat pumps and electric resistive heating represent a significant share of existing heat demand in commercial buildings. A mix of air-to-water heat pumps, air-to-air heat pumps, and heat networks complete the transition (Figure 14.6).
- The mix of heat pumps taken up could shift further towards cheaper air-to-air heat pumps (that can also provide cooling) if the cost savings become sufficient to outweigh the costs and risks of converting distribution systems. The conversion of distribution systems is not considered in our analysis.

Figure 14.5 Public sector heat demand by technology



Description: Public sector heat is mainly delivered by gas boilers in 2025 and transitions to a mix of heat pumps and heat networks in our Balanced Pathway.
Source: CCC analysis.

Figure 14.6 Commercial heat demand by technology



Description: Commercial heat is delivered by gas boilers and a mix of other technologies in 2025 and transitions to a range of low-carbon sources by 2050.
Source: CCC analysis.
Notes: The majority of existing heat pumps in commercial buildings are reversible air-to-air heat pumps.

14.2.4 Electrification of catering

More than half of non-residential catering energy is currently provided by gas and, to a lesser extent, oil-based products. Electric alternatives are readily available to replace these.

- Our analysis considers a range of catering equipment including hobs, fry tops, deck ovens, rack ovens, and combi-steamers.

- Assumptions on the stock, efficiency, and lifetime of different types of catering equipment are taken from ICF research conducted for the Government.[16] We couple this with more recent evidence on the costs of catering equipment provided by Eunomia.[17]

- We use these inputs to estimate the levelised costs of providing catering requirements and assess when a switch between the counterfactual technology and an electric equivalent becomes cost effective for each type of equipment.

- We assume the switch starts from the year this becomes cost effective, or 2027 if they are already cost effective to allow some time for policy development. Deployment is then based on natural stock replacement rates. We do not apply any supply chain constraint for these mature technologies. Based on this method, all technology replacements are electric by 2030 at the latest.

We use the following simplifying assumptions:

- Hobs are modelled as being replaced by radiant electric hobs. Induction hobs could also be an option, but we are not able to include these in the analysis in a comparable way due to input data sources.

- Our baseline approach, using the split of energy used for different purposes based on ECUK, implies there is currently around 3 TWh of oil-based products used for catering in the UK. Use of oil-based products for fuelling catering equipment is not widely documented. We treat oil-based products allocated to commercial catering as if they are all used in hobs (the technology with the largest share of energy use) and assume that these have similar properties to gas hobs. We do not analyse oil-based products used in public sector catering which is minor. This will show as a residual emission, but in practice we would expect to see these emissions abated.

14.2.5 Electrification of other fossil fuel uses

After accounting for heating, hot water and catering, there is a residual of 8 TWh of fossil fuels in the baseline. ECUK allocates these mainly under hospitals, leisure centres, and hotels. We expect these may include swimming pools for leisure centres and hotels. The source of any additional energy requirements within hospitals is not well documented.

- Given the uncertainty and the relatively small amount of emissions involved, we take a pragmatic approach.

  - We analyse only the natural gas element which represents over 90% of the fossil fuels remaining. Emissions from other fuels are treated as residual emissions, but in practice we would expect these to be abatable.

  - We treat this as though it is gas boilers converting to electric resistive heating. In some cases, e.g. with swimming pools, it is anticipated that heat pumps might be a likely option which would be more efficient.

- The Balanced Pathway starts the switch from gas in 2029 when it becomes cost effective. Deployment is in line with natural turnover of a gas boiler and assumes no supply chain constraints.

14.2.6 Anaesthetics

Anaesthetic gases used in healthcare emit nitrous oxide emissions of around 0.5 $MtCO_2e$ per year. There are a range of options to reduce these emissions including a shift from desflurane to alternatives with lower emissions; effective capture, destruction or reuse of these gases; and reduction in the atmospheric release from leftover nitrous gas canisters.[18]

- The Balanced Pathway includes a 40% reduction in nitrous oxide emissions from anaesthetics used in healthcare by 2032 compared to levels in 2019/20, through the use of waste reduction measures.

- This is in line with what the NHS expects to be achievable while maintaining patient care. We treat this as a cost-neutral measure.

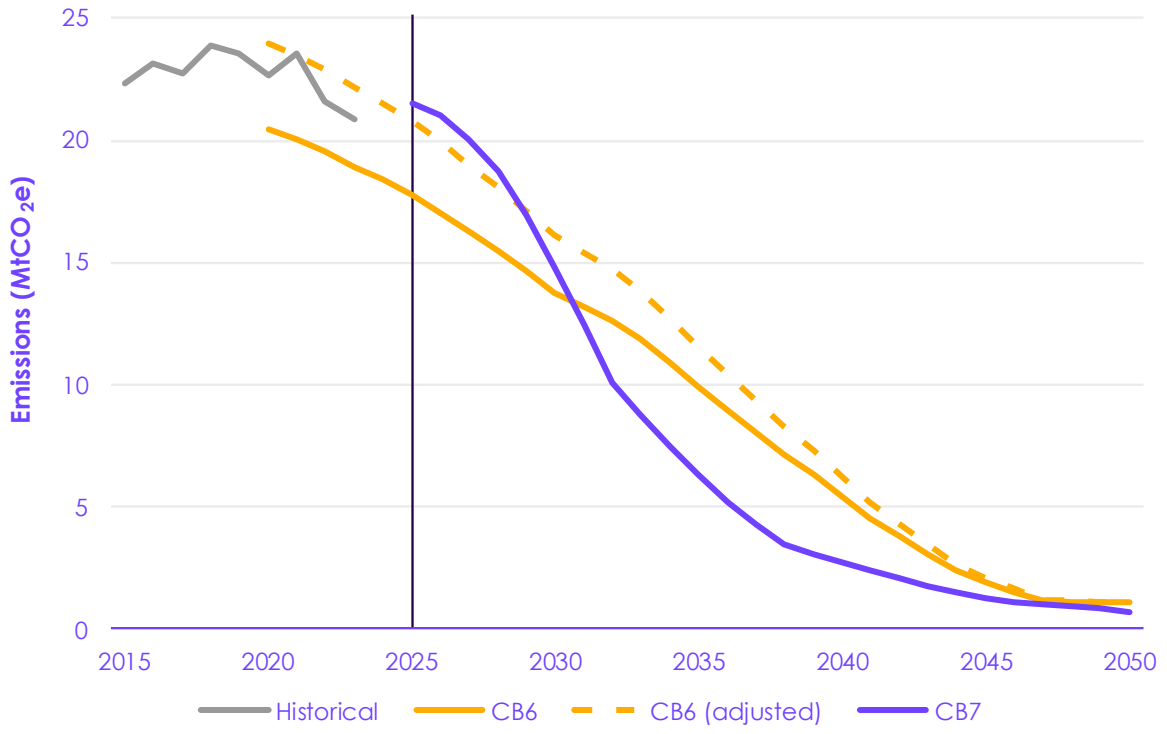
14.3 Changes since our Sixth Carbon Budget advice

14.3.1 Comparison with our Sixth Carbon Budget pathway

Updates to the emissions inventory have moved some emissions that were previously classified elsewhere into the non-residential buildings sector, meaning that the latest historical emissions data is higher than in our Sixth Carbon Budget pathway.* Our Balanced Pathway starts slightly above this historical data to account for recent warmer-than-average winters, but decarbonises more rapidly through the late 2020s and early 2030s (Figure 14.7).

* All comparisons in this section compare the Balanced Pathway in this advice with the Balanced Net Zero Pathway in our Sixth Carbon Budget. Our Sixth Carbon Budget advice also included four other exploratory pathways, which are not discussed here. Data for those pathways can be found in our Sixth Carbon Budget advice.

Figure 14.7 The Balanced Pathway for non-residential buildings compared to our Sixth Carbon Budget advice



Description: The Seventh Carbon Budget (CB7) Balanced Pathway for non-residential buildings starts from a higher level of emissions in 2025 than our Sixth Carbon Budget (CB6) pathway, before decreasing more rapidly in the 2030s.
Source: CCC analysis.
Notes: Estimates of emissions in this sector have been substantially affected by changes in emissions accounting methodologies in the inventory since our CB6 advice. Therefore, to enable easier comparison, we have included a 'CB6 (adjusted)' series estimating what the CB6 pathway would look like if it had used the latest inventory accounting.

14.3.2 Emissions changes since our Sixth Carbon Budget advice

Changes in emissions accounting and warmer-than-average winters have affected emissions from non-residential buildings since our Sixth Carbon Budget advice.

- Updates to the emissions inventory have moved some emissions associated with burning oil use into this sector instead of being classified under industry, meaning that the latest historical emissions data is higher than in our Sixth Carbon Budget pathway.
- The emissions reductions since 2021 have been partly driven by mild winters. To determine the starting point for our pathway, we adjust these emissions to account for this – this results in our Balanced Pathway starting slightly above the latest data.

14.3.3 Key pathway differences compared to our Sixth Carbon Budget advice

There are several key areas in which the deployment rates, measures included, or underlying assumptions in our updated Balanced Pathway have been revised since publication of our Sixth Carbon Budget advice in 2020. These include:

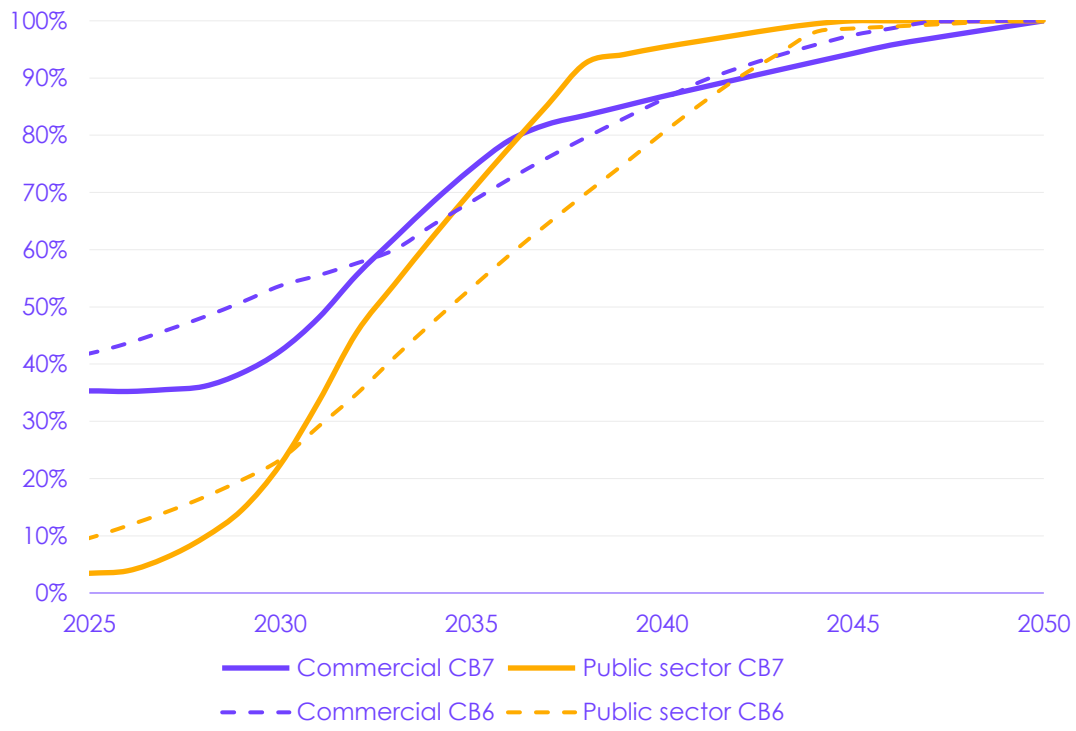
- **Low-carbon heating in non-residential buildings.** There is some delay compared to our Sixth Carbon Budget pathway in the 2020s, but by the end of the 2020s and through the 2030s, our Balanced Pathway has a more rapid roll-out of low-carbon heating (Figure 14.8). This is

partly as we have modelled early scrappage of gas and oil boilers in non-residential buildings. The pace of emissions reduction in non-residential buildings is steeper around 2030 than in our Sixth Carbon Budget pathway.

- The difference is particularly noticeable for public sector buildings where we have modelled a faster pace of decarbonisation, reflecting the aim for the public sector to lead in decarbonising and scaling up supply chains for low-carbon heating.

Figure 14.8 Key differences in deployment trajectories in the Balanced Pathway for non-residential buildings compared to our Sixth Carbon Budget advice

Share of heat delivered by low-carbon sources, for public and commercial buildings



Description: The share of low-carbon heat in the public sector increases more rapidly during the 2030s in our CB7 pathway than in our CB6 pathway. The share of low-carbon heat in commercial buildings in our CB7 pathway increases less during the 2020s but more rapidly in the 2030s than in our CB6 pathway.
Source: CCC analysis.
Notes: Low-carbon heating is including the following: heat pumps, hydrogen boilers (in the CB6 analysis only), biomass boilers, electric resistive heating, and low-carbon heat networks. The chart is shown out to 2050 to show the difference in deployment pace between the public sector and commercial subsectors over the full pathway.

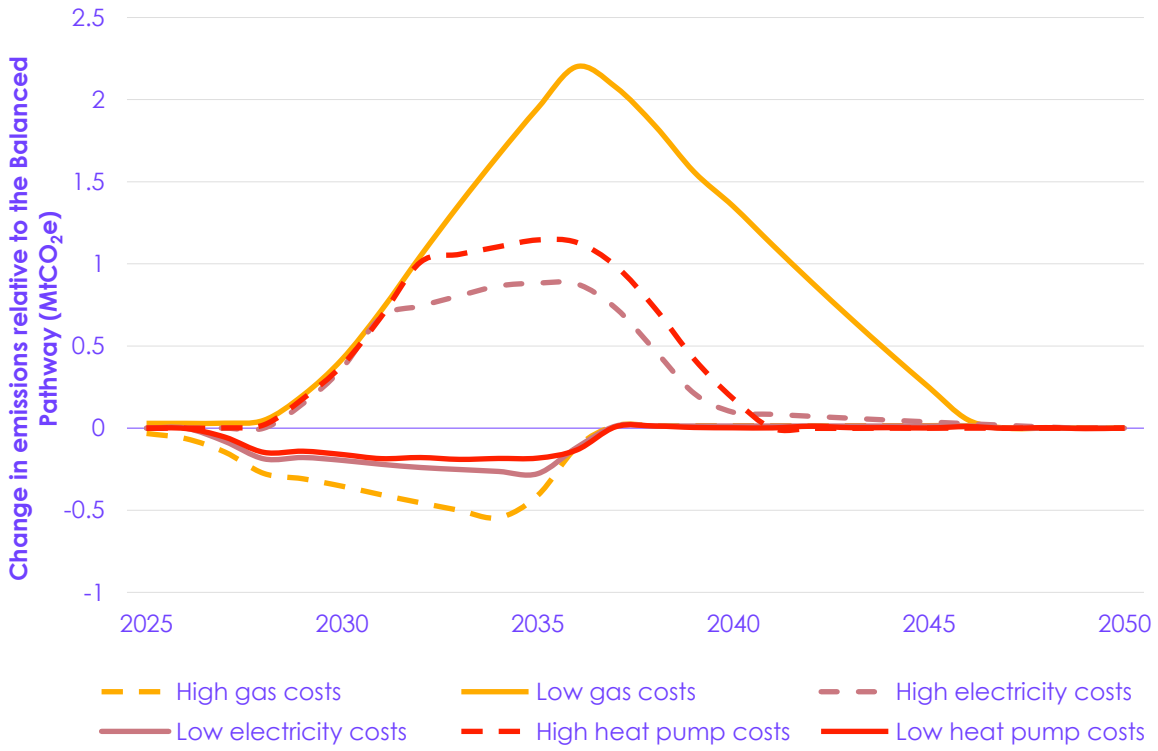
14.4 Uncertainties and sensitivity analysis

The key sensitivity tests that we undertake in the non-residential buildings sector are shown in Table 14.9 and Figure 14.9. See Chapter 5 for our general approach to uncertainty and contingency analysis, including descriptions of the methodology behind sensitivity tests that apply across multiple sectors.

Table 14.9
Key sensitivity tests for non-residential buildings

Sensitivity test	Description	Impact on emissions in 2040		
		$MtCO_2e$	% of sector emissions	% of total emissions
Gas costs	Higher gas costs and correspondingly higher electricity and hydrogen costs	0.0	0%	0%
Gas costs	Lower gas costs and correspondingly lower electricity and hydrogen costs	+1.4	+50%	+1%
Electricity costs	Higher electricity costs	+0.1	+4%	+0%
Electricity costs	Lower electricity costs	0.0	0%	0%
Heat pump costs	Higher heat pump capital costs	+0.2	+7%	+0%
Heat pump costs	Lower heat pump capital costs	0.0	0%	0%

Figure 14.9 Emissions impact of key sensitivity tests for non-residential buildings



Description: Low gas costs, high heat pump costs, and high electricity costs tests result in higher emissions compared to the Balanced Pathway during the 2030s before converging to the Balanced Pathway. High gas costs, low heat pump costs, and low electricity costs tests result in lower emissions in the early 2030s before converging to the Balanced Pathway.
Source: CCC analysis.

14.4.1 Gas costs

As the majority of emissions from non-residential buildings are associated with the use of gas, changes to the cost of gas can have a large impact. In particular, the relative cost of gas compared to electricity dictates when a switch from gas to a low-carbon technology becomes cost effective.

- Our assumptions on fuel costs associated with high and low gas costs can be found in the accompanying data tables. The sensitivity tests include the associated impact on electricity and hydrogen costs. The deployment pathway for building-level heat is adjusted according to the varying gas costs. The impact on the emissions pathway could be greater if the deployment of other measures is altered too.

- **Low gas costs** make the transition to low-carbon heat more challenging. In particular, air-to-water heat pumps (which are the main replacement for gas boilers in our analysis) only become cost effective against central carbon values in 2037. This significantly slows the commercial transition.

- **Higher gas costs** have a more limited positive impact on emissions savings. The switch towards air-to-water heat pumps is brought forward slightly in the commercial sector and we assume a higher level of scrappage is viable. However, the extent to which the public sector transition can be brought forward is likely to be limited since we already model a rapid pace in the Balanced Pathway.

14.4.2 Electricity costs

The majority of abatement in the Balanced Pathway is associated with a shift to using electricity. Changes in the cost of electricity will affect when that becomes cost effective.

- We reflect variation in electricity costs using assumptions on low and high electricity system costs with central gas costs (see the accompanying data tables). The deployment pathway for building-level heat is adjusted according to the varying electricity costs. The impact on emissions pathway could be greater if the deployment of other measures is altered too.

- **High electricity system costs** slow the commercial transition. Air-to-water heat pumps become cost effective from 2032 rather than 2029 and direct electric heating is cost effective to replace gas from 2039 instead of 2029 with central carbon values. The introduction of scrappage is also delayed accordingly. The public sector emissions pathway is unaltered, as air-to-water heat pumps remain cost effective at high carbon values with the high electricity system costs.

- **Low electricity system costs** provide increased emissions savings in the late 2020s and early 2030s. Air-to-water heat pumps and electric resistive heating become cost effective two years earlier in commercial buildings and a higher rate of scrappage can be introduced. The public sector pathway is unchanged, as it cannot reasonably be brought further forward.

14.4.3 Heat pump costs

Heat pumps are one of the most important abatement options underpinning the non-residential pathway. Changes in their cost will affect their cost effectiveness and the timing and cost of the low-carbon transition.

- There are expected to be economies of scale in the supply of heat. In these tests we use the cost for a low consumption user to test a high cost per kW and the cost for a high consumption user to test a low cost per kW (Table 14.10).[19] This implies a 12% increase in

capex inputs for air-to-water heat pumps and an 11% increase for air-to-air heat pumps for the high case; and a 9% reduction for air-to-water and 28% reduction for air-to-air heat pumps in the low case. The tests do not vary the cost of heat pump components of heat networks.

Table 14.10
Heat pump cost sensitivity test assumptions

	Capital cost (£/kW)		
	High consumption buildings (low cost test)	**Central value**	**Low consumption buildings (high cost test)**
Air-to-air heat pump	660	910	1,020
Air-to-water heat pump	1,590	1,760	1,970

Source: BEIS (2022) Evidence update of low carbon heating and cooling in non-domestic buildings; CCC analysis.
Notes: The values are adjusted to reflect 2023 prices.

- **High heat pump costs** delay progress during the 2030s, and accordingly the emissions reduction during this period. Air-to-water heat pumps become cost effective against central carbon values four years later than in our Balanced Pathway, delaying the commercial transition. In public sector buildings, we assume the start of scrappage is delayed by two years.
- **Low heat pump costs** allow air-to-water heat pumps to be introduced in commercial buildings two years ahead of the Balanced Pathway. Due to supply chain constraints during this time, this has a limited impact on emissions reduction.

14.5 Contingencies in non-residential buildings

Contingency options are action plans that can be implemented to deliver additional emissions reductions to make up for shortfalls in the pathway. The contingencies that we model in the non-residential buildings sector are shown in Table 14.11. See Chapter 5 for our general approach to contingency analysis.

Table 14.11
Contingency option in non-residential buildings

Contingency	**Description**	**Potential average annual emissions savings ($MtCO_2e$, % of sector emissions)**			
		2030	**CB6**	**CB7**	**2050**
Faster heat pump roll-out in commercial buildings	Accelerated deployment of commercial low-carbon heating including greater scrappage rates	0.5 3%	0.6 10%	0.5 18%	

Source: CCC analysis.
Notes: We have blanked out cells where the contingency measure in question is estimated to deliver less than 0.3 $MtCO_2e$ in potential emissions savings, to focus on high-yield options.

14.5.1 Faster decarbonisation of commercial heating

This contingency aligns with aspects of the approach to modelling public sector buildings in the Balanced Pathway and extends it to commercial buildings. The public sector is assumed to lead by example, while in the Balanced Pathway we assume the commercial sector would likely follow more in line with what is cost effective (under central assumptions). We do not consider a contingency option for the public sector since it is already modelled ambitiously in the Balanced Pathway.

- This contingency progresses from our Balanced Pathway by:
  - Using high carbon value assumptions to test the cost effectiveness of switching heating technologies to low-carbon alternatives and bringing forward the start to deployment accordingly.
  - Including a higher rate of scrappage of gas and oil boilers and starting this earlier. The level of scrappage is consistent with the switch being cost effective at the higher carbon values. We assume:
    - Gas boilers are replaced 3 years ahead of their natural replacement cycle from 2028.
    - Oil boilers are replaced 5 years ahead of their natural replacement cycle from 2027.
  - Relaxing the supply chain constraint applied to heat pump deployment to use a CAGR of 71% which is based on evidence from the top 5 international cases.
- This contingency option delivers 0.5 $MtCO_2e$ of additional emissions savings in 2040 compared to the Balanced Pathway.

Endnotes

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Chapter 15: Shipping

Introduction

Our analysis to develop the pathway for shipping combines several approaches. Shipping is split into three main subsectors: domestic, international, and naval. Domestic shipping is further split into coastal domestic shipping, and inland waterways and leisure shipping. Our definition of coastal domestic shipping also includes fishing.

Estimates of future emissions, costs, and energy use in the shipping baseline and Balanced Pathway are developed using the July 2024 version of the Department for Transport's (DfT's) Maritime Emissions Model for coastal domestic shipping and international shipping.[1] For both naval shipping and inland waterways and leisure shipping, the equivalent estimates are developed using assumption-driven internal analysis.

- For international and coastal domestic shipping, we used DfT's Maritime Emission Model to estimate greenhouse gas (GHG) emissions, energy use, and costs out to 2050. DfT's Maritime Emission Model applies regulatory constraints and undertakes a cost-optimisation to determine the uptake of new engines or propulsion systems, fuel types or electricity, and efficiency measures to meet the constraints, while considering all additional costs, including carbon values.[*]
  - Our shipping analysis uses slightly different accounting methods to the UK GHG inventory. Due to these emission accounting differences, shipping emissions in the baseline and Balanced Pathway start at a higher level in 2025 than in the most recent inventory estimates.
    - In line with previous CCC recommendations, our shipping analysis measures international shipping emissions based on the movements of ships on international voyages.[†] The inventory measures international shipping emissions based on bunker fuel sales.
    - Our analysis uses the same definition of domestic shipping as the inventory but uses 2019 activity data for estimates of emissions from coastal domestic shipping whereas the inventory uses 2014 activity data.[‡]
  - Further details can be found in the DfT's Maritime Emissions Modelling Framework and the Maritime Decarbonisation Strategy: Analytical Annex.[2]
- DfT's Maritime Emissions Model does not cover naval shipping. Our pathway for this subsector is based on assumptions-driven internal analysis using inventory emissions data. Due to limited public information about the operational and technical characteristics of the naval fleet, we make simplifying assumptions based on stakeholder engagement to

[*] Where it is cost effective to decarbonise faster than required by the regulations, the model would do so. Where meeting the regulations is not cost effective, the model would force vessels to decarbonise anyway.

[†] DfT's definition of UK's international shipping emissions includes 50% of emissions on voyages between a UK port or offshore installation in the UK's Exclusive Economic Zone (EEZ), and a port in another country.

[‡] DfT's definition of UK's domestic shipping emissions includes emissions from journeys between UK ports or offshore installations in the UK's EEZ and all emissions at berth in a UK port or at an offshore installation in the UK's EEZ.

develop a plausible emissions reduction pathway for naval shipping, set out in Section 15.2.5.

- DfT's Maritime Emission Model does not cover inland waterways and leisure shipping. Our pathway for this subset of domestic shipping is based on assumptions-driven internal analysis using inventory emissions data. Due to limited data on the operational and technical characteristics of the fleet, we make simplifying assumptions to develop a plausible emissions reduction pathway for inland waterways and leisure shipping, based on literature reviews and engagement with stakeholders. These are set out in Section 15.2.6.

15.1 Baseline emissions in shipping

15.1.1 The baseline for shipping

Our baseline represents a scenario in which there is no further decarbonisation action by either the UK Government, the EU, the International Maritime Organization (IMO), or the market in the shipping sector. It does not account for the planned inclusion of maritime in the UK ETS, nor does it include any impact from the EU's maritime decarbonisation policies, nor existing or expected IMO regulations. See Chapter 1 for our general approach to baselines.

Shipping emissions increase out to 2050 in the baseline (Figure 15.1). Shipping emissions have fallen since 2008, and in the baseline, they do not rebound to that level. See Figure 15.2 for historical shipping emissions split by international shipping, coastal domestic shipping, inland waterways and leisure shipping, and naval shipping. The baseline is based on the following assumptions:

- Shipping demand in the baseline is mainly based on an unpublished 2024 update of the DfT UK Port Freight Traffic: 2019 Forecasts.[3]
  - Detail about the 2019 forecast and factors that influence shipping demand can be found in the UK Port Freight Traffic: 2019 Forecasts publication.[4] Since we finalised the Seventh Carbon Budget analysis for shipping, DfT has updated the port freight forecast, resulting in lower forecasted demand than assumed in our analysis. The analysis for the March 2025 Maritime Decarbonisation Strategy is based on the same version of the forecast that we use.[5] In this forecast, shipped freight tonnage increases by 11% by 2040 compared to 2022.
  - For subsectors and vessel types where demand forecasts were not available, we assume that demand between 2025 and 2050 remains constant at 2019 levels.
- Estimates of future emissions, energy use, and costs for coastal domestic shipping and international shipping in the baseline are developed using the July 2024 version of DfT's Maritime Emissions Model (see Section 15.2.1 and the Maritime Emissions Modelling Framework for additional detail).[6]
  - Capital costs (capex) and operational costs (opex) for engines, propulsion systems, and efficiency measures for international shipping and coastal domestic shipping are based on estimates from DfT (see the Maritime Emissions Modelling Framework: Inputs and Assumptions for additional detail).[7] Fuel and electricity costs are based on internal analysis (see Chapters 10 and 12).
- Estimates of future emissions, energy use, and costs in the shipping baseline for naval shipping and inland waterways and leisure shipping are developed based on assumptions-driven internal analysis.

- For naval shipping and inland waterways and leisure shipping, we assume that emissions and energy use remain at 2019 levels between 2025 and 2050 for the baseline. Emissions and energy use are based on inventory estimates.[8,9] Opex only reflects the costs of the fuels used, which are based on internal CCC analysis (see accompanying data).

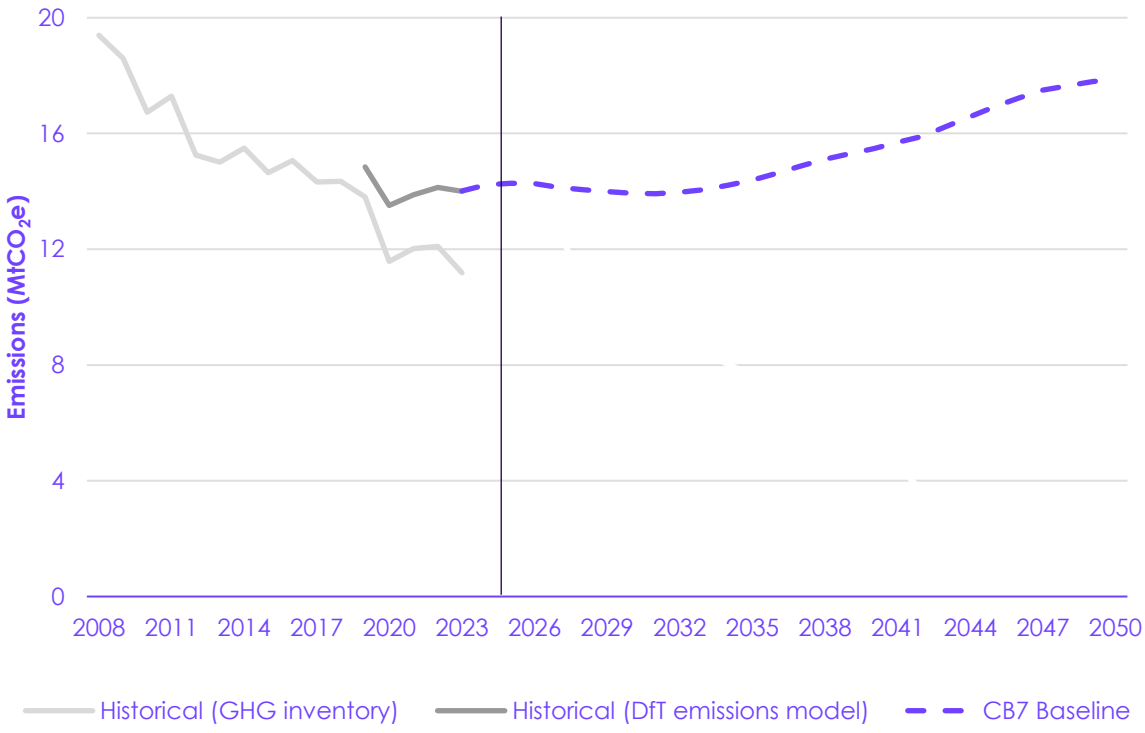
- Due to a lack of public data on the capex of these vessel fleets, we produce estimates based on the capex for coastal domestic shipping. We calculated the 2019 to 2050 average capex per tonne of CO_2e in the baseline for coastal domestic shipping. Using this capex per tonne of CO_2e estimate and our assumption of constant emissions and energy use, we estimate proxy capex for these fleets.

- In the baseline, we assume that only existing fossil fuel engine and fuel types are available until 2050 (see Section 15.2.2) and that new vessels take up the most cost-effective combination. We assume that no further efficiency-improving measures are taken up on vessels.

  - However, there are small improvements in fleet efficiency in the baseline for international shipping and coastal domestic shipping, driven by an assumed increase in vessels sizes over time.

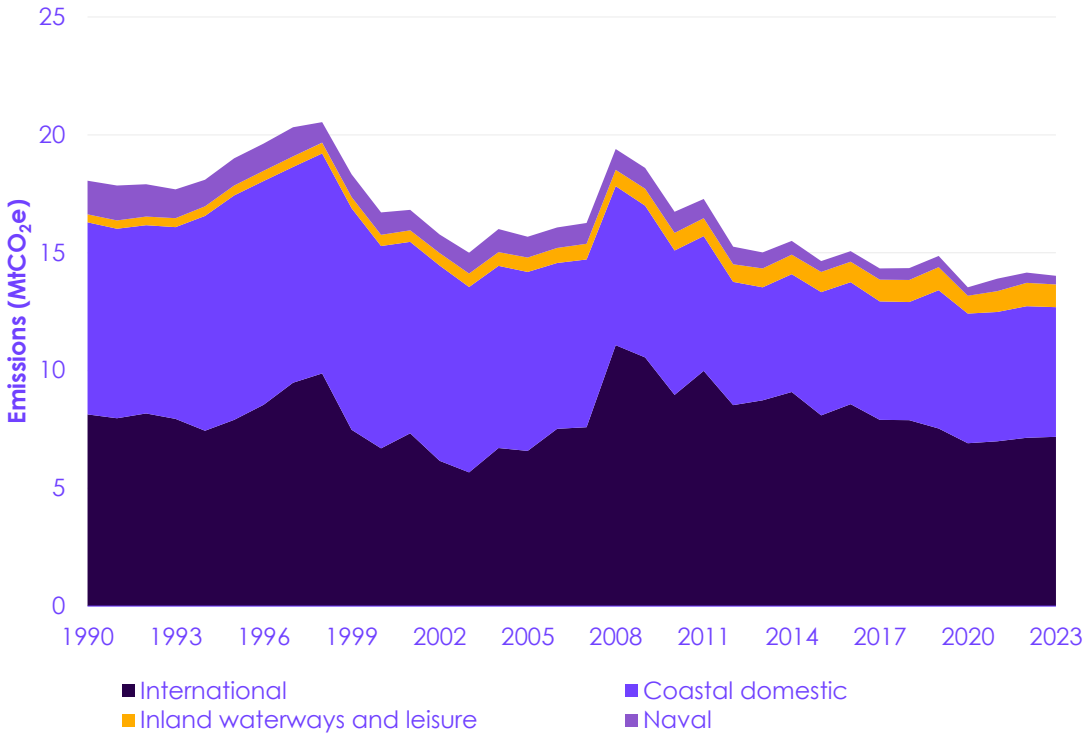
  - In the baseline, 97% of fuel comes from petroleum and 3% from liquified natural gas (LNG) in all years from 2022 to 2040.

Figure 15.1 Baseline emissions in shipping



Description: Shipping emissions increase out to 2050 in the baseline, but do not rebound to 2008 levels.
Source: Department for Energy Security and Net Zero (2024) *Provisional UK greenhouse gas emissions national statistics 2023*; DESNZ (2024) *Final UK greenhouse gas emissions national statistics: 1990 to 2022*; Department for Transport (DfT) (2025) *Maritime emissions modelling framework*; CCC analysis.
Notes: The light grey line shows historical emissions data based on GHG inventory estimates. The dark grey line shows historical emissions estimates based on the DfT's Maritime Emissions Model. We have used the latter as the basis for our pathway modelling (other than for naval shipping and inland waterways and leisure shipping, which are based on the inventory), which is why our pathway begins at a higher level of emissions than the shipping value in the published inventory.

Figure 15.2 Historical emissions by subsector in shipping



Description: Total shipping emissions decrease between 1990 and 2023. International shipping emissions are broadly the same in 1990 and 2023. Domestic shipping is split into coastal domestic shipping and inland waterways and leisure shipping. Total domestic shipping emissions and coastal domestic shipping emissions decrease, but emissions from inland waterways and leisure increase. Naval shipping emissions decrease.
Source: Department for Energy Security and Net Zero (2024) *Final UK greenhouse gas emissions national statistics: 1990 to 2022*; Department for Transport (DfT) (2025) *Maritime emissions modelling framework*; CCC analysis.
Notes: All historical emissions data are based on GHG emissions inventory estimates until 2018. From 2019, coastal domestic shipping and international shipping emissions estimates are based on DfT modelling.

15.2 Pathway assumptions and modelling for shipping

15.2.1 Modelling the Balanced Pathway for shipping

Overall modelling approach

Several approaches are adopted to develop the Balanced Pathway for shipping. The key analytical steps are outlined in Figure 15.3. The approach for coastal domestic shipping and international shipping is set out below. The approaches for naval shipping and inland waterways and leisure shipping are set out in more detail in Section 15.2.4. See Chapter 1 for our general approach to pathway analysis.

Estimates of future emissions, energy use, and costs for coastal domestic shipping and international shipping in the Balanced Pathway are developed using the July 2024 version of DfT's Maritime Emissions Model. A detailed description of the model can be found in DfT's Maritime emissions modelling framework.[10]

- DfT's model uses coastal domestic and international shipping emissions estimates from 2019 as the base year for its forecasts. These estimates are produced using global automated identification systems (AIS) activity data, and global fleet data which provide detail about the vessels, including their type, size, and engine.

- All emissions from energy use onboard vessels are captured by the model – including for both propulsion and auxiliary services.

- The model forecasts the development of the fleet over time, producing estimates for energy use, emissions, and costs. There are three key assumptions underlying the methodology:

  - Ships are assumed to be removed from the fleet when they reach the end of their lifespan, which is assumed to be 25 years for all ship types.

  - The number of ships in the fleet is kept at a sufficient level to meet demand.

  - Ship owners are assumed to act to minimise all costs (including carbon costs) while complying with regulations.

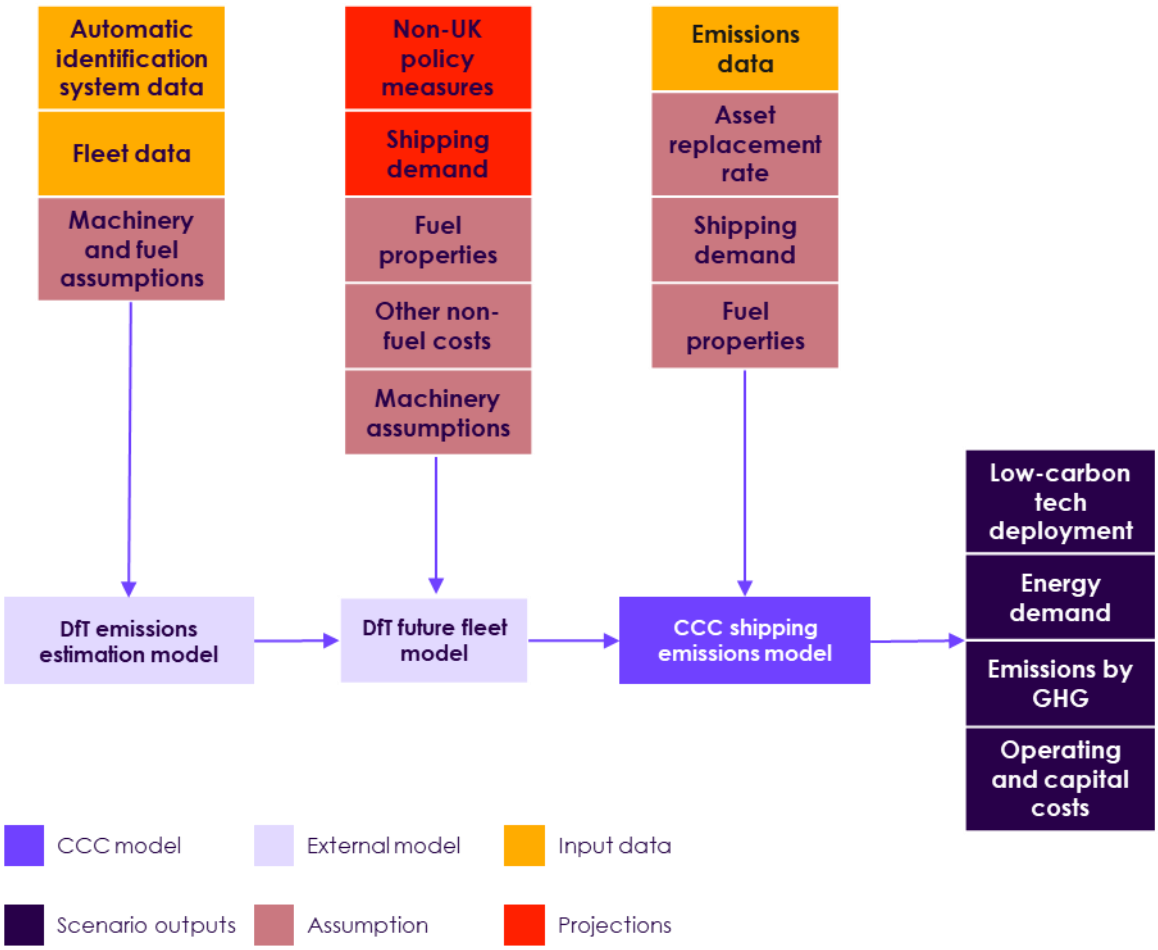
- As for the baseline, shipping demand is mainly based on an unpublished 2024 update of the DfT UK Port Freight Traffic: 2019 Forecasts.[11] For vessel types where demand forecasts were not available, we assume that demand between 2025 and 2050 remains constant at 2019 levels.

- Each individual ship's engines and efficiency improving technologies and operational measures are reassessed every five years, based on the year the ship entered the fleet, to determine the most cost-effective option to meet regulations. However, fuels are selected each year to achieve optimal cost effectiveness, subject to compatibility with the installed engines.

- Cost effectiveness is calculated based on a net present value (NPV) approach, calculated over the remaining lifespan of a ship, using a 3.5% social discount rate.

- The model does not assume any restrictions on availability of low-carbon fuels or the necessary port infrastructure.

Figure 15.3 Modelling schematic for shipping



Source: Department for Transport (DfT) (2025) *Maritime emissions modelling framework*; CCC analysis.
Notes: DfT's analysis covers international shipping and coastal domestic shipping. CCC's analysis also covers naval shipping and inland waterways and leisure shipping.

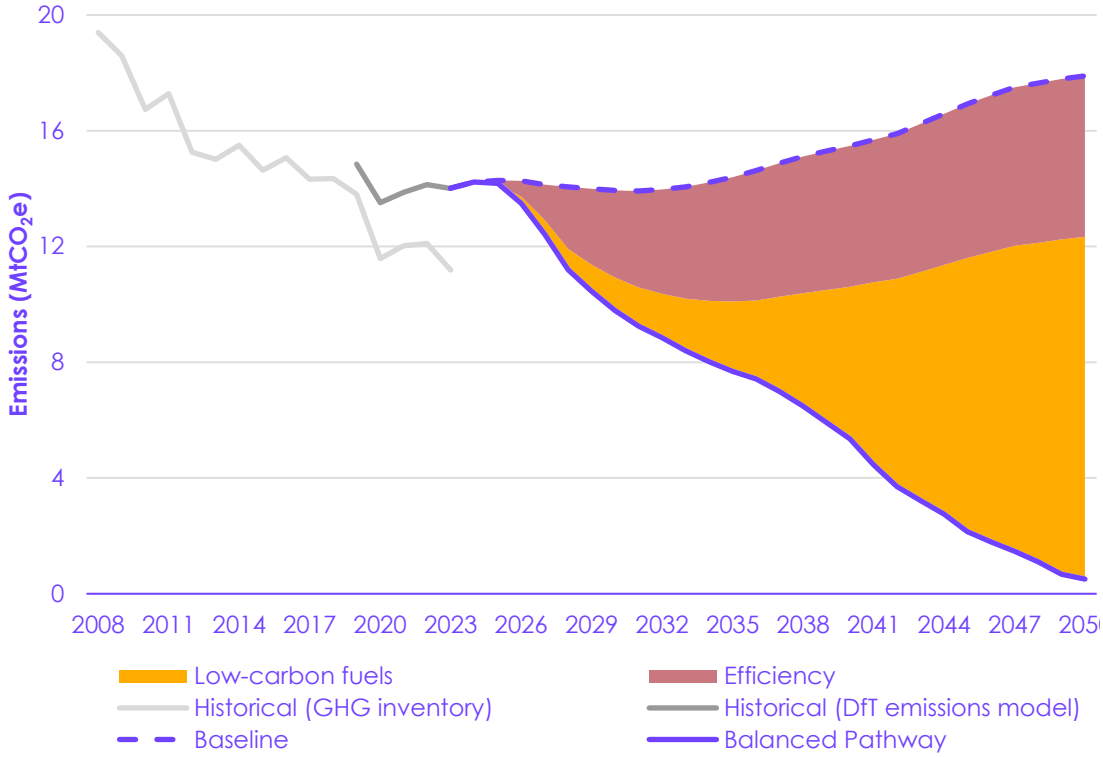
The Balanced Pathway for shipping

The shipping sector can decarbonise through a combination of improving efficiency and switching to low-carbon fuels and electricity. In the Balanced Pathway, shipping emissions fall, relative to 2022 levels, by 62% to 5.4 $MtCO_2e$ by 2040 (the middle of the Seventh Carbon Budget period) and to 0.5 $MtCO_2e$ by 2050 (Figure 15.4).*

In 2040, switching to low-carbon fuels and electricity accounts for 52% of the emissions reduction in shipping, with the remaining 48% coming from efficiency improvements.

* To note, we do not explore the additional global warming impact of international regulations of sulphur levels in shipping fuels in this analysis.

Figure 15.4 Sources of abatement in the Balanced Pathway for shipping



Description: The largest share of emissions reductions in shipping until 2040 is from efficiency improvements, before low-carbon fuels become the main driver of abatement in later years.
Source: DESNZ (2024) *Provisional UK greenhouse gas emissions national statistics 2023*; DESNZ (2024) *Final UK greenhouse gas emissions national statistics: 1990 to 2022*; Department for Transport (DfT) (2025) *Maritime emissions modelling framework*; CCC analysis.
Notes: (1) The light grey line shows historical emissions data based on GHG emissions inventory estimates. The dark grey line shows historical emission estimates based on the DfT's Maritime Emissions Model. We have used the latter as the basis for our pathway modelling (other than for naval shipping and inland waterways and leisure shipping, which are based on the inventory), which is why our pathway begins at a higher level of emissions than the shipping value in the published inventory. (2) We generally account for emissions reductions due to measures to reduce demand for high-carbon activities (including low-carbon choices and efficiencies) first, before the impact of low-carbon technologies.

The measures in our pathway

Table 15.1 summarises the measures for reducing emissions in the shipping sector that are considered within our modelling, how these lead to emissions reductions, and the key factors that influence their uptake. The methodology used to develop the assumptions and analysis underpinning these is described in the rest of this section.

Table 15.1
Measures considered within our modelling for shipping

Decarbonisation measure	How does this measure influence emissions in our modelling?	What are the key factors that affect uptake in our modelling?
Low-carbon fuels and electricity	Vessels take up engines and propulsion systems capable of running on low-carbon fuels or electricity. As vessels switch to low-carbon fuels and electricity, emissions decrease. Low-carbon ammonia and synthetic methanol are the main	For international and coastal domestic shipping, the model selects the engine/propulsion system and fuel/electricity combination that most cost effectively makes each vessel meet the relevant fuel standards or provides a cost saving when the carbon value is added to the cost of fuels. The model considers both capex and opex. Not all engine types

	low-carbon fuels used in the pathway, but low-carbon hydrogen, other synthetic fuels, electricity and biofuels are also used.	are suitable for all vessel types, and the model restricts uptake based on compatibility. For naval shipping and inland waterways and leisure shipping, simplifying assumptions about switching to low-carbon fuels and electricity are used.
Efficiency improving measures	A range of technical and operational efficiency-improving measures are adopted by vessels to reduce the energy used, thereby reducing emissions.	For international and coastal domestic shipping, the model selects the efficiency-improving measures that most cost effectively makes each vessel meet the relevant fuel standards or provides a cost saving when the carbon value is added to the cost of fuels. Not all measures are suitable for all vessel types or in combination with other measures, and the model restricts uptake based on compatibility. No efficiency-improving measures are assumed to be taken up for naval shipping or inland waterways and leisure shipping in the pathway.
Source: Department for Transport (DfT) (2025) *Maritime emissions modelling framework*; CCC analysis.		

15.2.2 Switching to low-carbon fuels and electricity

The vast majority of energy currently used in shipping comes from oil, with some LNG also used.[12;*] To decarbonise shipping, vessels will need to switch to low-carbon fuels and electricity. Several engines and propulsion systems capable of running on low-carbon fuels are under development, and some options are already commercially available. The following low-carbon engines and propulsion systems are included in our analysis.[13;14;†]

- **Methanol engines.** Engines capable of running on methanol are already commercially available and have been ordered by several ship owners. As synthetic methanol is not yet available, these engines are initially assumed to run on fossil methanol.[15;16]
- **Ammonia-powered engines.** These are under development, and limited numbers of ammonia-fuelled vessels have been ordered.[17;18;19]
- **Hydrogen propulsion systems.** Vessels powered by hydrogen fuel cells or engines are also being developed, with a small number of commercial vessels, such as ferries, already operating on hydrogen.[20]
- **Electric propulsion.** There has been some deployment of fully electric vessels, but this is so far limited to smaller vessels on short voyages in the UK.[21;22;‡]

* The inventory does not report any LNG use for shipping, but DfT's Maritime Emissions Model estimated that around 1.1 TWh LNG was used for shipping contributing to the UK's shipping emissions.

† Other measures, such as nuclear propulsion and onboard carbon capture and storage may also contribute to decarbonise shipping. These were not included in DfT's Maritime Emissions Model, and are, therefore, not included in our Balanced Pathway for shipping.

‡ Hybrid-electric vessels are commercially available, but these are not covered by DfT's Maritime Emissions Model.

- **Biofuel engines**. Some biofuels can be used as drop-in fuels in existing engines.[23;24;*]

In our analysis, vessels can take up 2-stroke and 4-stroke spark ignition engines, dual-fuel engines, and compression ignition engines, and Proton Exchange Membrane (PEM) fuel cells. The fuels available to vessels in the pathway are low-sulphur fuel oil (LSFO), marine diesel oil (MDO), LNG, fossil methanol, synthetic methanol, synthetic MDO, synthetic LNG, low-carbon ammonia, low-carbon hydrogen, electricity, and biodiesel.[†] Of these, the synthetic fuels, low-carbon ammonia, low-carbon hydrogen, electricity, and biodiesels count as low-carbon in our analysis. All others count as high carbon.

We have aligned our assumptions about when different engine types become available and their related storage systems' capex and non-fuel opex with DfT assumptions, which can be found in the Maritime Emissions Modelling Framework: inputs and assumptions.[25] Table 15.2 below sets out all fuels included in the Balanced Pathway for shipping, and the years from which we assume they are available. This is based on review of current policy and regulations, and global supply forecasts.

Table 15.2
Fuels and electricity in the Balanced Pathway for shipping

Availability	Fuels	Explanation
Today	Low-sulphur fuel oil, marine diesel oil (MDO), liquified natural gas (LNG), and fossil methanol.	Fuels that are already used in shipping are allowed in the model straight away.
2028	Domestic low-carbon hydrogen and domestic low-carbon ammonia.	The earliest domestic production site of hydrogen is due to be operational in 2028 (see Chapter 12). As low-carbon ammonia is produced from hydrogen we assume 2028 as the year domestic ammonia becomes available.
2030	Electricity, imported low-carbon hydrogen, imported low-carbon ammonia and biofuels.	We align our assumption about when electric propulsion vessels enter the fleet with DfT assumptions. Low-carbon hydrogen and ammonia are assumed to be available to import from 2030, in line with broader energy supply assumptions. We have not allowed biofuels to be used for coastal domestic or international shipping but have allowed them to be used in inland waterways and leisure shipping from 2030 in our analysis. This is based on analysis of where the limited supply of sustainable biofuels can best deliver emission reductions across sectors (see Chapter 12).
2035	Synthetic fuels (synthetic methanol, synthetic MDO and synthetic LNG).	These fuels are produced through combining low-carbon hydrogen with CO_2 from direct air capture (DAC). Intergovernmental Panel on Climate Change (IPCC) inventory guidelines are unclear regarding reporting of emissions savings from such fuels. As a result, we assume that all synthetic fuels are produced domestically and are available from the same year that DAC becomes available – 2035 (see Chapter 18).[‡]

* Due to limited availability of sustainable biofuels, they are only used for the inland waterways and leisure shipping fleet in our analysis (see Chapter 12).

† Synthetic fuels are produced through combining low-carbon hydrogen with CO_2 from direct air capture.

‡ However, due to DfT's Maritime Emissions Model smoothing results over five years, low amounts of synthetic fuels begin to be used in 2033 in the shipping sector.

15.2.3 Uptake of efficiency-improving measures

Efficiency-improving measures include a variety of technological and operational measures that improve the energy efficiency of a vessel and thereby reduce emissions.[26] Some efficiency measures are already cost effective and being adopted globally.[27] However, due to limited evidence regarding the current adoption of efficiency-improving measures on vessels contributing to the UK's shipping emissions, no efficiency measures are adopted before 2025 in the model.

- In our analysis, only coastal domestic shipping and international shipping take up efficiency-improving measures.
- Table 15.3 below sets out all efficiency-improving measures available in our analysis for the Balanced Pathway for shipping, and a brief description of each. We have aligned our assumptions about efficiency-improving measures (costs, impacts on air pollutants and fuel consumption, and which vessel types they are suitable on) with DfT assumptions.
- The Maritime Emissions Modelling Framework: inputs and assumptions workbook contains details about the different efficiency measures covered in our analysis, the years in which they are allowed, on which vessels they are allowed, and which measures can be adopted in combination with other measures. [28]

Table 15.3
Efficiency improving measures in the Balanced Pathway for shipping

Efficiency improving measure	Definition
Air lubrication bubbles	Introduction of air bubbles under the ship's hull to reduce friction and improve fuel efficiency.
Wind assistance (rotors/sails/wings)	Use of wind-powered devices like rotors, sails or wings to assist the ship's propulsion and reduce fuel consumption.
Wind assistance (kites)	Use of kite-like structures to capture wind energy and assist the ship's propulsion.
Organic Rankine Cycle waste heat recovery	Organic Rankine Cycle systems recover waste heat from a ship's engine and use it to power an alternator for auxiliary power.
Steam waste heat recovery	Use of waste heat to generate steam, which powers turbines to generate electricity.
Rudder bulb	A bulbous protrusion fitted to the rudder of a ship designed to improve hydrodynamics by reducing flow separation and drag.
Pre-swirl propeller ducts	A device fitted around the propeller designed to increase the inflow velocity, leading to increased propulsive efficiency.
Vane wheel	A rotating disc fitted to the stern of a ship designed to increase propulsive efficiency by reducing rotational losses.
Contra-rotating propeller	A system in which two propellers rotate in opposite directions on a single shaft, increasing propulsion efficiency.
Twisted rudders	Rudder design that is twisted along its length to improve manoeuvrability and reduce drag.
Boss-cap fin	A small fin mounted on the hull near the propeller, used to reduce turbulence and increase propulsive efficiency.

Turbo-compounding in series	A system in which waste heat from the engine is used to drive a turbine, which then powers a generator to produce electricity.
Solar power	The conversion of sunlight into electricity using photovoltaic (PV) cells or panels.
Energy saving lighting	The use of energy-efficient lighting systems to reduce energy consumption and operating costs.
Engine derating	The reduction of engine power to improve fuel efficiency and reduce emissions.
Energy storage battery + power take-off	A system that uses batteries to store electrical energy to then power the propeller shaft (as a hybrid vessel) or for auxiliary purposes.
Hull coating management	Management of the ship's hull coating to prevent corrosion and reduce biofouling.
Trim optimisation	Adjusting the angle of a ship's hull to achieve the most efficient balance between speed, fuel consumption, and stability.
Draft/displacement optimisation	Adjusting the weight and balance of a ship to achieve the most efficient draft and displacement, improving speed, fuel consumption, and stability.
Speed optimisation	The reduction of ship speed to reduce fuel consumption and emissions.

Source: Department for Transport (2025) *Maritime emissions modelling framework*.

15.2.4 International and coastal domestic shipping

This section sets out the specific assumptions applied in DfT's Maritime Emissions Model to develop the Balanced Pathway for international and coastal domestic shipping, and additional internal analysis.

- **Fuel standards.** Fuel standards set targets on vessels, or vessel fleets, that requires them to decrease the emissions intensity (emissions per unit of energy use) of their energy or fuel usage. We assume that the EU's existing fuel standard is applied to all ships within its scope from 2025, and that the size limit drops from 5,000 gross tonnes (GT) to 400 GT in 2037.[29] In addition, we assume that an IMO fuel standard is introduced in 2027 and applies to all vessels over 5,000 GT (dropping to 400 GT in 2037) on international voyages. The IMO fuel standard is based on DfT analysis of what would be required to meet the targets set out in the IMO's 2023 GHG Strategy.[30] It is loosened slightly to allow fossil methanol and MDO until 2035, when synthetic alternatives become available in our analysis (see Chapter 12). See Figure 15.5 for an overview of the fuel standards.

- **Emission pricing.** For coastal domestic shipping, which the UK Government regulates, we applied the Government's central carbon value, phased in linearly from 0% in 2024 to reach 100% in 2030.[31] For voyages between the UK and the EU, 50% of emissions are already included in the EU ETS. We applied an internally developed estimate of the EU ETS carbon price to all shipping in scope of the EU ETS between 2025 and 2027, then expanded it to apply to all vessel types and sizes from 2028. To estimate the EU ETS carbon price, we calculated the annual average of several forecasts between 2024 and 2030.[32] For 2031 to 2050 we used a projection of the UK's ETS carbon price scaled by the 2028 to 2030 average ratio between the EU ETS forecast and the UK ETS projection.[33] Figure 15.6 shows our estimates of the EU ETS carbon price over time.

- **Fuel properties.** We assume constant fuel properties over time for fuel density, calorific values, and combustion emission values for CO_2, N_2O and CH_4. Fuel density and calorific

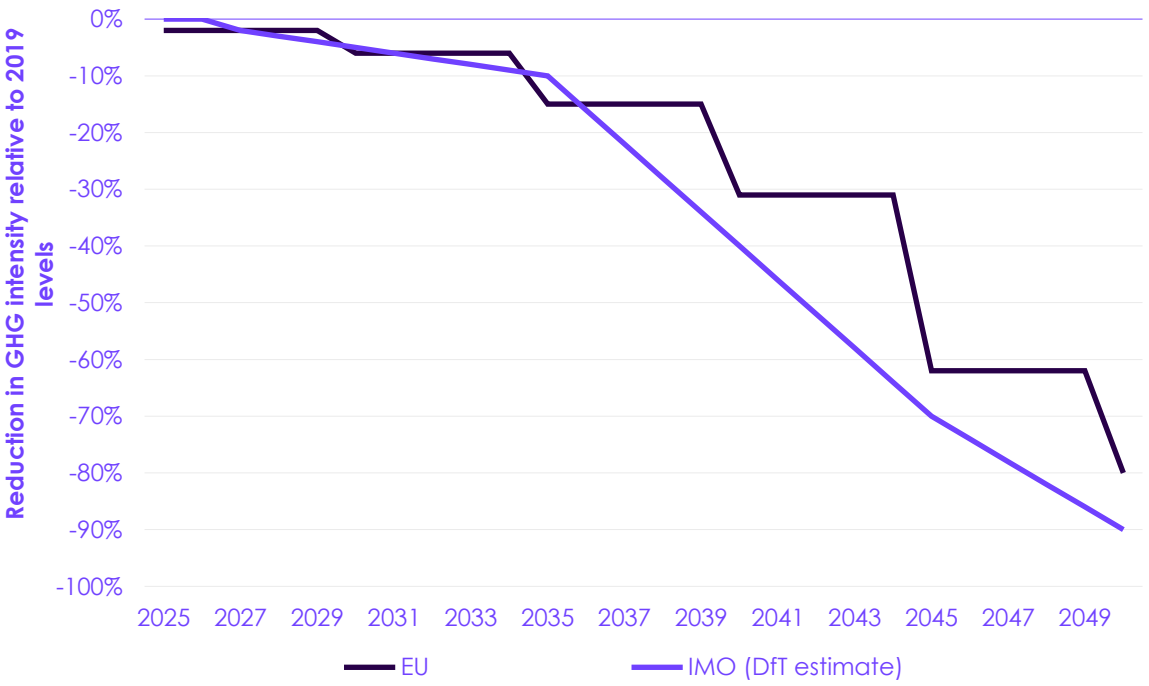
values are taken from DESNZ estimates.[34] Combustion emission values are based on DfT estimates.[35]

- **Energy costs.** Fuel and electricity long-run variable costs (LRVC) are developed internally (see Section 1.7.2). All hydrogen, electricity, and ammonia before 2030 is assumed to be produced domestically. Fossil fuels and ammonia from 2030 are assumed to be imported. We use LRVC estimates for both imported and domestically produced synthetic fuels in our analysis, as described below:

  – Current international carbon reporting guidelines are unclear regarding reporting of emissions savings derived from imported non-biofuels. See the UK's 1990-2021 Greenhouse Gas Inventory, Section 1.8.2.3, for the relevant guidelines.[36] Intergovernmental Panel on Climate Change (IPCC) inventory guidelines currently do not allow for internationally produced synthetic fuels to count as low carbon in the UK and the guidelines will need to be clarified to allow for imported non-biofuels to contribute to UK territorial emissions savings.

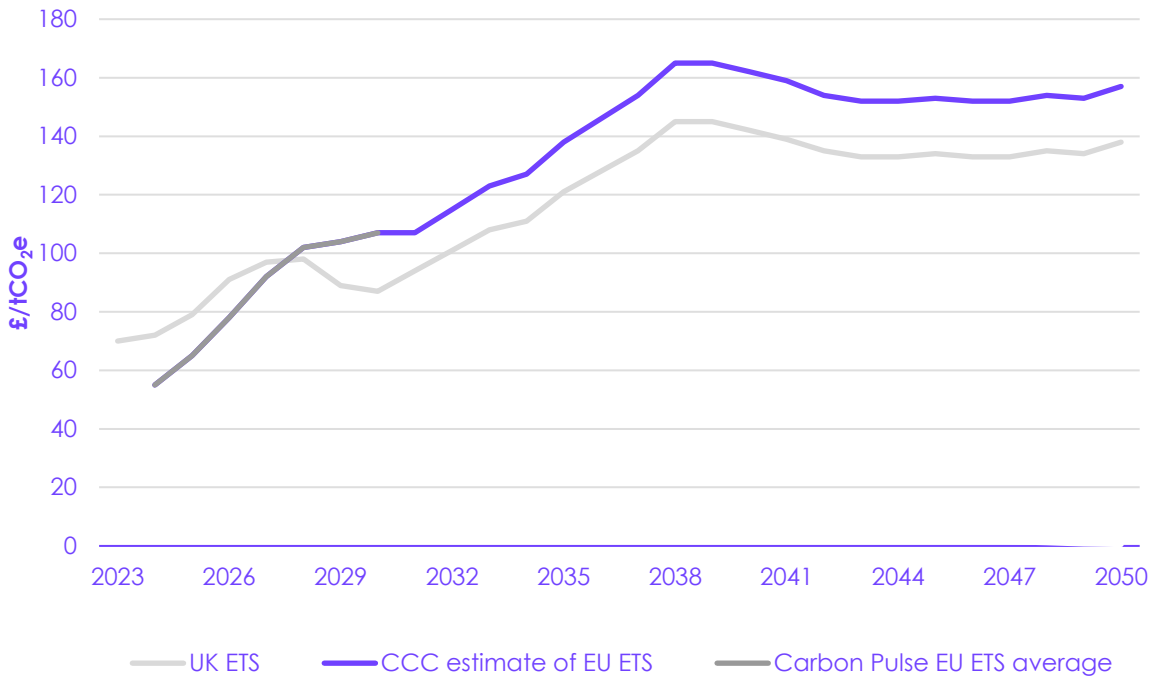
  – In practice, future synthetic fuel production and supply is likely to operate in an international market. The DfT Maritime Emissions Model runs used to develop the pathway for coastal domestic and international shipping use estimates of international LRVCs for synthetic fuels in their optimisation. However, given the uncertainty in accounting for internationally traded synthetic fuels, we thereafter adjust upwards the fuel costs based on estimates of domestic synthetic fuel prices.

Figure 15.5 EU and IMO fuel standards for shipping



Description: The GHG intensity of vessel energy use required by both the EU fuel standard and DfT's estimate of the IMO fuel standard tightens out to 2050.
Source: European Union (2023) *Regulation (EU) 2023/1805 of the European Parliament and of the Council of 13 September 2023 on the use of renewable and low-carbon fuels in maritime transport, and amending Directive 2009/16/EC*; Department for Transport (DfT) analysis.
Notes: The IMO fuel standard is estimated by DfT, based on the IMO's lower targets, and loosened to allow some fossil fuels until 2035, when our modelling allows synthetic fuels.

Figure 15.6 UK and EU emissions trading scheme carbon prices



Description: The CCC estimate and the average Carbon Pulse estimate of the future EU ETS carbon value increase up to the late 2030s, after which they decrease slightly and remain broadly flat out to 2050.
Source: Department for Energy Security and Net Zero (2023) *Traded carbon values used for modelling purposes, 2023*; Carbon Pulse (2024) *POLL: Analysts again slash EUA price forecasts amid no signs of demand recovery*; CCC analysis.
Notes: This graph is in 2023 prices.

15.2.5 Naval shipping

Naval shipping accounted for around 0.4 $MtCO_2e$ of shipping emissions in 2022. Information about the naval fleet and its operational patterns is restricted, resulting in uncertainty over which energy sources and efficiency measures will be suitable for the naval fleet.

- **Energy demand.** Due to uncertainty about future naval activity, we assume that naval energy demand remains at 2019 levels between 2025 and 2050.
- **Timing.** Drawing on stakeholder engagement, we assume that fuel switching to low-carbon fuels and electricity does not start until 2035.
- **Uptake of low-carbon energy sources.**
  - We assume that vessels in the fleet have a 25-year lifetime to align with the assumptions in DfT's emissions model. We assume that the fleet has a constant replacement rate, leading to the assumption that 4% of the naval fleet's energy use switches to low-carbon sources each year from 2035.
  - We assume that the low-carbon energy mix in each year has the same mix of fuels as coastal domestic shipping in each year from 2035.
- **Efficiency improving measures.** We assume no take-up of any efficiency measures on the naval fleet.
- **Costs.** As the capex for naval vessels are not publicly available, we use the 2019 to 2050 average capex per tonne of CO_2e abatement for coastal domestic shipping as a proxy to

estimate the capex per tonne of CO_2e abatement for naval shipping. Opex reflects the cost of the fuels used.

15.2.6 Inland waterways and leisure shipping

Inland waterways and leisure shipping accounted for around 1.0 $MtCO_2e$ of shipping emissions in 2022. The fleet is made up of inland goods-carrying vessels, motorboats and workboats, personal watercraft, and sailing boats with auxiliary engines. There is limited evidence about the existing fleet regarding vessel types, ages, and operational patterns. As the most suitable decarbonisation solutions of a vessel vary depending on these factors, we make simplifying assumptions to develop a plausible decarbonisation pathway for inland waterways and leisure shipping.[37]

- **Energy demand.** We assume that energy demand from inland waterways and leisure shipping remain at 2019 levels between 2025 and 2050.

- **Uptake of low-carbon energy sources.** We assume that half of the fleet (by energy use) switches to electric propulsion and that the other half switches to drop-in biofuels.

  – Based on detailed review of the literature, electric propulsion will likely play a key role to decarbonise this part of shipping, and some electric vessels are already available on the market.[38] However, it is uncertain whether electric propulsion will be suitable for all vessel types.

  – Many vessels have long lifetimes, and the embodied carbon is high compared to the carbon emitted from their usage.[39] For these vessels, and vessels where electricity is not a suitable option, biofuels could be an appropriate decarbonisation solution.

- **Timing.** There is limited enabling infrastructure for electric propulsion at present and there is a need to develop suitable policies for the use of biofuels for shipping. Decarbonisation of inland waterways and leisure shipping is therefore delayed until 2030 in our Balanced Pathway.[40] From 2030, we assume a constant rate of fuel switching to biofuels and electricity, with complete uptake by 2050.

- **Costs.** Due to a lack of data about the inland waterways and leisure fleet, we use the 2019 to 2050 average capex per tonne of CO_2e abatement for coastal domestic shipping as a proxy to estimate the capex per tonne of CO_2e abatement for inland waterways and leisure shipping. Opex reflects the cost of the fuels used.

- **Efficiency-improving measures.** Inland waterways and leisure shipping is assumed to not take up any efficiency measures due to limited evidence about the existing fleet.

15.2.7 Scotland, Wales and Northern Ireland

Our approach for apportioning UK emissions to Scotland, Wales and Northern Ireland varies by subsector, depending on how the subsector pathways have been developed. DfT's base year (2019) results are split by nation, but the forecasting model only provides UK-wide results for 2020 onwards for coastal domestic and international shipping. For historical emissions until 2022, we use the inventory's emissions estimates for Scotland, Wales, and Northern Ireland.[41] The below sets out our approach for estimating emissions by nation, both for previous years where inventory estimates by nations are not yet published, and for future emissions projections.

- **International shipping.** For 2023 and 2024, we adjust DfT's UK-wide emissions estimates using the average ratio between DfT and inventory estimates for international shipping between 2019 and 2022. We use the inventory's 2019 international shipping emissions split by nation. From 2025 onwards, we use DfT's UK-wide emissions estimates and DfT's 2019 international shipping emissions split by nation.

- **Domestic shipping.** For 2023 and 2024, we adjust DfT's UK-wide emissions estimates for coastal domestic shipping using the average ratio between DfT and inventory estimates for coastal domestic shipping between 2019 and 2022. We add emissions from inland waterways and leisure shipping (assumed to remain at 2019 levels). We then use the inventory's 2019 domestic shipping emissions split by nation. From 2025 onwards, we combine DfT's coastal domestic shipping estimates and our internally developed estimates for inland waterways and leisure shipping. We then use a combination of DfT's 2019 estimate for coastal shipping and the inventory's 2019 estimate for inland waterways and leisure shipping to apportion emissions between Scotland, Wales, and Northern Ireland.

- **Naval shipping.** We use the inventory's 2019 naval shipping emissions split for each nation, held constant out to 2050.

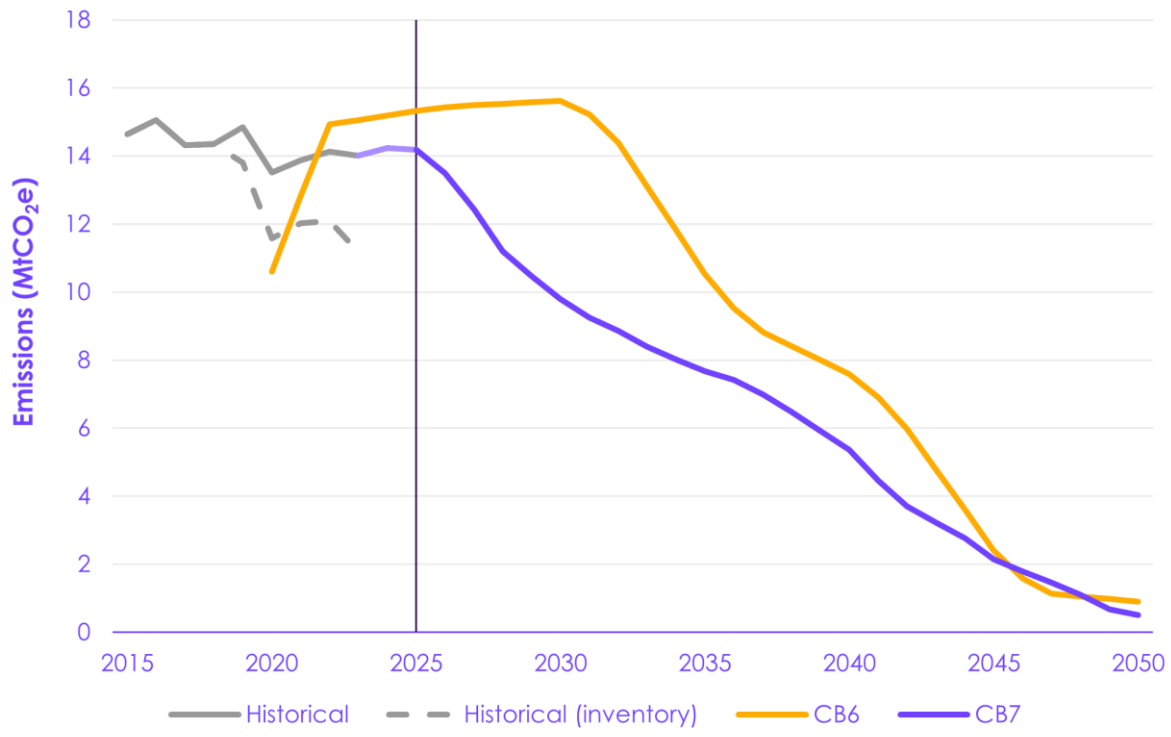
15.3 Changes since our Sixth Carbon Budget advice

15.3.1 Comparison with our Sixth Carbon Budget pathway

Emissions reductions in shipping start from today (2025) in our Balanced Pathway, rather than only beginning from the early 2030s as in our Sixth Carbon Budget analysis.* Our Balanced Pathway is largely developed using the DfT's Maritime Emissions Model, which has a higher estimate of shipping emissions than the published inventory due to emissions accounting differences. This largely negates the reduction in shipping emissions reported in the inventory over recent years, meaning that the starting point of our Balanced Pathway is similar to that for our Sixth Carbon Budget pathway (Figure 15.7).

* All comparisons in this section compare the Balanced Pathway in this advice with the Balanced Net Zero Pathway in our Sixth Carbon Budget. Our Sixth Carbon Budget advice also included four other exploratory pathways, which are not discussed here. Data for those pathways can be found in our Sixth Carbon Budget advice.

Figure 15.7 The Balanced Pathway for shipping compared to our Sixth Carbon Budget advice



Description: The Sixth Carbon Budget (CB6) emissions pathway for shipping starts at a higher point in 2025 compared to that for the Seventh Carbon Budget (CB7), and emissions increase out to 2030 before beginning to decrease. In the CB7 pathway, shipping emissions start decreasing from 2025, reaching slightly lower residual emissions in 2050 compared to CB6.
Source: Department for Energy Security and Net Zero (2024) *Final UK greenhouse gas emissions national statistics: 1990 to 2022*; Department for Transport (DfT) (2025) *Maritime emissions modelling framework*; CCC analysis.
Notes: Historical emissions are based on GHG inventory estimates until 2018. From 2019 onwards, the grey line shows historical emissions estimates based on DfT's Maritime Emissions Model, and the dotted grey line shows historical emissions estimates based on the inventory. We have used DfT's modelling as the basis for our pathway modelling for CB7 (other than for naval shipping and inland waterways and leisure shipping, which are based on the inventory), which is why our pathway begins at a higher level of emissions than the shipping value in the published inventory. For CB6, we used inventory estimates as the basis for our shipping pathway.

15.3.2 Emissions changes since our Sixth Carbon Budget advice

Reductions in emissions from shipping since our Sixth Carbon Budget advice and changes in the emissions accounting approach on which our pathway is based have had opposite effects on the estimate of emissions used as the starting point for our Balanced Pathway for shipping.

- **Emissions.** Emissions from shipping have decreased since our Sixth Carbon Budget analysis. Following the COVID-19 pandemic, there has been a decline in internationally shipped tonnage and the number of sea passengers.[42] It remains to be seen whether shipping emissions might increase beyond pre-pandemic levels.

- **Emissions accounting.** Our Balanced Pathway is based on a different emissions accounting approach, which has increased the estimated emissions starting point for our shipping pathway compared to the accounting approach used for our Sixth Carbon Budget advice.

  - For our Sixth Carbon Budget advice, we used inventory estimates of coastal domestic shipping emissions, whereas we have used DfT estimates of coastal domestic shipping emissions for this analysis.

  - For our Sixth Carbon Budget advice, for international shipping emissions, we converted modelled emissions estimates based on activity data onto a bunker fuel sales basis to

align with inventory estimates, using the 2019 ratio between inventory estimates and model estimates. For our Balanced Pathway analysis, we base international shipping emissions on activity-based estimates.

15.3.3 Key pathway differences compared to our Sixth Carbon Budget advice

There are several key areas in which the deployment rates, measures included, or underlying assumptions in our updated Balanced Pathway have been revised since the publication of our Sixth Carbon Budget advice in 2020. These include:

- **Demand forecast.** In our Sixth Carbon Budget analysis, future shipping demand was based on the DfT UK Port Freight Traffic: 2019 Forecasts.[43] This forecast predicted significantly higher demand than the forecast we use for our Balanced Pathway analysis. This difference is largely a result of updated forecasts for GDP.

- **Emissions model.** For our Sixth Carbon Budget analysis, we used results from UMAS' Global Transport Model (GloTraM) for DfT's Clean Maritime Plan.[44] The GloTraM operates on similar logic to DfT's Maritime Emissions Model – using an NPV approach to cost optimise shipowner and operator decisions, while considering regulations and emissions pricing. However, the models also have differences and used different assumptions. A detailed overview of UMAS' modelling can be found in Smith et al. (2018).[45]

- **Initial uptake of decarbonisation measures.** In our Sixth Carbon Budget advice, uptake of efficiency improving measures and low-carbon fuels and electricity did not start until 2030. By contrast, we now assume that uptake of decarbonisation measures starts from 2025, reflecting that several measures are already available or will be available before 2030, and to align with the approach taken for analysis in other sectors (Figure 15.8). This results in earlier, but less steep, decarbonisation.

- **Fuel mix.** Our Balanced Pathway now includes a wider fuel mix than our Sixth Carbon Budget advice, for which the fuel mix was dominated by low-carbon ammonia with limited uptake of synthetic methanol. This is largely a result of changes related to fuel-cost estimates.

- **Modelling scope.** There are several differences in modelling scope compared to our Sixth Carbon Budget pathway:

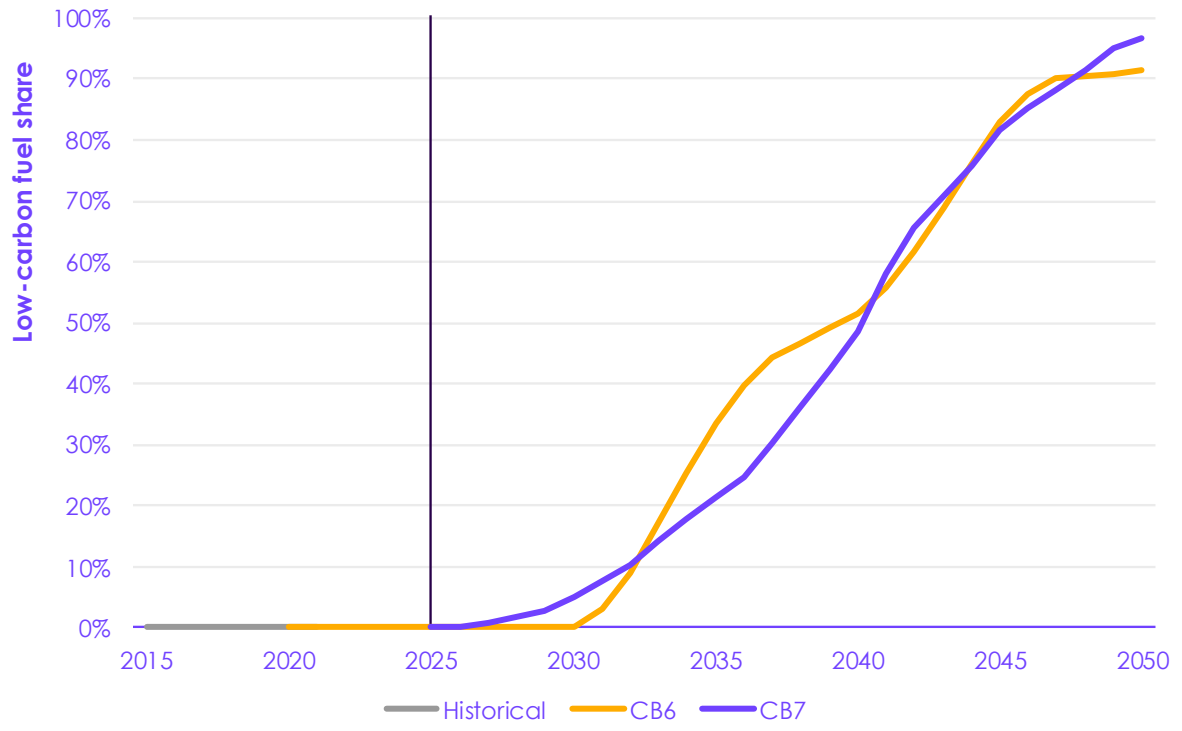
  - In our Sixth Carbon Budget advice, we assumed no emissions reductions of naval shipping. We now assume limited uptake of low-carbon fuels for naval shipping in our Balanced Pathway.

  - In the Balanced Pathway, we assume that inland waterways and leisure shipping will decarbonise using electricity and biofuels, following stakeholder engagement and review of the literature. In our Sixth Carbon Budget pathway, we assumed that it would use the same fuel mix as coastal domestic shipping and international shipping.

  - Our Sixth Carbon Budget advice included uptake of shore power. Due to the scope of DfT's Maritime Emissions Model, our Balanced Pathway now does not include shore power.

Figure 15.8 Key differences in deployment trajectories in the Balanced Pathway for shipping compared to our Sixth Carbon Budget advice

Low-carbon fuel share of UK shipping fuel



Description: Uptake of low-carbon shipping fuels start earlier but ramps up more slowly in the CB7 pathway compared to the CB6 pathway.
Source: CCC analysis.
Notes: For CB6, low-carbon fuels include low-carbon ammonia, synthetic fuels, and low-carbon hydrogen. For CB7, it additionally includes electricity and biofuels.

15.4 Uncertainties and sensitivity analysis

There are inevitably uncertainties around how the drivers of our pathway will develop over the next 25 years. We undertake sensitivity tests to explore the effect of some of the main uncertainties which influence our pathway, namely: energy costs, international shipping regulations, technology costs, and future shipping demand.

All sensitivity tests are carried out using DfT's Maritime Emission Model as described above, with different assumptions for the relevant variables.* Table 15.4 and Figure 15.9 set out how the emissions change based on the different sensitivities. See Chapter 5 for our general approach to uncertainty, including descriptions of the methodology behind sensitivity tests that apply across multiple sectors.

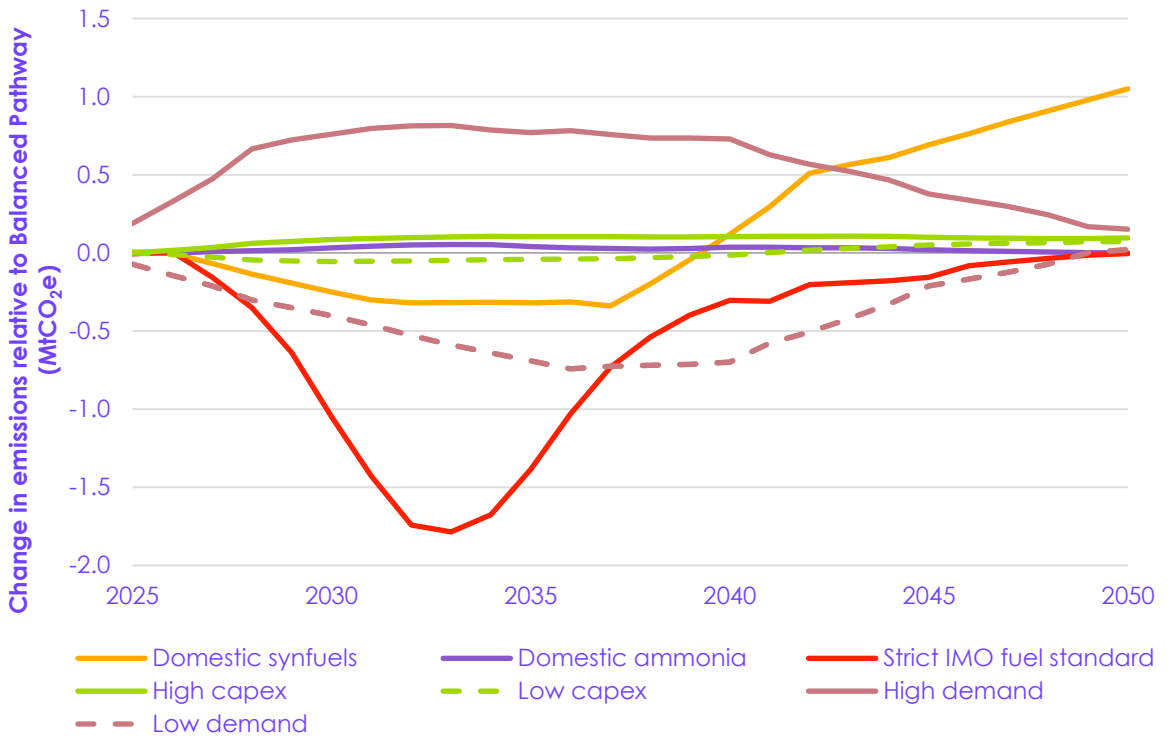
* Sensitivities were developed based on the September 2024 version of the Maritime Emissions Model.

Table 15.4
Key sensitivity tests for shipping

Sensitivity test	Description	Impact on emissions in 2040		
		$MtCO_2e$	% of sector emissions	% of total emissions
Fuel costs	IPCC guidelines are not changed to allow for imported synthetic fuels to be counted as low-carbon fuels in the UK and all synthetic fuels are assumed to be domestically produced. For this sensitivity, the Maritime Emissions Model optimises using domestic LRVCs for synthetic fuels.	+0.1	+1%	0%
	All ammonia is assumed to be domestically produced.	0.0	0%	0%
International shipping regulations*	A stricter IMO fuel standard is assumed.	-0.3	-3%	0%
Capital costs	Capex for low-carbon technologies are assumed to be 10% higher compared to the Balanced Pathway.	+0.1	+1%	0%
	Capex for low-carbon technologies are assumed to be 10% lower compared to the Balanced Pathway.	0.0	0%	0%
Shipping demand	Future shipping demand is assumed to be 19% higher in 2040 compared to the Balanced Pathway, based on DfT's high demand forecast.[46]	+0.7	+7%	1%
	Future shipping demand is assumed to be 14% lower in 2040 compared to the Balanced Pathway, based on DfT's low demand forecast.[47]	-0.7	-7%	-1%

Source: Department for Transport (2025) Maritime emissions modelling framework; CCC analysis.
Notes: *See Figure 15.10 for a comparison of the IMO fuel standard used for the Balanced Pathway and for this sensitivity test.

Figure 15.9 Emissions impact of key sensitivity tests for shipping



Description: All sensitivities have limited impact on overall shipping emissions, with no sensitivity changing 2040 shipping emissions by more than 1MtCO2e.
Source: Department for Transport (2025) *Maritime emissions modelling framework*; CCC analysis.

15.4.1 Energy costs

Future energy costs are inherently uncertain, as many of the technologies underpinning the fuel use are still under development, and it is unclear whether fuels will be imported or produced domestically. We explore the impact of different cost assumptions for low-carbon ammonia and synthetic fuels, as these are the key fuels used to decarbonise shipping in our Balanced Pathway.

- **Synthetic fuels.** As detailed in Section 15.2.4, international guidelines are currently unclear regarding reporting of emissions savings derived from imported non-bio synthetic fuels. We therefore explore the impact on emissions of letting the DfT Maritime Emissions Model optimise using estimates of domestic LRVCs for synthetic fuels. A higher cost of synthetic fuels changes the fuel mix used to decarbonise shipping, but has a limited impact on the level of emissions. This sensitivity test results in 0.1 $MtCO_2e$ higher emissions in 2040, compared to the Balanced Pathway.

- **Low-carbon ammonia.** To explore the impact of a higher cost for low-carbon ammonia, we assume that all ammonia is domestically produced for this sensitivity. This does not impact shipping emissions in 2040.

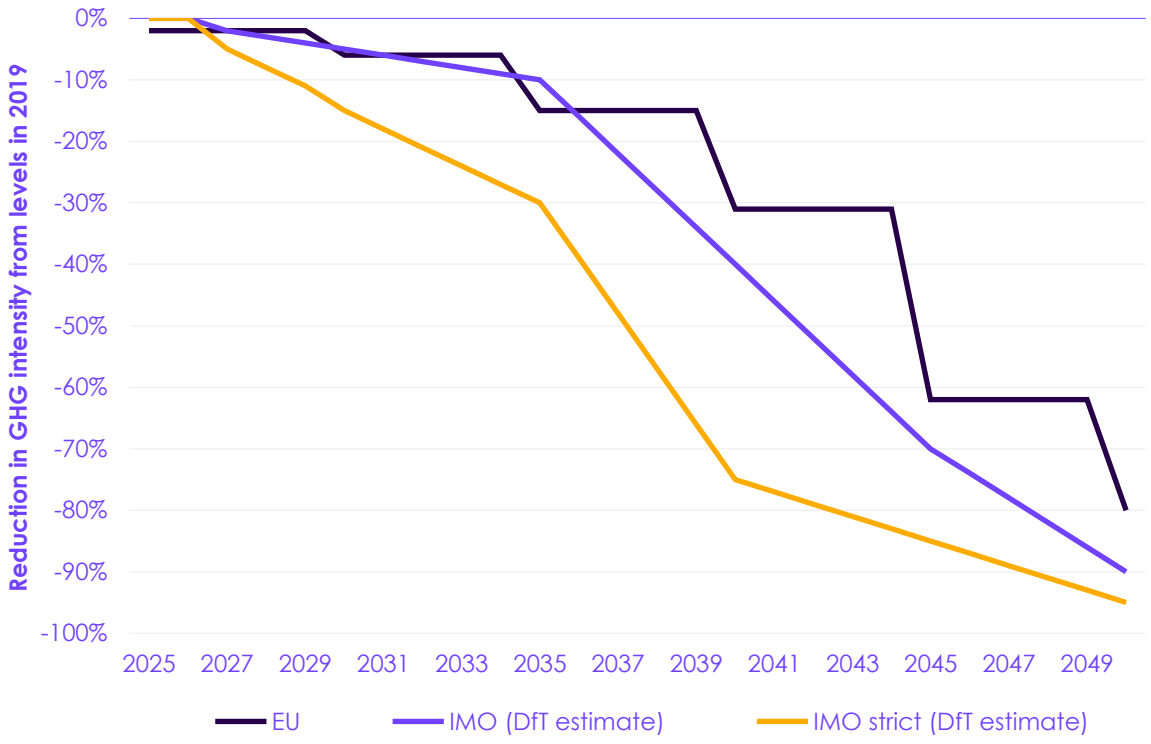
15.4.2 International shipping regulations

International shipping regulations are still under development. The IMO is developing a fuel standard and an emission pricing mechanism for international shipping, but the design and stringency of these measures were not confirmed at the time of analysis.[48] We explore a scenario with a stricter IMO fuel standard, where the stringency of the required reductions in GHG emissions

intensity of shipping energy use increases faster than in the Balanced Pathway. As can be seen in Figure 15.9, this results in a faster emissions reduction, especially until the mid-2030s.

- Figure 15.10 shows how the stricter IMO fuel standard compares to the fuel standards used in the modelling for the Balanced Pathway.

Figure 15.10 EU and IMO fuel standards for shipping



Description: The EU fuel standard and DfT's estimate of two IMO fuel standards all decrease out to 2050.
Source: European Union (2023) *Regulation (EU) 2023/1805 of the European Parliament and of the Council of 13 September 2023 on the use of renewable and low-carbon fuels in maritime transport, and amending Directive 2009/16/EC*; Department for Transport (DfT) analysis.
Notes: The IMO fuel standards are estimated by DfT: the less strict one is based on the IMO's lower targets, and loosened to allow some fossil fuels until 2035, when our modelling allows synthetic fuels; the stricter IMO fuel standard is based on IMO's more ambitious targets.

15.4.3 Technology costs

Many of the propulsion and efficiency improving technologies used in the Balanced Pathway for shipping are still under development, and so their costs are uncertain. We explore two additional scenarios, looking at the impact of 10% higher and 10% lower technology capex.

- **Higher capex.** If technology capex is 10% higher than assumed in the Balanced Pathway, this has limited impact on emissions in 2040, increasing shipping emissions by 0.1 MtCO2e.

- **Lower capex.** If technology capex is 10% lower than assumed in the Balanced Pathway, this has very limited impact on shipping emissions across the pathway and has no impact on emissions in 2040.

15.4.4 Future shipping demand

Shipping demand is closely linked to GDP and is therefore uncertain.[49] We explore two additional demand scenarios, looking at the impact of lower and higher demand for shipping. We use DfT's demand scenarios: compared to the shipping demand assumed for the Balanced Pathway, in

2040, shipping demand is 19% higher in the high demand scenario, and 14% lower in the low demand scenario.[50] These sensitivity scenarios have the biggest impact on emissions in 2040, with higher demand resulting in 0.7 $MtCO_2e$ higher emissions, and lower demand resulting in 0.7 $MtCO_2e$ lower emissions.

15.5 Contingencies in shipping

The contingency we model for shipping is set out in Table 15.5. See Chapter 5 for our general approach to contingency analysis.

Table 15.5
Contingency option in shipping

Contingency	Description	Potential average annual emissions savings ($MtCO_2e$, % of sector emissions)			
		2030	CB6	CB7	2050
Stronger regulation of domestic shipping vessels	This contingency action explores the potential impact of the UK introducing a fuel standard for domestic shipping.	0.5 5%	0.7 10%	0.5 10%	

Source: Department for Transport (DfT) (2025) Maritime emissions modelling framework; CCC analysis.
Notes: We have blanked out cells where the contingency measure in question is estimated to deliver less than 0.3 MtCO2e in potential emissions savings, to focus on high-yield options.

15.5.1 Stronger domestic regulation

As set out in Section 15.2.4, fuel standards aim to reduce emissions by regulating the GHG intensity of the energy used onboard vessels. We explore the impact of including a fuel standard for domestic shipping – applying to vessels above 5,000 GT from 2027 and expanding to vessels above 400 GT in 2037. This results in a 0.7 $MtCO_2e$ decrease in shipping emissions in 2040.

- The limited additional impact of a domestic fuel standard is a result of both the central carbon value used for domestic shipping having a significant value relative to the difference in fuel costs, and the international fuel standards applying to many vessels contributing to UK shipping emissions in our Balanced Pathway.

- The UK fuel standard that is used for this contingency analysis aligns with the less strict IMO fuel standard in Figure 15.10.

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Chapter 16: F-gases

Introduction

This chapter describes the modelling approach for the F-gases sector, and the process of updating this for the Seventh Carbon Budget. The F-gases included in the UK's targets are hydrofluorocarbons (HFCs), sulphur hexafluoride (SF6) and perfluorocarbons (PFCs).

- The F-gases sector is made up of three subsectors: refrigeration, air conditioning and heat pumps (RACHP); metered-dose inhalers (MDI); and other F-gases (covering Industrial processes and a range of other uses).
- The CCC commissioned Ricardo and Gluckman Consulting to update the CCC F-gases Projections and Mitigations Model. This model was originally developed for our Sixth Carbon Budget advice and was updated to include the latest policy and evidence for the Seventh Carbon Budget. This involved revisions to historic emissions, the latest assumptions surrounding the technologies and global warming potential estimates, the latest population estimates, and a review of the literature and evidence related to F-gases policy.

16.1 Baseline emissions in F-gases

16.1.1 The baseline for F-gases

Our baseline for F-gases is based on the following assumptions. See Chapter 1 for our general approach to baselines.

- Baseline demand is derived from the latest data for 2022 from the National Atmospheric Emissions Inventory (NAEI).
  - The baseline forecast uses the latest Energy and Emissions Projections (EEP) which projects emissions from 2022 to 2040.
  - Population growth assumptions use the ONS 2021-based interim national population projections.
- Policies in place as of 2023 continue to operate in the baseline. However, new policy beyond 2023 is included in emissions and costs in the pathway but not the baseline.
  - We assume the 2015 EU F-Gas Regulation is in place, which set 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, compared to the average usage between 2009 and 2012.
  - 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.

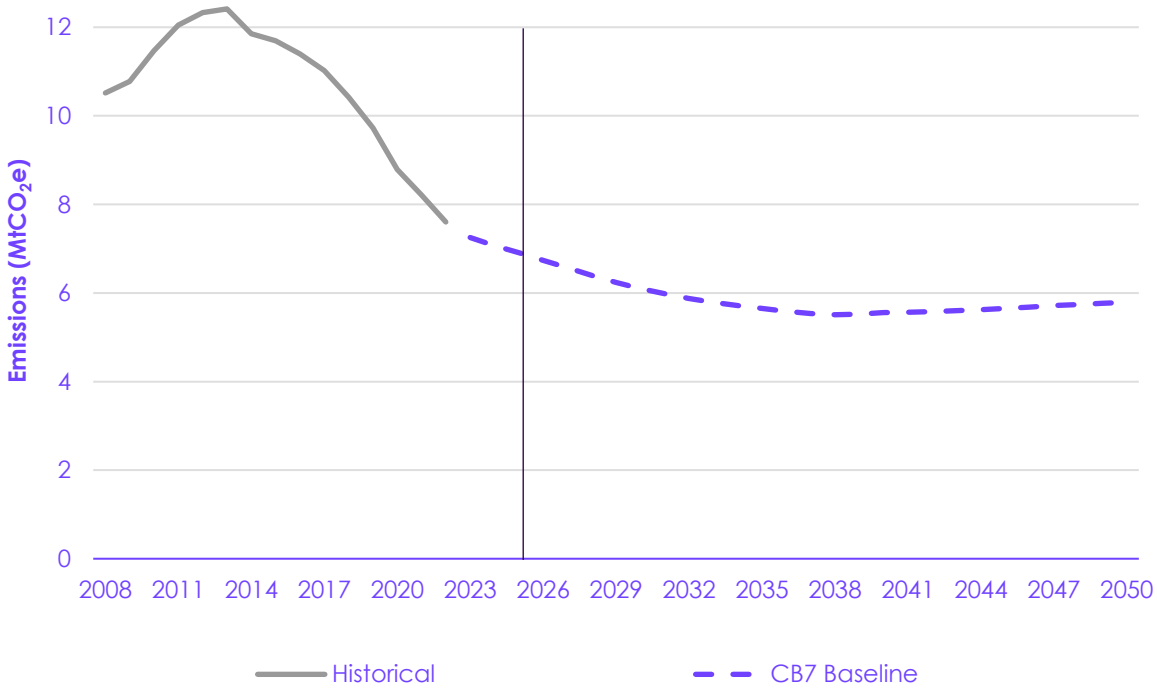
– The regulation strengthens existing obligations in terms of mandatory 'management measures' including regular leak checks and repair, gas recovery at end-of-life, record keeping, training and certification of technicians and product labelling.

In this baseline scenario, emissions would fall by 27% from 2022 levels by 2040 (the middle of the Seventh Carbon Budget period) and by 24% by 2050 (Figure 16.1).

- In the baseline no new policy occurs beyond 2023. However, emissions continue to fall during 2025-2040 as existing units reach end-of-life and are superseded by lower emitting replacements under existing regulations.

- Between 2040 and 2050 emissions remain broadly flat at just under 6 $MtCO_2e$. There is a small increase in emissions due to increases in population growth over that period.

Figure 16.1 Baseline emissions in F-gases



Description: In the baseline, F-gases emissions continue to fall before stabilising out to 2050.
Source: CCC analysis.

16.2 Pathway assumptions and modelling for F-gases

16.2.1 Modelling the Balanced Pathway for F-gases

Overall modelling approach

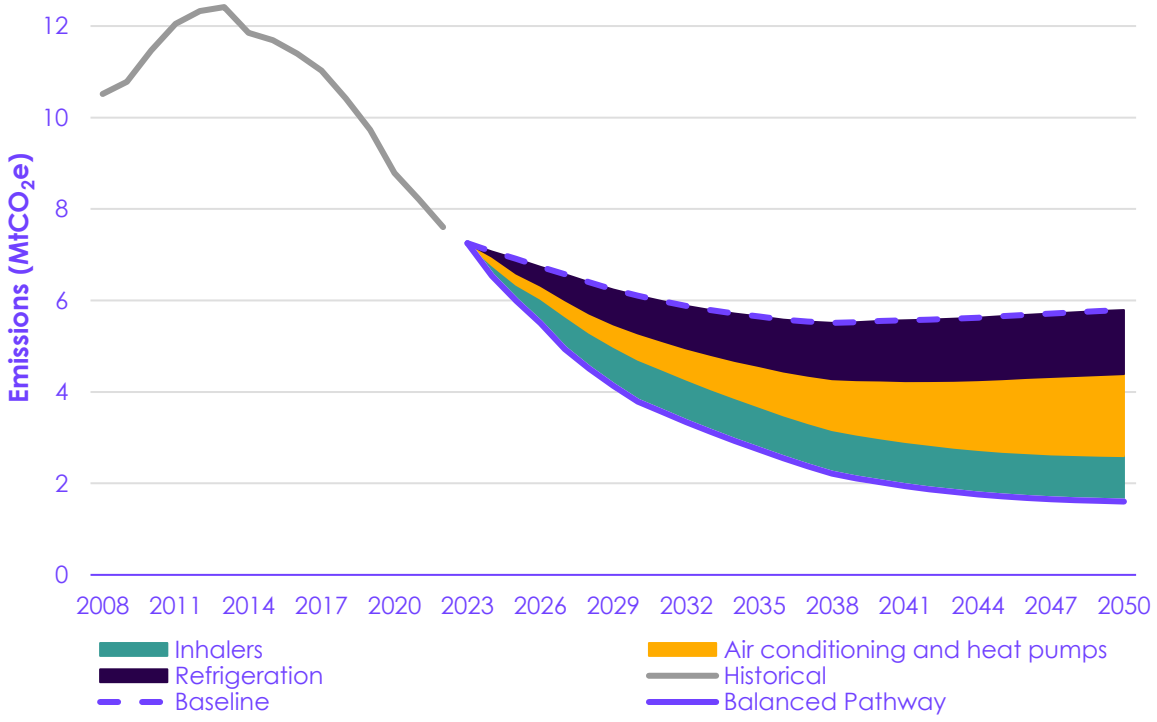
Emissions reductions in the F-gases sector come from changes to refrigerants used in air conditioning, heat pumps, and refrigeration as well as the use of alternative propellants in metered-dose inhalers (Figure 16.2).

The modelling assesses the costs of potential decarbonisation measures against the central carbon value. Only measures which have costs below this value are selected for the Balanced Pathway. See Chapter 1 for our general approach to pathway analysis.

The Balanced Pathway for F-gases

In our Balanced Pathway, F-gases emissions are projected to fall, relative to 2022 levels, by 73% to 2.0 MtCO2e by 2040 (the middle of the Seventh Carbon Budget period) and to 1.6 MtCO2e by 2050 (Figure 16.2).

Figure 16.2 Sources of abatement in the Balanced Pathway for F-gases



Description: The largest share of emissions reductions in in F-gases by 2040 comes from the use of lower GWP refrigerants and propellants in refrigeration, air conditioning and heat pumps, and inhalers.
Source: DESNZ (2024) *Provisional UK greenhouse gas emissions national statistics 2023*; DESNZ (2024) *Final UK greenhouse gas emissions national statistics 1990-2022*; CCC analysis.
Notes: (1) Historical emissions are shown only to 2022 because provisional 2023 emissions data are not published for GHGs other than CO_2. (2) We generally account for emissions reductions due to measures to reduce demand for high-carbon activities (including low-carbon choices and efficiencies) first, before the impact of low-carbon technologies.

The measures in our pathway

Table 16.1 summarises the measures for reducing emissions in the F-gases sector that are considered within our modelling, how these lead to emissions reductions in our modelling, and the key factors that influence their uptake. The methodology used to develop the assumptions and analysis underpinning these is described in the rest of this section.

Table 16.1
Measures considered within our modelling for F-gases

Decarbonisation measure	How does this measure influence emissions in our modelling?	What are the key factors that affect uptake in our modelling?
Refrigeration: avoiding 448A and 449A (HFO-HFC blends)	Using low-GWP refrigerants in refrigeration systems that are due to be replaced, reducing the impact of any leakage from refrigeration systems.	Whether the replacement GWP technology can be applied at scale at low enough cost.
Refrigeration, air conditioning and heat pumps: leakage reduction and better end-of-life gas recovery	Reduces leaking and improves capture of high global warming potential gases used in cooling.	Current usage levels of F-gases and expected leakage rates.
Inhalers: replacing the use of high global warming potential propellants in inhalers	Prevents high global warming potential propellants being released into the atmosphere when inhalers are used.	Whether the replacement GWP technology can be applied at scale at low enough cost and whether people are able to switch to the alternative technology.

16.2.2 Key modelling assumptions

- The F-gases baseline assumes take-up of heat pumps in line with the Balanced Pathway for buildings (see Chapter 7) to avoid undercounting appliances containing F-gases. The F-gases Balanced Pathway then accounts for actions needed to mitigate F-gas emissions from those appliances.

- The shape of the costs before and after 2036 reflects stylised assumptions across these periods based on the most recent EU impact assessment from March 2022.[1] This analysis describes a short-term trend of stable costs until 2036. Between 2036 and 2050 the capital costs of refrigeration are expected to fall compared to the baseline.

Scotland, Wales and Northern Ireland

Baseline and pathway emissions for Scotland, Wales and Northern Ireland, are based on the UK modelling, apportioned by population.

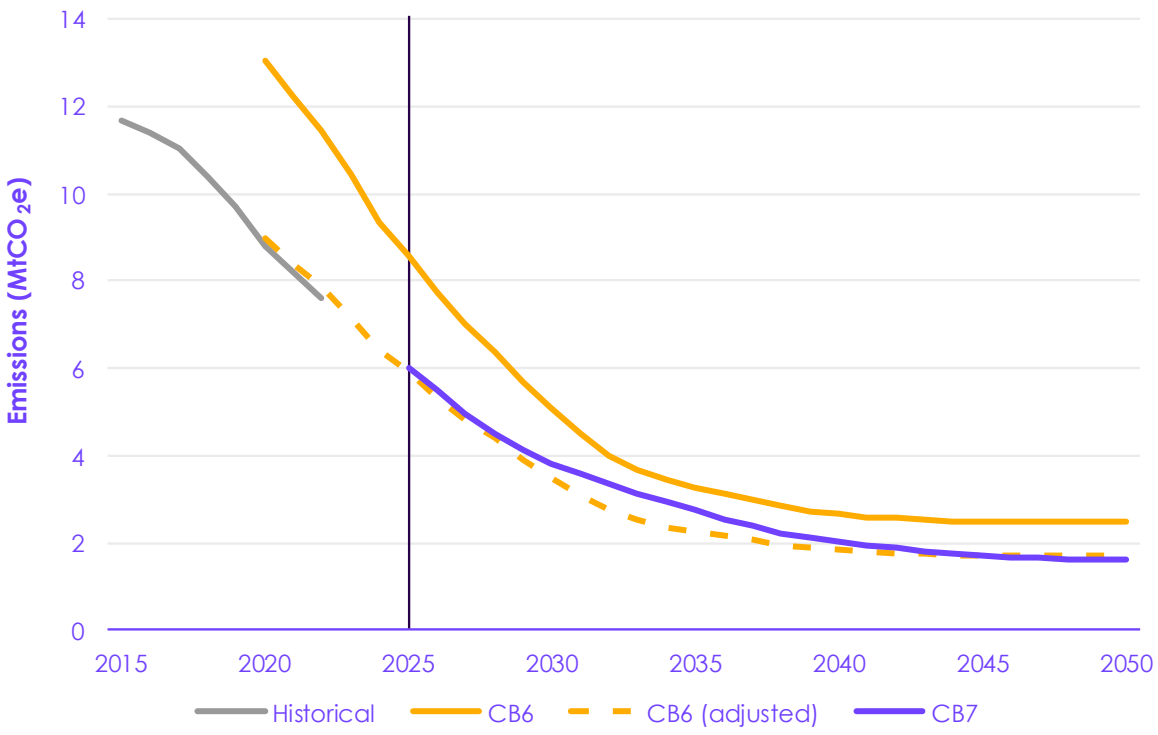
- Population assumptions use the ONS 2021-based interim national population projections (published in 2024). The only exception to this is Magnesium and Aluminium fugitive emissions which are entirely attributed to England.

16.3 Changes since our Sixth Carbon Budget advice

16.3.1 Comparison with our Sixth Carbon Budget pathway

Estimates of emissions in this sector have been revised down due to changes in emissions accounting since our Sixth Carbon Budget advice.* Our Balanced Pathway is very similar to how our Sixth Carbon Budget pathway would have looked using the updated accounting methodology. The pace of emissions reduction is slightly more gradual in the 2030s than it was previously (Figure 16.3).

Figure 16.3 The Balanced Pathway for F-gases compared to our Sixth Carbon Budget advice



Description: Changes in emissions accounting mean that our Seventh Carbon Budget (CB7) Balanced Pathway begins lower than our Sixth Carbon Budget (CB6) pathway.
Source: CCC analysis.
Notes: Estimates of emissions in this sector have been substantially affected by changes in emissions accounting methodologies in the inventory since our CB6 advice. Therefore, to enable easier comparison, we have included a 'CB6 (adjusted)' series estimating what the CB6 pathway would look like if it had used the latest inventory accounting.

* All comparisons in this section compare the Balanced Pathway in this advice with the Balanced Net Zero Pathway in our Sixth Carbon Budget. Our Sixth Carbon Budget advice also included four other exploratory pathways, which are not discussed here. Data for those pathways can be found in our Sixth Carbon Budget advice.

16.3.2 Emissions changes since our Sixth Carbon Budget advice

Estimates of emissions in this sector have been revised down due to changes in emissions accounting since our Sixth Carbon Budget advice.

16.3.3 Key pathway differences compared to our Sixth Carbon Budget advice

There are several key areas in which the deployment rates, measures included, or underlying assumptions in our updated Balanced Pathway have been revised since publication of our Sixth Carbon Budget advice in 2020. These include:

- **Emissions modelling.** Our updated modelling uses a new model (HFC Outlook).[2] This replaces the former ICF model for Refrigeration, Air Conditioning and Heat Pump (RACHP) emissions used in our Sixth Carbon Budget advice.

- **Baseline approach.** In the Sixth Carbon Budget, the baseline for F-gases included all EEP policies which resulted in a much steeper decline in emissions than in our baseline for the Seventh Carbon Budget.

Endnotes

[1] EU (2024) *Support contract for an evaluation and impact assessment for amending Regulation* https://op.europa.eu/en/publication-detail/-/publication/8e33bf60-b61f-11ec-b6f4-01aa75ed71a1/language-en.

[2] HFC (2024) *HFC outlook modelling* https://www.gluckmanconsulting.com/hfc-outlook-modelling/#:~:text=The%20HFC%20Outlook%20model%20provides,consumption%2C%20GHG%20emissions%20and%20banks.&text=RACHP%20equipment%20creates%20two%20distinct,of%20refrigerant%20into%20the%20atmosphere.

Chapter 17: Land use

Introduction

The land use analysis first considers land allocation to priorities such as maintaining food production (per capita), settlement growth and housing needs, and other economic activity for a growing population out to 2050, alongside measures which release land from agriculture.* Sectoral analysis then assigns land to new uses and management to support emissions reduction and carbon sequestration.

- **Options for reducing emissions and increasing sequestration.** These include actions that address restoration of degraded land as well as land use change to support increased rates of carbon stored in vegetation and soils. Our approach is informed by a detailed review of available evidence, including academic research, stakeholder engagement, analysis of domestic and international trends, as well as two externally commissioned analysis projects on land use pathways and land use archetypes published alongside this advice.[1]

- **LULUCF modelling.** The CCC commissioned UKCEH to quantify carbon sequestration and greenhouse gas abatement potential from the implementation of land management and land use change actions such as woodland creation and management, peatland restoration and sustainable management, energy crops, and agroforestry.

- **Net Zero land and agriculture.** By 2050, land use change and new management approaches offset residual emissions in agriculture enabling the combined sectors to reach Net Zero.

- **Reducing risk and increasing resilience.** Carbon stores must be resilient and protected in the face of climate change if they are to be effective in supporting Net Zero. In our modelling approach, we embed principles of a resilient land use transition.

In our advice reports on the UK's Seventh Carbon Budget, Northern Ireland's Fourth Carbon Budget, Wales' Fourth Carbon Budget, and Scotland's carbon budgets, we discussed the pathway for agriculture together with that for land use. This is because these two sectors are inherently linked, together playing an important role to deliver a transformation in UK land use. This chapter sets out our modelling for the land use sector; our agriculture methodology can be found in Chapter 9.

17.1 Baseline emissions in land use

17.1.1 The baseline for land use

Our baseline for land use is based on the following assumptions. See Chapter 1 for our general approach to baselines.

- Land area under different land use categories in 2021 for the UK and individual nations is used as a starting point for our analysis.† These 2021 areas come from agricultural surveys

* See Chapter 9 for further details.

† Land use categories include forest (conifer and broadleaf), grasslands (permanent, temporary, rough grazing), cropland, settlement land, peatland, inland water bodies, and other land. The modelling approach uses land use data from 2021 as this was the most current available at the time of analysis.

and data sources used in the national GHG emissions inventory that add up to the total country areas reported in the Office for National Statistics Standard Area Measurements (ONS 2017).

- Land is then allocated to maintain food production (per capita, taking account of a growing population), settlement growth and housing and infrastructure needs for a growing population out to 2050. See Chapter 9 on agriculture, which details this first step which is underpinned by the CCC land release model.

- Baseline emissions and allocation of land is derived from the analysis by UKCEH which informed this report.[2]

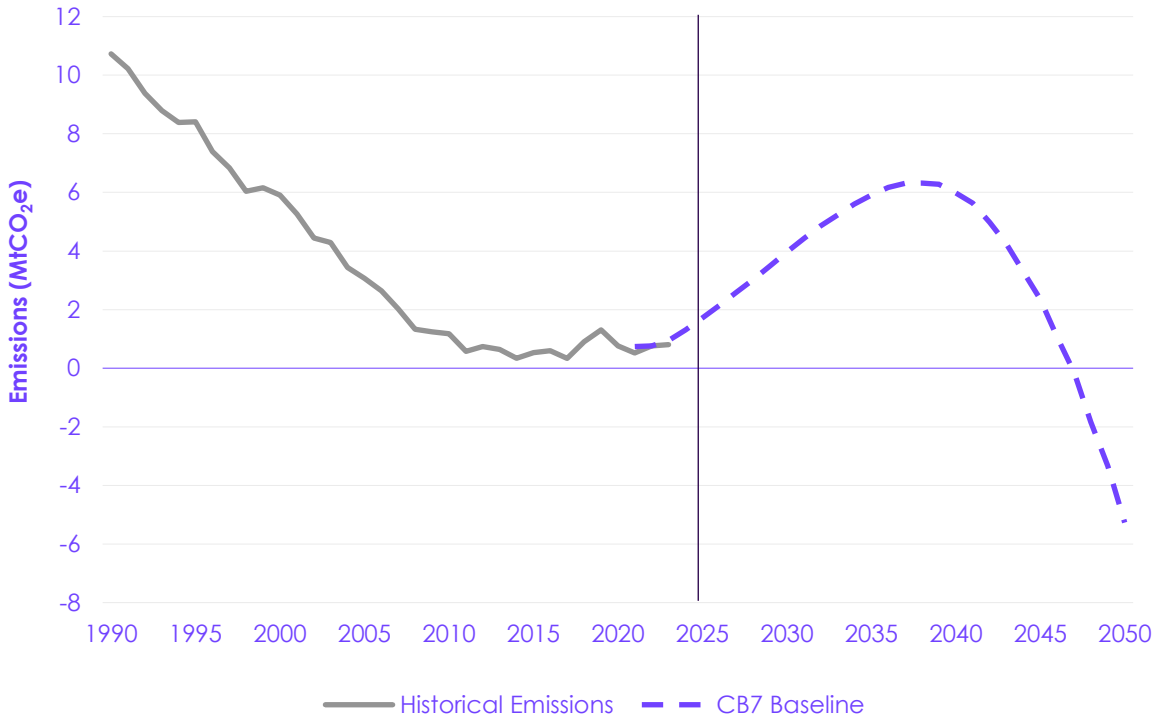
  - It is assumed that the average rate of land use change (for example, woodland creation) over the period 2020 to 2022 continues across England, Scotland, Wales, and Northern Ireland.* This is then projected forwards through to 2050.

  - Land carbon stocks can take many years to reach equilibrium following a change of use. Emissions that occur over the 2025 to 2050 baseline due to a change of land use before 2022 are modelled using the UK GHG emissions inventory land use change model.

In this baseline scenario, emissions would rise to 6 $MtCO_2e$ by 2040 (the middle of the Seventh Carbon Budget period) before falling to a sink of -5.3 $MtCO_2e$ by 2050 (Figure 17.1). This represents a scenario where the current annual rates of delivery in woodland creation (around 15,000 hectares/year) and peatland restoration (around 7,000 hectares / year) continue. Land-based actions such as agroforestry and energy crops are not included in the baseline due to uncertainty regarding current activity.

* The assumption that the land use baseline is informed by a continuation of current activity is different than the centrally defined baseline in other sectors, which typically assume a maintenance of existing stocks. See Chapter 1 of this report for further detail.

Figure 17.1 Baseline emissions in land use



Description: The land use baseline emissions increase before falling to 2050, based on modelled activity based on existing trends in land use over the period 2020 to 2022.
Source: DESNZ (2024) Final UK greenhouse gas emissions national statistics 1990-2022; UKCEH (2025), CCC analysis.

17.2 Pathway assumptions and modelling for land use

17.2.1 Modelling the Balanced Pathway for land use

Overall modelling approach

The analysis undertaken for our advice was based on a range of approaches. These include taking account of latest developments and trends in the sector, academic research and literature, stakeholder engagement, as well as data modelling and analysis both in-house and via commissioned external reports. We convened advisory groups and expert workshops across topics such as peatland restoration, farming and agriculture, and principles for land use change. See Chapter 1 for our general approach to pathway analysis.

The key elements in our land use modelling are:

- As in the baseline (described in section 17.1.1), the Balanced Pathway for land use uses the 2021 land category areas from agricultural surveys and data sources used in the national GHG emissions inventory as a starting point. These align to the total country areas reported in the Office for National Statistics Standard Area Measurements (ONS 2017). Land is then assigned to maintaining food production (per capita), settlement growth and housing needs, and other economic activity for a growing population out to 2050.

- The CCC land release model then applies five measures to facilitate the release of land from agriculture. These measures are human diet change, food waste reduction, crop yield improvement, increased stocking rates, and indoor horticulture. This model is described in detail in Chapter 9 Agriculture. This released land and its management is then allocated to abatement measures in the land use sector.

- Land use change, and on what type of land it occurs on, is specific to each measure. The impact of land use change is highly dependent on where it occurs in a landscape. To build resilience and mitigate the risk of unintended consequences we consider the following when setting assumptions at a measure-level.

  - **Right measure, right place:** measures are located on land types most suitable and available for change. For example, woodland creation modelling avoids organic soils and uses land availability outputs by nation to define planting areas.

  - **Following regulatory principles:** where available and considered robust, our analysis follows regulatory principles. For example, our woodland creation assumptions align with UK Forestry Standard open ground requirements for biodiversity.

  - **Long-term transition:** land use change measures are longstanding to give confidence for future investment and commitment to changing approach. For example, UK-grown domestic energy crops are based on perennial types to minimise disturbance of the land and to build soil carbon.

  - **Sharing the load:** deployment of land use change measures is spread proportionally across the UK, based on land type and release from other land management approaches. This allows for a more resilient mix of measures across a range of locations and land types.

- The Balanced Pathway for Scotland, Wales and Northern Ireland are derived by a combination of taking the same analytical approach as at the UK-scale and applying it proportionately across the UK based on the scale and availability of suitable land.

  - Land use change for each nation is underpinned by the outputs of the CCC Land Release model which uses productivity and stocking density based on nation specific data for current use of agricultural land. Impacts of behavioural changes via a shift to the consumption of lower-carbon food and reducing food waste is based on UK-wide data.

  - While the underlying land use change assumptions are applied consistently across the nations, there is considerable diversity in the make-up of the baseline agricultural land which drives the resulting differences in advice for each devolved administration.

- The UKCEH land use model then quantifies the carbon sequestration and greenhouse gas abatement potential from implementation of land management and land use change. Other outputs include harvested forestry and biomass outputs.

  - Where possible, this aligns to the reporting of land use in the GHG inventory regarding use of emission factors and use of Global Warming Potential (GWP) AR5 low.*

- Capital and operating costs associated with the land use pathway are derived from the commissioned Land Use Archetypes project, published alongside this methodology report.[3]

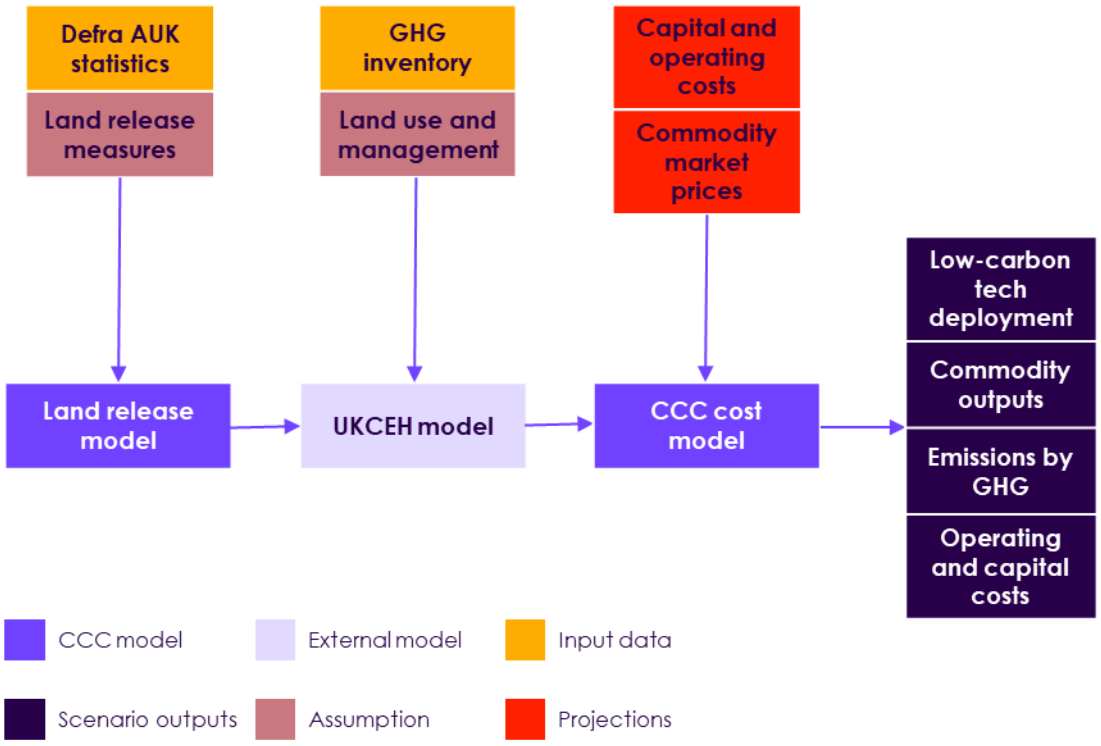
* The IPCC's lower AR5 global warming potentials are now internationally adopted and embedded in our analysis. See Section 1.8.2 for more detail.

- Where possible we have used hectarage costs based on site level data relevant for each nation. Further detail is provided in the measure sections below.

- Costs of changing land use and ongoing management are highly site specific, and dependent on a range of variables. While we have not been able to account for this variability in our analysis, we have used costing evidence we consider representative.

The modelling workflow for the land use sector is described in Figure 17.2.

Figure 17.2 Modelling schematic for land use

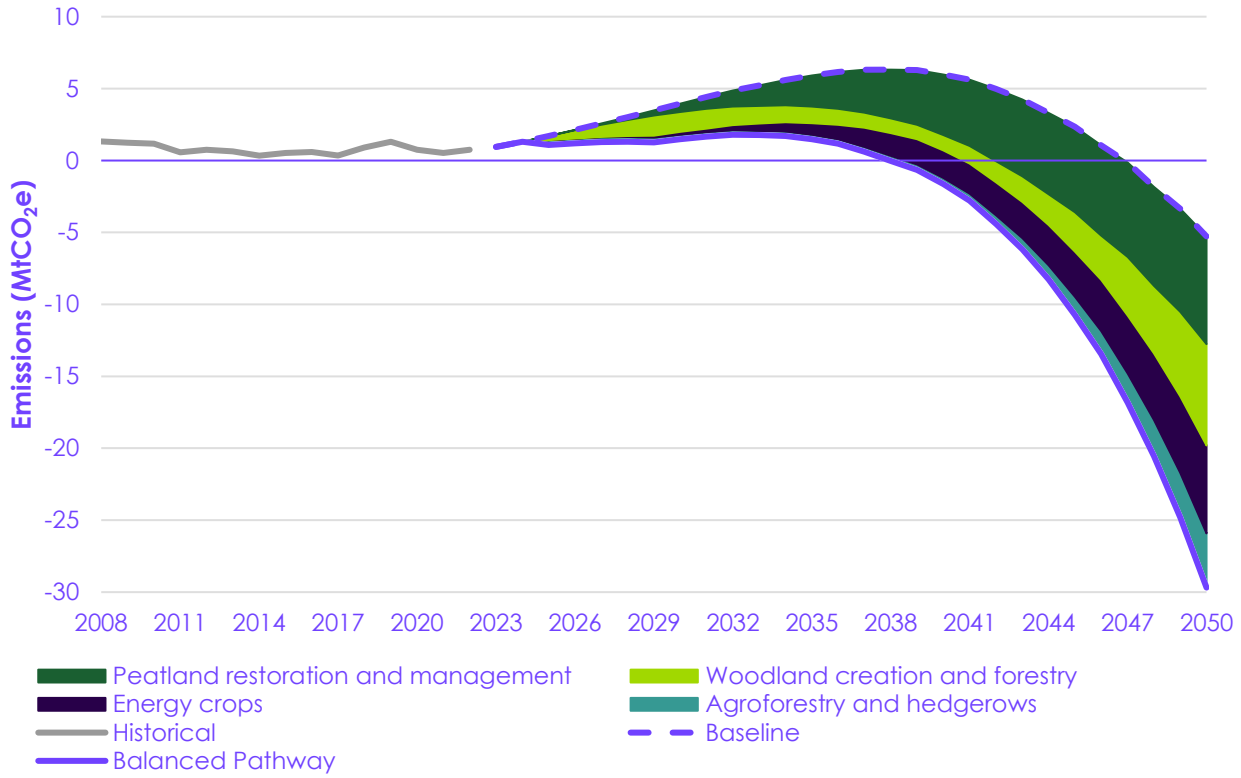


Source: CCC analysis.
Notes: Modelling in the land use sector uses outputs from the CCC land release model. This is described in Chapter 9 Agriculture.

The Balanced Pathway for land use

In our Balanced Pathway, the land use sector's emissions are projected to fall from 0.8 $MtCO_2e$ in 2022 to-1.9 $MtCO_2e$ by 2040 (the middle of the Seventh Carbon Budget Period) and to -29.9 $MtCO_2e$ by 2050 (Figure 17.3). Land use emissions initially rise and then are slow to fall in the early stages of the pathway due to the time taken by new woodlands to reach peak rates of sequestration. In the Balanced Pathway, the sector becomes a net sink in 2038. Sources of emissions fall by 31%, while the land use sector sink increases by 123% by 2050.

Figure 17.3 Sources of abatement in the Balanced Pathway for land use



Description: The largest share of emissions reduction is from actions to rewet and restore peatlands. Woodland creation rapidly increases its abatement share over the 2040s. Other land use actions include agroforestry and hedgerows and energy crops.
Source: DESNZ, CCC analysis.

The measures in our pathway

Table 17.1 summarises the measures for emissions reduction in the land use sector that are considered within our modelling, how these lead to emissions reductions in our modelling, and the key factors that influence their uptake. The methodology used to develop the assumptions and analysis underpinning these is described in the rest of this section.

Table 17.1
Measures considered within our modelling for land use

Decarbonisation measure	How does this measure influence emissions in our modelling?	What are the key factors that affect uptake in our modelling?
Peatlands - rewetting and management	Raising of water levels, revegetation and stabilisation of the peat surface reduces GHG emissions associated with decomposition of the peat substrate.	By 2050, 76% of peatland area is in rewetted condition. The peatland area ambition and annual rates of delivery for rewetting are derived from stakeholder engagement, expert and Committee judgement, and considered availability of land and feasibility of action.
Peatlands – water level management	Sustainable management of cropland on organic soils involves the manipulation of the water table to reduce GHG emissions	By 2050, 75% of deep cropland peats and 40% of wasted peat is under rewetted or sustainable management. The peatland area ambition and annual rates of delivery for rewetting are derived from stakeholder engagement, expert and

	under continuing agricultural production.	Committee judgement, and considered availability of land and feasibility of action.
Woodland creation	Appropriately located and managed woodland and forestry sequester CO_2 directly from the atmosphere, storing it in their vegetation and soils.	By 2050, 1.2 million hectares of new woodland planted between 2025 to 2050. The ambition for new woodland creation is derived from a feasible upscaling from current delivery, as assessed from comparisons with historical and international examples, and stakeholder engagement, as well as consideration of the availability of land as it is released from agriculture.
Woodland management	Sustainable management of broadleaf woodlands can increase productivity and enhance resilience to risks such as pests, disease, and fire.	The sustainable management of broadleaf woodland rises to reach 80%, from the currently estimated 20%, by 2035. This ambition is based on stakeholder engagement and examples from existing sites. It is assumed that conifer plantations are currently under active management.
Energy crops	Appropriately sited, UK-based energy crops sequester CO_2 directly from the atmosphere, storing it in vegetation and soils. They also support displacement of fossil fuels, and GHG removals when combined with carbon capture and storage (CCS) technology.	The energy crop area ambition is derived from analysis by the Energy Technology Institute (ETI). Around half of the ETI's central estimate is embedded in the land use pathway as informed by land availability. Uptake of energy crops starts in 2027 to enable policy and incentive design to be put in place.
Agroforestry – Silvopasture and silvoarable	Incorporating trees into agricultural systems supports the sequestration of carbon in vegetation and soils whilst supporting continuation of agricultural production.	Agroforestry is applied to 10% of agricultural grassland and cropland with ambition based on stakeholder engagement. Annual delivery rates are just under 8,000 hectares each year over the course of the transition to 2050.
Hedgerow creation and management	Establishment of hedgerow field boundaries store carbon in vegetation and soils.	Establishment of new hedgerows is based on a 10% increase on the lengths reported in the 1984 Countryside Survey. Annual delivery rates represent an even split across the transition to 2050.
Marine carbon	Marine and coastal vegetation and sediments store carbon, which can be managed to contribute to emissions reduction.	This measure was not included in the modelling for land use. Marine carbon is not yet represented in the inventory.
Natural regeneration of woodlands and scrub	Natural regeneration is the establishment of trees and vegetation via in-situ seed dispersal rather than by active planting.	This measure was not included in the modelling for land use. More information is required on the spatial and temporal variability of natural regeneration before it can be incorporated into emission pathways.

17.2.2 Peatland restoration and management

Peatlands and organic soils represent a diverse range of habitats and land use types across the UK, playing an important role in nature conservation and provision of ecosystem services, as well as in agriculture and food security. Their soils represent the largest terrestrial carbon store of UK ecosystems.[4]

- Functioning peatlands in good ecological condition can accumulate carbon over many millennia, but drainage and disturbance can cause these stocks to be released, and UK peatlands are a net source of emissions.

- Degraded peatlands, currently under agricultural, extraction and forest land use, result in these deep carbon stores becoming a net GHG source, rather than sink of emissions.

- Restoration, rewetting, and management interventions will reduce GHG emissions from these habitats and soils, rather than result in net sequestration.* This is due to the long-term time profile required for such habitats to recover, as well as the relatively slow rate of peat formation in natural systems.

The analytical approach taken aligns with the IPCC approach for wetlands and is underpinned by empirical, UK-based evidence.[5;6] Emissions factors† and starting areas are the same as those used in the UK National GHG Inventory Report for 1990-2022.[7] The peatland types, and their categorisation and alignment to rewetted categories, is set out in Table 17.2.

Table 17.2
CCC peatland modelling alignment to GHG emissions inventory categories

Land use	Condition category	Location	Restored peatland type
Grassland	Semi-natural, drained or undrained	Upland	Rewetted modified bog
	Eroded, drained or undrained	Upland	Rewetted bog
	Intensive	Lowland	Rewetted fen
	Extensive	Lowland	Rewetted bog
	Extensive	Lowland	Rewetted fen
Cropland	Cropland (restoration)	Lowland	Rewetted fen
	Cropland (water level management)	Emission factors for continuous and dynamic water level management and paludiculture are proportional to water-table depth.	
Extraction	Extraction (industrial)	Lowland	Rewetted fen
	Extraction (domestic)	Upland	Rewetted bog
Forestry	Forest	n/a	Rewetted bog
Near natural	Existing near natural (bog / fen)	Upland / lowland	n/a
Rewetted	Existing rewetted (bog / fen)	Upland / lowland	n/a

Source: UK GHG inventory; UK CEH.
Notes: Formal emission factors for water level management on cropland peatlands are currently not available. Near natural and rewetted peatlands do not transition to new categories and are shown here for completeness.

* While GHG modelling is based on rewetting, aligning to the inventory approach, we assume that this action is accompanied by other restoration measures where relevant to support the future formation of peat. Such approaches include the blocking of drains to raise water-levels, stabilisation of eroded peat, revegetation of bare surfaces, and the cessation of other damaging practices.

† For unrestored, restored, and near-natural peatlands only. A different approach was taken for the sustainable management of croplands on peat, which is detailed in the relevant section below.

Warmer and drier conditions under future climate change are likely to increase the rate of carbon losses from degraded peatlands and reduce the water-holding and filtering capacity of degraded peat. Their restoration and management will be critical in building resilience in these systems, helping to mitigate carbon emissions from further degradation, and maintaining ecosystem services.

- Peat restoration ambition and rates of delivery were derived from bilateral and roundtable stakeholder engagement and Committee judgement. The area of restoration achieved by 2050 aligns with previous CCC analytical work which informed the Sixth Carbon Budget advice. While this was considered challenging, the expert feedback suggested it should be maintained both for emissions reduction and protecting the peat resource.
    - Though peatland restoration is internationally recognised as an important nature-based action to reduce GHG emissions, quantitative evidence regarding deployment rates of restoration actions is lacking and typically reports at site or project scale rather than nationally.

Capex costs for peatland restoration are based on per hectare costs provided by Natural England and the Scottish Government, based on project level and grant scheme data.[8;9;10*] Costs specific to Wales and Northern Ireland were not available and capex costs instead were based on the England and Scotland evidence. Opex costs represent ongoing management of restored peat soils and are on a per hectare basis. This was informed by the Land use archetypes project accompanying this methodology.[11]

- Capex and costs are not available for the sustainable management of peat actions in our pathway due to these approaches currently being in development and not yet applied at scale. For these we used costs associated with restoration approaches and acknowledge this is likely to be an underestimate.

- It is not yet possible to include the costs associated with the infrastructure needed for water level management at landscape scale. This is currently unknown.

Upland grassland on peat soils

Upland peatlands represent the largest area of UK peatlands, totalling around 2.5 million hectares and 84% of the total peatland area of the UK. Of this, around 71% is in a degraded condition due to drainage and/or erosion, typically due to extensive grazing of sheep. We assume that 90% of this peatland type is under restoration by 2050.

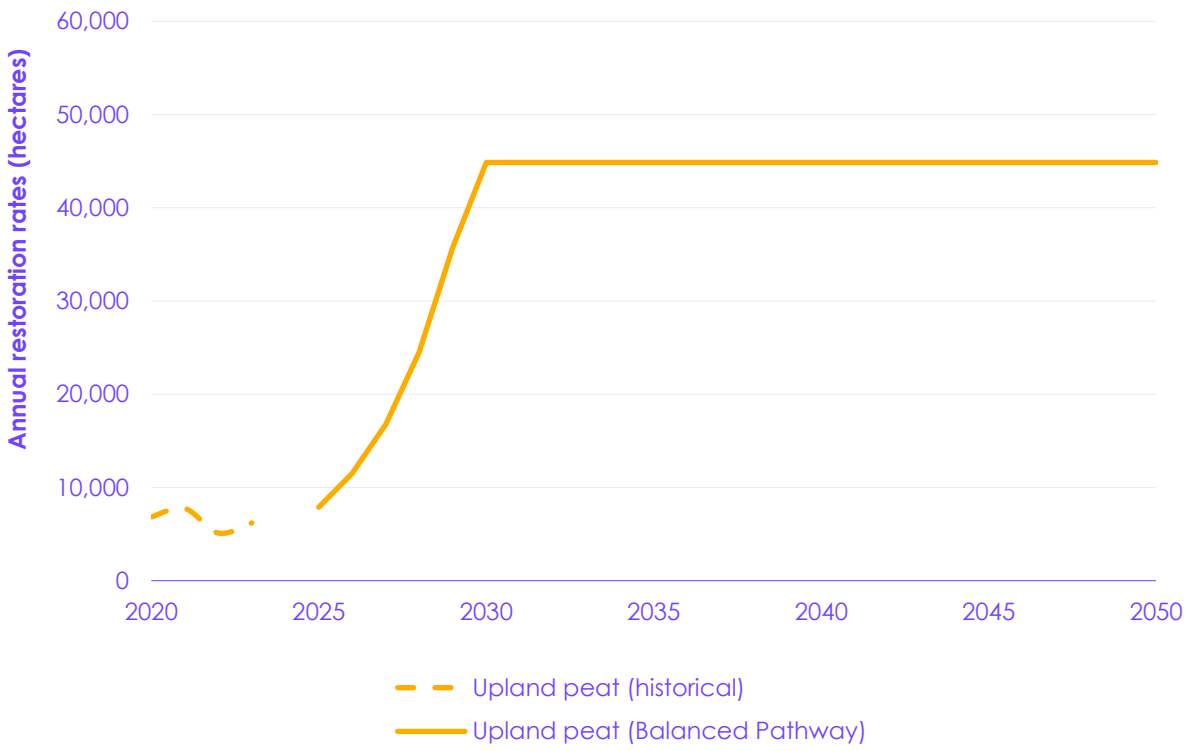
- Upscaling of activity happens from 2025 onwards with annual rates of upland peatland restoration rising from around 6,000 hectares per year to reach 45,000 hectares per year by 2030. This is then maintained through to 2050 (Figure 17.4). Restoration ambition and rates of delivery are informed by stakeholder engagement and Committee judgement.

- Following restoration, upland grasslands are assumed to be returned to a rewetted/modified state.

- Restoration of degraded upland peatlands would be expected to take them out of current agricultural usage. However, in some cases seasonal grazing at appropriate levels may be suitable to manage vegetation or maintain the conservation interest that peatlands support.

* English data was derived from Nature for Climate Projects, and Scottish data was compiled from Peatland ACTION programme projects between 2018 and 2023.

Figure 17.4 Annual rates of restoration on upland grassland peat soils



Description: Upland peatland rewetting and restoration rapidly ramps up in the Balanced Pathway, reaching peak rates in 2030, and then maintains this through to 2050.
Source: DESNZ, CCC analysis.
Notes: Historical areas of peat restoration are derived from the UK GHG inventory that reports projected areas of rewetted peat.

Lowland peat soils

Lowland peats are utilised under a range of land uses, including intensive and extensive grassland and cropland. They also underpin increasingly rare natural habitats such as fens and lowland raised bogs. Lowland peatlands are more emissions intensive than their upland counterparts, largely due to their long and continued intensive agricultural use that has resulted in deep drainage and disturbance through cultivation.

Around 92% of UK lowland peatlands are currently in a degraded state and it is estimated that there is 53,000 hectares in a 'wasted' state (former deep peat that has been lost due to agricultural activity). Under the rates of delivery in the Balanced Pathway, informed by stakeholder engagement, the total restored or near-natural area of lowland peatland increases from the current 8% to reach 31% by 2040 and 56% by 2050.

Lowland grasslands on peat soils

Lowland grasslands on peat soils consist of intensive and extensive grassland types, with intensive systems expected to have undergone fertilisation, have higher density grazing, and likely to have soils disturbed via ploughing and reseeding. Extensive grasslands currently do not receive fertiliser inputs and are grazed at lower densities. Intensive grasslands dominate the lowland grasslands on peat soils, making up around 78% of the total area.

Under the Balanced Pathway, 69% of lowland grassland is rewetted by 2050, with the ambition and rates of delivery informed by stakeholder engagement and Committee judgement. Extensive grasslands are aligned to their upland counterparts, with 90% under rewetting by 2050. Just over 60% of intensive grassland fall under rewetting action over the same time-period.

- Delivery activity rises from the current 700 hectares of annual rewetting on extensive grasslands, to reach 1,500 hectares from 2031 onwards. Intensive grasslands rise from the current 235 hectares to reach 6,000 hectares under rewetting management from 2035 onwards (Figure 17.5).

Lowland croplands on peat soils

Our Balanced Pathway advice places 75% of deep cropland peats and 40% of wasted peat under rewetted, or sustainable, management by 2050. This ambition, and the measure level targets in this section, are based on stakeholder engagement and Committee judgement. In our analysis we include three different approaches to reducing emissions from the management of cropland on peat soils – restoration, paludiculture, and water-level management (Figure 17.5).

- **Full restoration to near-natural condition.** This measure assumes the removal of land out of agriculture with land use typically being placed into habitat restoration and nature objectives. Under the Balanced Pathway, 25% of cropland on both deep and wasted peat soils are rewetted to near-natural condition.

- **Paludiculture** or 'wet-farming' is an agricultural approach to peatland management, where wetland crops are grown under a high-, near natural, water table maintained at around a 10 cm depth.* Under the Balanced Pathway, 15% of cropland on deep and wasted peat is placed under paludiculture use.

  - Cropland is converted to paludiculture management from 2031, reaching peak annual rates of 1,600 hectares in 2035.

Sustainable management of cropland on organic soils involves the manipulation of the water table to reduce GHG emissions while maintaining agricultural production. This will require significant advancements in research and development of technology to support water level management across landscapes of a diverse topographical nature. Reflecting the challenges and barriers these actions face, they do not start until 2031 in our pathway. Paludiculture and water-level management currently do not have representative emission factors. It is assumed that emissions are proportional to water table depth.[12]

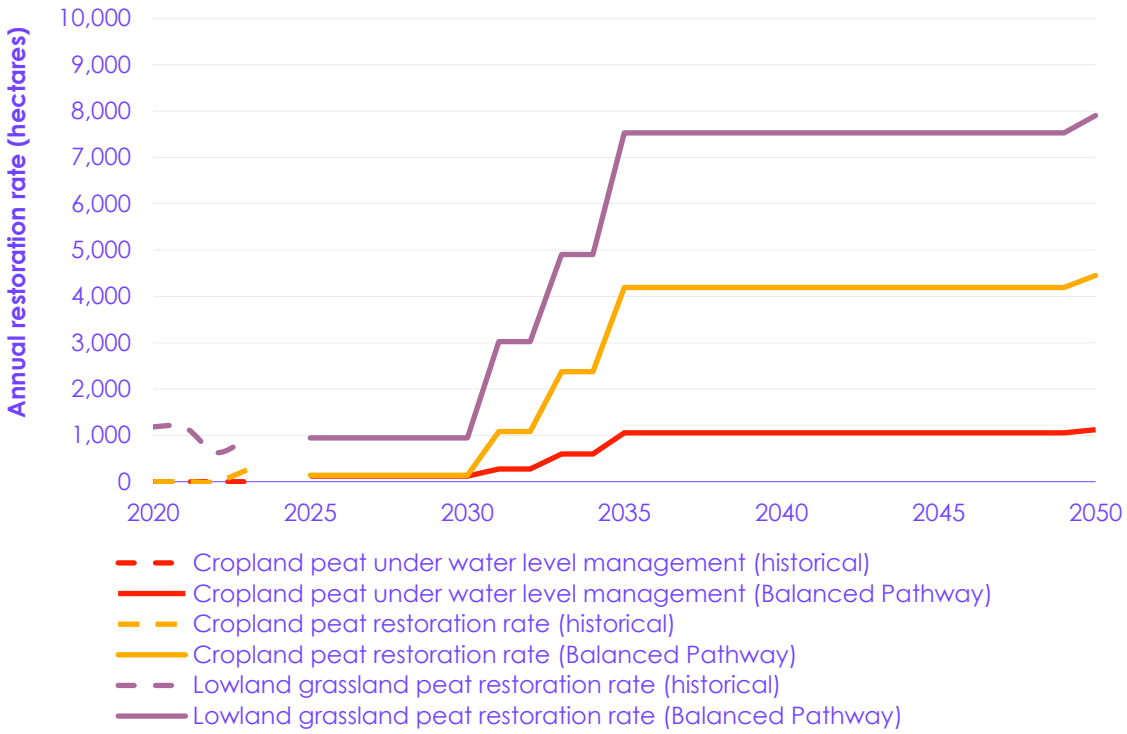
- **Water-level management.** In some areas water tables may be held lower than is necessary to continue agricultural production or water storage for flood management. Controlled rising of water levels can support reduced emissions of carbon dioxide whilst enabling peatland to remain under productive use. Only deep cropland peats are placed under these actions, with 20% converted to dynamic water table management and 15% are converted to continuous raised water table management by 2050.

  - Dynamic water table management assumes a seasonal pattern of temporary deep drainage in summer (80-100 cm), while a continuously raised water table is assumed to have a mean year-round depth of 40 cm and near-inundation in winter (10 cm).

  - Sustainable water level management activities start in 2031 and reach peak annual rates of 1,100 hectares in 2035.

* Paludiculture crops are those which thrive in wet environments, and the approach is considered a novel production system yet to occur at scale in the UK. Potential crops include rushes, reeds, sphagnum moss, and berries.

Figure 17.5 Annual restoration and sustainable management delivery rates on lowland agricultural peat soils



Description: Lowland agricultural peat soils are represented by three main approaches in the Balanced Pathway – the rewetting and restoration of cropland and grassland, and water-level management on cropland peatlands. These actions increase in their rates of delivery in the early 2030s. before reaching a plateau in the late 2030s.
Source: DESNZ, UKCEH, CCC analysis.
Notes: Historical areas of peat restoration are derived from the UK GHG inventory that reports projected areas of rewetted peat.

Other peatlands

In our analysis we also consider peatlands that are currently outside of agricultural use but still require restoration due to damaging activities such as peat extraction and establishment of woodland.

- **Extraction sites.** Peat extraction is extremely damaging as it involves the stripping away of the vegetation layer of peatland habitats, leaving underlying peat drained and exposed to degradation and carbon loss. Industrial extraction has typically been on lowland raised bogs, where milling has produced substrate used typically in horticultural activities while domestic extraction is typically removal as a fuel for heating homes. The UK Government is still to fulfil its commitment to ban the retail sale of peat, originally proposed for 2024. Licenses for the industrial extraction of peat are expected to run out by 2042.

  – Under the Balanced Pathway all industrially and domestically extracted peats are placed under rewetting management by 2042. This equates to peak annual delivery rates of 9,300 hectares from 2030 to 2042.

- **Low yield class trees on peat.** Forestry on peat can drawdown the water table due to transpiration by trees, exposing a greater depth of peat to oxidation.[13] In our modelling we assume a proportion of these are felled and the peatland rewetted.

- Trees planted on peatland soils occupy around 462,000 hectares, with 77% of this area in Scotland. We estimate around 66,000 hectares of this is low-productive trees with a yield class of below 8.

- Under the Balanced Pathway, restoration of forestry sites via felling of trees with a yield class of below 8 and rewetting rise from around 900 hectares in 2025 to reach 2,600 hectares annually from 2030 – 2050. By 2050, 14% of forestry on peat is under restoration.

17.2.3 Woodland creation and management

The expansion of new woodlands on previously unforested land delivers carbon sequestration direct from the atmosphere and storing it in vegetation and soils. Currently, around 13% of the UK's area is classified as woodland, but this varies considerably by nation with Scotland currently having the highest proportion of woodland, at 19%, and Northern Ireland having the lowest, at 8%.[14]

When appropriately sited and managed to be resilient, land use change to woodlands can deliver a diverse range of benefits beyond carbon, including for climate change adaptation, biodiversity, flood management, air quality, and the health and wellbeing of communities. However, planting in unsuitable spaces will bring risks, including to priority habitats and other environmental priorities, as well as to the carbon stocks themselves. This will typically depend on site-by-site decisions beyond the resolution of our modelling approach.

- The Forestry Commission estimate that 2.9 million hectares in England alone would be considered 'low risk' for woodland consideration, when taking into account peatland soils, agricultural land quality, biodiversity, and historic interests.[15]

- A spatial study considering biodiversity and historic interests, farmland quality, and higher and lower risk soil types in their analysis estimates around 4.6 million hectares are potentially suitable for woodland creation across the UK.[16] However, over 2.5 million hectares are on higher risk organo-mineral soils where woodland creation may not result in net sequestration, depending on the establishment technique used.

The woodland creation models estimate the carbon stock changes in forest biomass (including deadwood and litter) and soils and then converts these into carbon dioxide emissions and removals.[17] This approach is derived from the Forest Research Quantifying Sustainable Forestry and is consistent with the CARBINE model used in the UK GHG inventory.[18] This represents an update to our approach since the Sixth Carbon Budget advice which is detailed in section 3.3.

Woodland expansion and rates of planting

Under the Balanced Pathway the proportion of the UK under woodland cover rises to 18% by 2050, with an additional 1.3 million hectares delivered between 2025 to 2050.* In setting this ambition we have considered what has been achieved in past UK delivery, examples from other countries regarding feasible planting rates, the amount of suitable land and its release from agriculture, and expert input from the industry.

- Annual planting rates averaged 40,000 hectares in the early 1970s in Great Britain and close to 30,000 hectares in the late 1980s across the UK (Figure 17.6).† This increases to over 50,000 hectares and over 40,000 hectares in the 1970s and 1980s respectively, if restocking of felled areas is considered.

* This figure includes open space as required for biodiversity value.

† Annual forestry planting data for Northern Ireland is available from 1976 onwards.

- The woodland area in France increased by almost 4 percentage points between 2000 and 2020, from 28% to 32%. During the 2010s planting rates were equivalent to almost 49,000 hectares a year.

- New Zealand has seen a rapid upscaling in tree planting driven by the Emissions Trading Scheme. Between 2019 and 2023 annual planting rates increased from 7,000 to 69,000 hectares.[19]

- The National Wood Strategy, led by the productive forestry sector and with a focus on domestic timber, suggest ambition in England should be to achieve at least 17.5% woodland cover by 2050.[20] This is consistent with the creation of new woodlands in the Balanced Pathway.*

New woodlands exhibit a lag between planting and reaching peak sequestration rates. It is critical that woodland creation rates are scaled up in the late 2020s and early 2030s if new woodlands are to deliver significant carbon sequestration before 2050.

- The Balanced Pathway assumes a planting rate of 14,800 hectares in 2025. This then increases linearly to reach just under 60,000 hectares / year in 2036 and is then held through to 2050 (Figure 17.6). In the baseline, average annual rates of woodland creation over 2020 to 2022 are maintained from 2025 to 2050.

  - The land required for woodland creation is initially based on land allocation patterns reported between 2013 – 2022 and then adjusted so rates of creation balance with land released from agriculture.† Based on this, new woodland is created on a mix of agricultural pasture grassland, rough grazing grassland, cropland, and settlement areas.‡

- Of the area converted to woodland, 15% is included as open ground. Areas of open ground in woodlands can benefit and enhance biodiversity. This exceeds the minimum 10% as set out by the UK Forestry Standard.

Woodland creation is assumed in the modelling to occur via the planting of nursery stock of trees, and will be dependent on the supply chain scaling up to meet the ambition. There is increasing interest in the role of natural regeneration of trees, where the expansion of woodlands is driven by seed dispersal rather than planting of young trees previously raised elsewhere. However, more information is required on the spatial and temporal variability of natural regeneration before it can be incorporated into emission pathways.

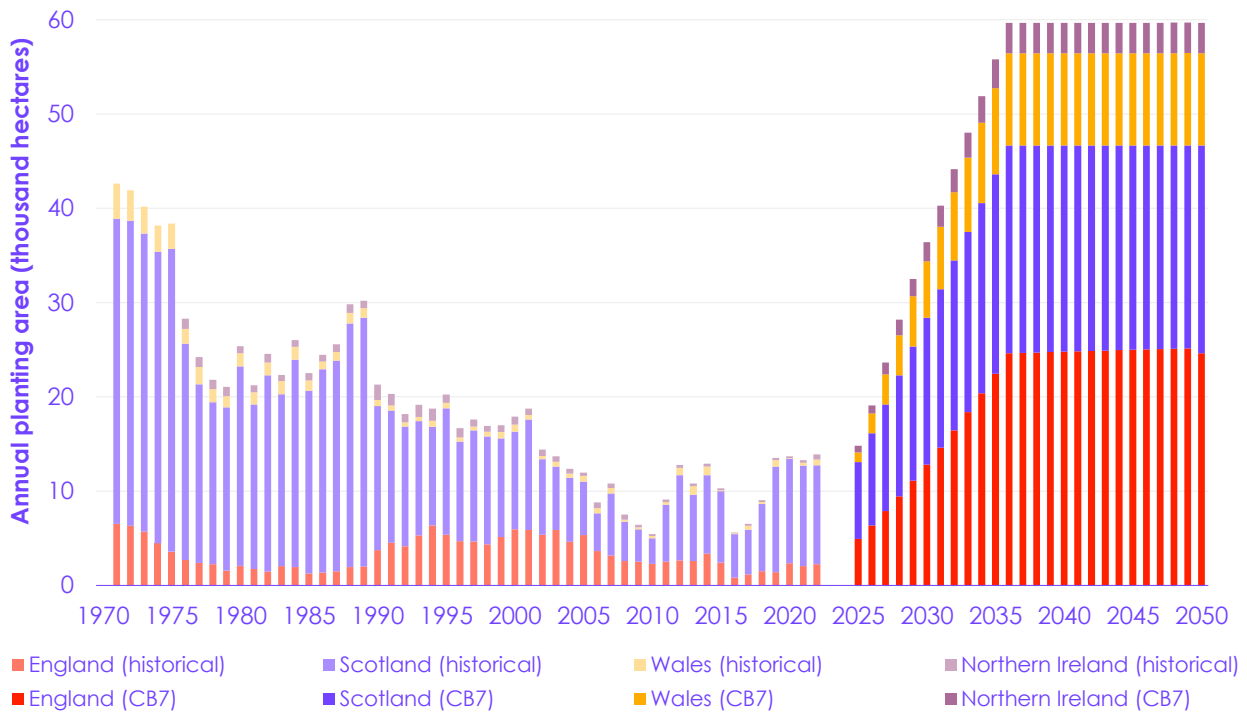
Capex and opex costs for woodland creation in the Balanced Pathway are based on per hectarage values derived from the John Nix Pocketbook for establishment of conifer plantations and a landscape-scale nature recovery project for broadleaf woodland creation.[21] This was informed by the Land use archetypes project accompanying this methodology.[22]

* This is at the midpoint of CCC advice where England reaches 18.3% of tree cover, when all tree types are included (e.g agroforestry and tree-based energy crops), and 16.4% when woodland alone is considered.

† The annual rate of woodland planting is allocated between nations: England has 32% of the UK total in 2024, rising to 40% in 2037-2050; Scotland has 58% in 2024 falling to 37% in 2036-2050; Wales has 6% in 2024, rising to 18% for 2029-2050; and Northern Ireland has a stable allocation of 5% of total UK woodland creation in all years.

‡ Settlement land is urban and suburban land, recreational grassland, infrastructure and vacant land.

Figure 17.6 Historical woodland creation rates (1971 - 2022) and new woodland creation in the Balanced Pathway



Description: Reported rates of woodland creation are shown to the left of the chart through to 2022, while modelled planting rates are shown in bold colours, from 2025 onwards. In the Balanced Pathway, tree planting rapidly increases, reaching peak rates in 2036 which are maintained through to 2050. The largest areas of new planting occur in England and Scotland.
Source: Forest Research, UKCEH, CCC analysis.
Notes: Planting data 1971 to 2022 is based on annual Forestry Statistics report (2023) and was used to inform the analysis for the woodland creation analysis. The 2024 Forestry Statistics reported woodland creation of 21,000 hectares. This is not included here as was reported after completion of the Seventh Carbon Budget Analysis. From 2025 onwards, planting rates shown are based on CCC modelling for the Seventh Carbon budget.

Woodland type and density

We use a combination of tree species in the Balanced Pathway to represent the resilient and diverse mix of woodlands that will be required in the Net Zero transition. Both broadleaf and conifer woodlands are included in our analysis.

- At the UK-scale, woodland cover is currently split 52% to 48%, conifers to broadleaves. This is largely due to post-Second World War policies which heavily favoured the planting of timber plantations. However, this varies depending on location, with broadleaves dominating in England (77%) and conifers dominating in Scotland (71%) due to soil and climate conditions.[23]

- Between the mid-1990s and mid-2010s new planting was dominated by broadleaves, driven by biodiversity led grant support schemes. In recent years the planting split is even between conifers and broadleaves.

- In the Balanced Pathway, by 2050 both types of woodlands have expanded across the UK offering opportunities for both biodiversity, timber, and other wood products. However, broadleaves will have increased their share, making up 55% of UK woodlands compared to 45% for conifers.

Our assumptions on the mix of tree species aligns to guidance of the UK Forestry Standard which prohibits the planting of mono-cultures and limits the planting of any one species on one site.[24]

- In our model, broadleaf woodlands are represented by sycamore/ash/birch. This species mix aligns to a wide range of relevant tree species and is often used as a proxy to assess carbon sequestration from other mixed stands of large and medium trees. It should not be considered prescriptive for future planting plans.
  - In England, Wales and Northern Ireland, 80% of new planting is assigned to broadleaves reflecting the land and climate conditions. In Scotland, it is 42%.
  - Broadleaf planting is assumed to be Yield Class 6 (YC), with a density of 1,800 stems/hectare, aligning to the average density observed in grant schemes delivering biodiversity objectives in the early 2020s.
- Sitka spruce is used as the proxy species for non-native conifers in all UK nations, and again, should not be considered prescriptive. In Scotland, Scots pine is also used for native conifers and represents both biodiversity and timber-led assumptions.
  - In England, Wales and Northern Ireland, 20% of new planting is assigned to conifers. In Scotland it is 58%, reflecting the land and climate conditions. Conifers in Scotland are split between sitka spruce (41%) and Scots pine (17%).
  - Conifers are planted at higher density of 3,000 stems/hectare, necessary to support quality timber production, with YC16 assumed. In Scotland, the conifer area is split between YC16 (assumed to be non-native conifer plantation species), and YC8 (low density 1,800 stem/hectare) and YC14 (productive 3,000 stems/hectare) native conifer species.
- We consider a range of management approaches in the Balanced Pathway for new woodlands:
  - Continuous cover management is assumed for broadleaves and Scots pine YC14.
  - No thinning and no felling management is assumed for low density native Scots pine in Scotland.
  - Standard thinning and rotation management is assumed for planted Sitka spruce.
- We recognise that the species mix, density and management of new woodlands in the UK is more diverse than what can be accommodated in our modelling approach, with our proxies intending to represent a much wider diversity of species, appropriate for the UK now and under future climate change.

Sustainable management of broadleaf woodlands

In the UK, currently only 20% of broadleaf woodland is considered to be under management.[*];[25] Introducing sustainable management to previously un-managed woodlands can support both benefits for carbon and the wider environment.

- It can enhance productivity, increasing rates of carbon sequestration via improved woodland health and increased survival rates of young trees.

[*] We assume that all conifer woodlands are under management.

- Opening up dense canopies lets in light and supports improved woodland habitat condition via diversifying ground vegetation and associated biodiversity.

- Increases the resilience of woodlands to wind, fire, pests, and diseases, which could increase under a warming climate.

- Management can generate woodland products and offers land managers a diversification in their operations.

Under the Balanced Pathway, the sustainable management of broadleaf woodland rises to 80% by 2035. Based on stakeholder engagement, this is higher than the previous target set by Defra to reach 67%, but aligns to current site-based projects such as the National Forest, where 80% of the woodland area is in active management.[26]

- The C-Flow model was used to estimate the impact of sustainable management of broadleaves on the net biomass and soil carbon stock for the Sixth Carbon Budget Analysis.

- In the absence of having access to the C-Flow model for our current advice, we applied the percentage difference in annual broadleaved net carbon stock changes between the Sixth Carbon Budget baseline and Balanced Pathway (which also assumed an 80% ambition) to the baseline projections for forestry based on the 1990-2021 GHG inventory. This method estimated the impact of increasing sustainable management on broadleaved woodland established before 2022 for the Balanced Pathway.

The softwood and hardwood production forecasts from Forest Research were used to estimate the timber and wood fuel production from existing UK forests. The analytical approach is described in the accompanying contractor report and the outputs represented in Chapter 12 Fuel Supply.

17.2.4 Energy crops

An appropriately sited, sustainable UK supply of perennial energy crops is important in contributing to Net Zero by displacing fossil fuels and removing carbon from the atmosphere when combined with carbon capture and storage (CCS) technology. The land use sector accounts for the net carbon sequestration retained on site in vegetation and soils following the harvesting of the energy crop.

- The Balanced Pathway includes three perennial crops – miscanthus, short rotation coppice (SRC), and short rotation forestry (SRF).* The area of miscanthus and SRC is currently estimated at 13,000 hectares, while the area of SRF is unknown.[27] Current rates of delivery are negligible.

  - Perennial crops are used to minimise soil disturbance and carbon loss (when compared to the counterfactual agricultural uses such as arable crops and grass leys). Wider impacts of energy crops are dependent on their careful siting in agricultural landscapes.

  - Planting energy crops on degraded land can support the increase of soil carbon stocks, as well as that held in vegetation. Energy crops are only planted on existing agricultural land and not allocated to organic soils to prevent carbon loss.

Our Balanced Pathway assigns 710,000 hectares of energy crops to the UK by 2050, 3% of the total UK land cover. This area is half of the central estimate for energy crops modelled by the Energy Technology Institute.[28] This work only considered sparing of land for energy crops, whilst the CCC land use analysis considers a much broader set of land-based measures to which land needs to be

* In the Balanced Pathway, we define these as energy crops as this is their primary use. However, such perennial crops can also be used for alternative uses, such as animal bedding, feed, biochar, and packaging materials.

allocated. We therefore refined the planting area based on expert engagement and Committee judgement. The annual rate of deployment is based on the rate of land transitioning from agriculture and the availability of land-types as described above.

- Rapid upscaling in energy crop planting will be required to meet this ambition. Annual rates increase to 12,000 hectares by 2030. This then rises to 38,000 hectares each year by 2037 and is then maintained until 2050. However, considering current activity is low, we delay ramping up planting of energy crops until 2027 to enable policy and incentive design. Across the UK there is a close to even split across the three energy crop types.

- Energy crops are assigned to each nation based on the starting land uses as informed by the 2021 June agricultural survey.

  - Miscanthus and SRC are apportioned between nations based on the availability of arable and temporary grassland. Miscanthus is assumed to be planted on cropland only and SRC is split equally between cropland and temporary grassland.

  - SRF is split between permanent, temporary, and rough grassland.

  - Wales has a low share of arable land compared to the rest of the UK and is lacking the infrastructure to plant and make use of energy crops at scale. We therefore exclude the planting of energy crops in Wales under our pathway.

Yields from energy crops are variable and dependent on a range of factors including local climate, planting methods, and species used. We assume productivity improvements via better agronomy, appropriate siting, and improved plant breeding (including genetic modification) will increase the yield of miscanthus and short rotation coppice from 12 to 15 oven dried tonne/hectare by 2050, based on yield estimates from bioenergy datasets published by the UK Government.[29] These crops are harvested three years after planting. Short rotation forestry was assumed to be broadleaved yield class 12 with no thinning management. The carbon stock changes in SRF were modelled based on the forestry approach taken as described in Section 17.2.3.

Short rotation forestry has a harvesting rotation of 26 years and does not produce a crop before 2050. However, rotation length is species and location dependent, and a crop could be produced earlier depending on circumstances. We include it in the energy crop category as it offers a diversification option for farmers to support energy production in the future. Capex and opex costs for energy crops are based on the John Nix Pocketbook and applied here on a per hectare basis. This was informed by the Land Use archetypes project accompanying this methodology. A UK value is applied to all nations due to the lack of national level data.

Our modelling includes the carbon benefits (e.g. carbon stock changes in the soil and biomass) of bioenergy crops. The use of energy crops is described in Chapters 12 (fuel supply) and 18 (engineered removals).

17.2.5 Agroforestry and hedgerows

Agroforestry is the integration of trees and shrubs onto arable (silvoarable) and agricultural grasslands (silvopasture). Along with the management and expansion of hedgerows, these measures support continued productive use of land, whilst sequestering carbon in the vegetation and soils.

- Agroforestry areas aren't officially reported in UK land use statistics. However, it is estimated that 3% of the utilised agricultural area (UAA) of the UK was under agroforestry practices in 2017, compared to the European average of 9%.[30]

- Silvopasture such as wood pasture, parkland, and wooded commons make up the majority of agroforestry systems currently established in the UK. Silvoarable systems are less common but will offer adaptation benefits for cropping systems under future climate change.

- There are estimated to be around 800,000 kilometres of hedges in the UK. This is taken from the 2007 GB and Northern Ireland Countryside Surveys. This has not been repeated at the UK scale, but a 2024 survey at England-scale suggests managed hedgerow length remains similar.[31]

- Capex and opex costs for agroforestry and hedgerows are based on the John Nix Pocketbook and applied here on a per hectare basis. This was informed by the Land Use archetypes project accompanying this methodology. A UK value is applied to all nations due to the lack of national level data.

Agroforestry

In practice, agroforestry systems represent a spectrum of actions, with different planting design, density, and tree species depending on location. For the purposes of the modelling, we have adopted a defined set of assumptions to act as representative of silvoarable and silvopastoral measures. We assume that 10% of agricultural land is converted to agroforestry approaches by 2050. This scale of land use change to agroforestry is based on stakeholder engagement.

- The low-density planting that characterises this land use measure means that only a proportion of the converted area is changed from its original use of grazing or arable crops. Planting densities used in the modelling are consistent with guidance provided to landowners.

  - **Silvopasture:** 10% of permanent pasture and rough grazing land is converted to silvopasture in the Balanced Pathway. Overall, 14% of this area is under trees, equating to a planting density of 400 trees per hectare. This is at the higher end of silvopastoral planting densities and was chosen to maximise sequestration whilst maintaining grazing area in the near-term.[32]

  - **Silvoarable:** 10% of arable and temporary grassland is converted to silvoarable. Such a transition in arable systems is expected to have a minimal impact on productivity.[33] Just under 7% of this land is under tree cover, equating to a planting design of a 2 metre-wide strip for each tree row, with 8 metres between trees in a row and 30 metres between each row. Row width is based on a compromise between the need to maintain crop productivity and carbon sequestration.[34;35]

- Agroforestry planting starts in 2025 and continues at a constant rate to 2050. This equates to 7,800 hectares of agroforestry creation each year in the UK.

- The silvopasture measure assumes a broadleaved yield class 6 with no thinning management, and the silvoarable approach assumes yield class 12 with no thinning management. Carbon sequestration rates were calculated using the approach as described under the woodland creation and management section.

Hedgerows

Hedgerows are linear features in agricultural landscapes, where tree and shrub species are planted to contain livestock or to designate field boundaries. The current extent of hedgerows is much reduced from historical levels, with post-World War II agricultural policy leading to their removal due to emphasis on increased agricultural production and mechanisation.

Under the Balanced Pathway, hedgerow length increases to reach a 10% increase on the lengths reported in the 1984 Countryside Survey (as used in the previous carbon budget), recognising that

pre-1984 the historical record suggests a much greater extent of hedgerows as boundaries.[36] This increase is applied across the nations.

- Hedgerows are planted along existing boundary (for example, fence lines) or remnant hedge lines, and do not result in the subdivision of existing field areas. We assume hedgerows are managed to be 1.5m wide, in line with current management advice under agri-environment schemes.[37]

- Density of the biomass stock is derived from the BEIS Biomass Extension project.[38] Management for biomass is on a 15-year cycle for 30% of hedgerows, with 60% of the increase in biomass removed (see Chapter 12 Fuel Supply). Hedgerows require regular cutting to support their role as a dense, vegetated barrier.

- As well as carbon stored in vegetation, hedgerows can provide benefits for soil carbon by reducing soil disturbance, increasing return of leaf litter, and having deeper rooting woody species when compared to adjacent fields. We apply annual soil carbon sequestration rates of 1.4 tonnes carbon per hectare as an average across all hedgerows.[39]

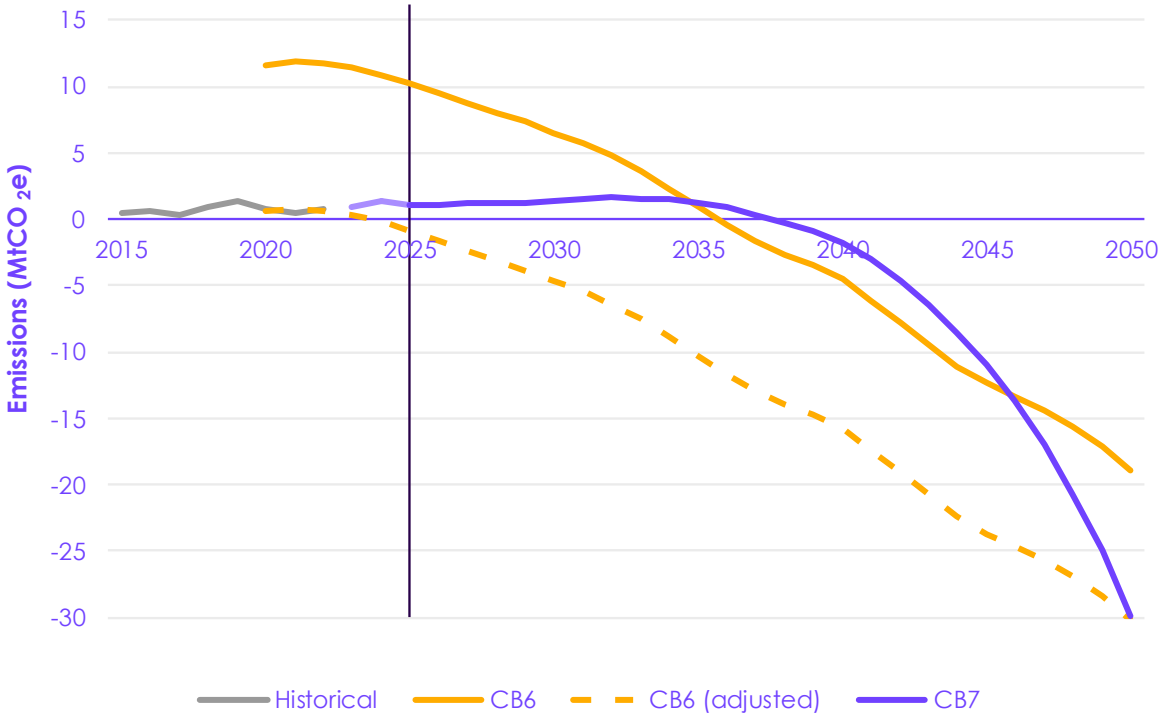
17.3 Changes since our Sixth Carbon Budget advice

17.3.1 Comparison with our Sixth Carbon Budget pathway

Our Balanced Pathway for land use begins as a small net source of emissions, and remains around this level for the coming decade. This is considerably lower than our Sixth Carbon Budget pathway, as a result of the impact of changes to emissions accounting over recent years.* Thereafter, carbon sequestration in land use sinks scales up through the 2040s, later but more quickly than in our Sixth Carbon Budget advice (Figure 17.7). This reflects improved modelling of the soil disturbance emissions from tree planting and the time lag before meaningful levels of sequestration are achieved in new woodlands.

* All comparisons in this section compare the Balanced Pathway in this advice with the Balanced Net Zero Pathway in our Sixth Carbon Budget. Our Sixth Carbon Budget advice also included four other exploratory pathways, which are not discussed here. Data for those pathways can be found in our Sixth Carbon Budget advice.

Figure 17.7 The Balanced Pathway for land use compared to our Sixth Carbon Budget advice



Description: Changes in emissions accounting over recent years mean that the starting point for our Seventh Carbon Budget (CB7) Balanced Pathway is considerably below our Sixth Carbon Budget (CB6) pathway.
Source: DESNZ, CCC analysis.
Notes: Estimates of emissions in this sector have been substantially affected by changes in emissions accounting methodologies in the inventory since our Sixth Carbon Budget advice. Therefore, to enable easier comparison, we have included a 'CB6 (adjusted)' series estimating what the Sixth Carbon Budget pathway would look like if it had used the latest inventory accounting.

17.3.2 Emissions changes since our Sixth Carbon Budget advice

Since our Sixth Carbon Budget advice was published in 2020, the UK GHG inventory has undergone significant improvements to the reporting of emissions from the LULUCF sector (See Figure 17.7), which has had an impact on the CCC's land use analytical outputs.

- The 1990 to 2019 GHG inventory, published in 2021 expanded the representation of peatlands (via peat condition categories and associated emission factors), becoming consistent with the 2013 IPCC Wetlands Supplement.
  - The Sixth Carbon Budget pathways were developed before these adjustments had been made to the inventory and so used the AR5-high global warming potentials (GWPs) in the modelling, taking a cautious approach to the inclusion of peatlands. It was assumed the impact would be at the higher range of the projected changes so as to not recommend targets which might be rendered unachievable by a subsequent choice of emissions accounting methodology.
  - The UK GHG inventory went on to use a lower emissions factor for forestry peats than we assumed and it was agreed at COP26 to use AR5-low GWPs, reducing the emissions of non-CO_2 GHGs.
- The 1990 to 2020 inventory update relevant to the land sector included an improvement in the data and methodology used to estimate emissions. A Bayesian data assimilation

approach was used, integrating land use data sources with national-scale census data to construct emission estimates associated with land use change.

- Subsequent changes to the methodology in the 1990 to 2021 inventory saw further adjustments to peatland emissions that addressed CO_2 emissions from wasted organic soils, forested peat mapping, and improved alignment with the peatland code.

- The 1990 to 2022 inventory had adjustments to the carbon accounting models, adjusting the soil model and including urban trees, as well as updated peat maps with the inclusion of 2,674 hectares of rewetted bog in England.

- Overall, this series of changes mean that estimated LULUCF emissions in the 1990 to 2022 inventory (used for our updated Balanced Pathway) are lower than the 1990 to 2018 inventory (used for the Sixth Carbon Budget Balanced Pathway), with the LULUCF sector currently a small net source of emissions.

17.3.3 Key pathway differences compared to our Sixth Carbon Budget advice

There are several key areas in which the deployment rates, measures included, or underlying assumptions in our updated Balanced Pathway have been revised since publication of our Sixth Carbon Budget advice in 2020. These include:

- **Woodlands emissions modelling.** Alongside inventory changes, the CCC has updated the modelling approach to woodland to improve alignment with the GHG inventory which uses the Forest Research model, CARBINE. This has resulted in a change to the pathway trajectory, where improved representation of soil emissions offsets sequestration, resulting in a flattening of the pathway until the late 2030s.

  - We have used the 2022 Forest Research report 'Quantifying the sustainable forestry carbon cycle' (QFORC), a CARBINE-based model approach that allows assessment of different options for woodland creation and management.[40]

  - Carbon stock changes in forest biomass (including deadwood and litter) and soils are estimated, and converted into carbon dioxide emissions/removals, using data tables for each species, yield class and management combination. The data tables have been derived from the CARBINE model.

  - This approach represents an improved assessment of carbon stock losses associated with forest establishment compared with the C-Flow methodology used in the Sixth Carbon Budget analysis.

  - However, the estimation of net emissions from soils, particularly in the first few decades following woodland creation, continues to have high uncertainty and varies according to the species, former land use, establishment technique and management (see chapter 5 which covers uncertainty in more detail).

- **Woodland creation.** Delayed action has meant that tree planting rates have not ramped up consistently towards the levels required from 2025 in our Sixth Carbon Budget analysis. However, the latest data for 2024 (provisional) – published after our modelling was undertaken – shows a significant increase in planting rates.[41] We assume a ramp-up from the average planting rates across the latest three years of data available when the modelling was undertaken, reaching and then exceeding Sixth Carbon Budget levels by 2030 (Figure 17.8a).

- **Peatland restoration.** Similarly, delays mean that current restoration rates are falling short of previous projections (although the latest data – published after our modelling was

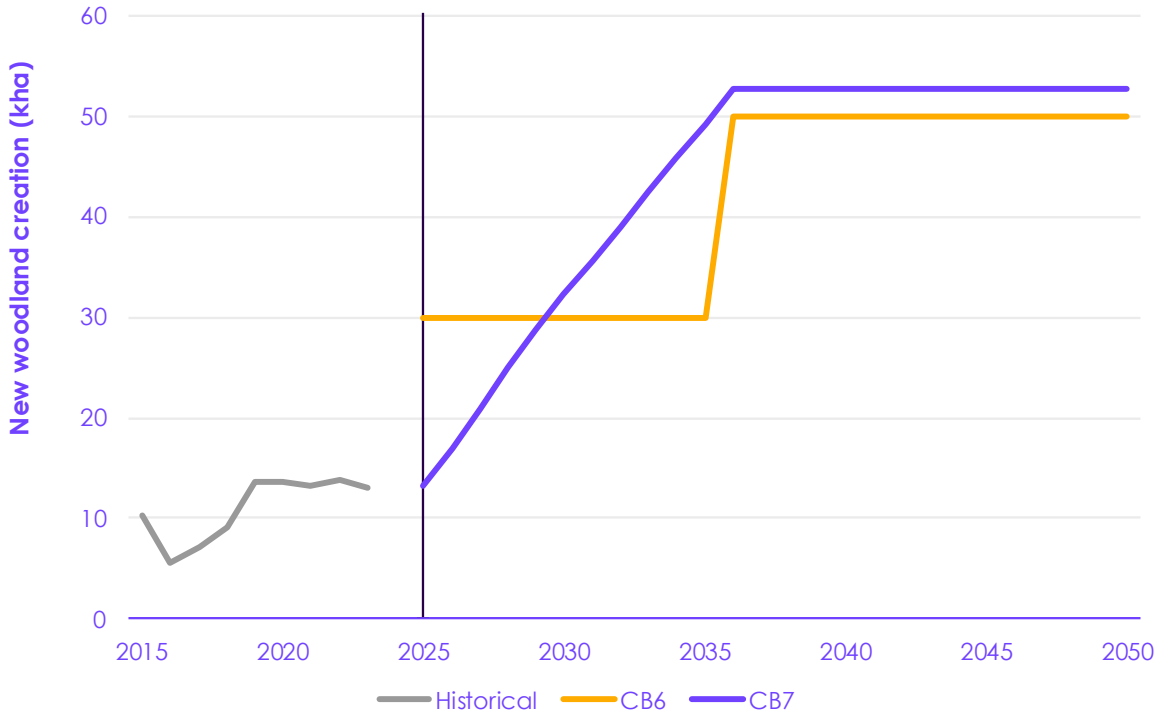
undertaken – shows some initial sign of increase). As with woodland creation, we assume a ramp-up from today, although reaching a lower peak level than in our Sixth Carbon Budget advice (Figure 17.8b).* This is due to mapping updates indicating changes to peatland extent, as well as a reduction in ambition for upland peat restoration from 100% in the Sixth Carbon Budget advice to 90% by 2050.†

* Due to changes in peat categorisation and mapping between carbon budget advice, we cannot make a direct comparison at a GHG inventory peatland condition level. However, for the peatlands overall, the Seventh Carbon Budget advice will result in 76% of UK peatlands being brought under rewetting actions, similar to the 79% advice under the Sixth Carbon Budget.

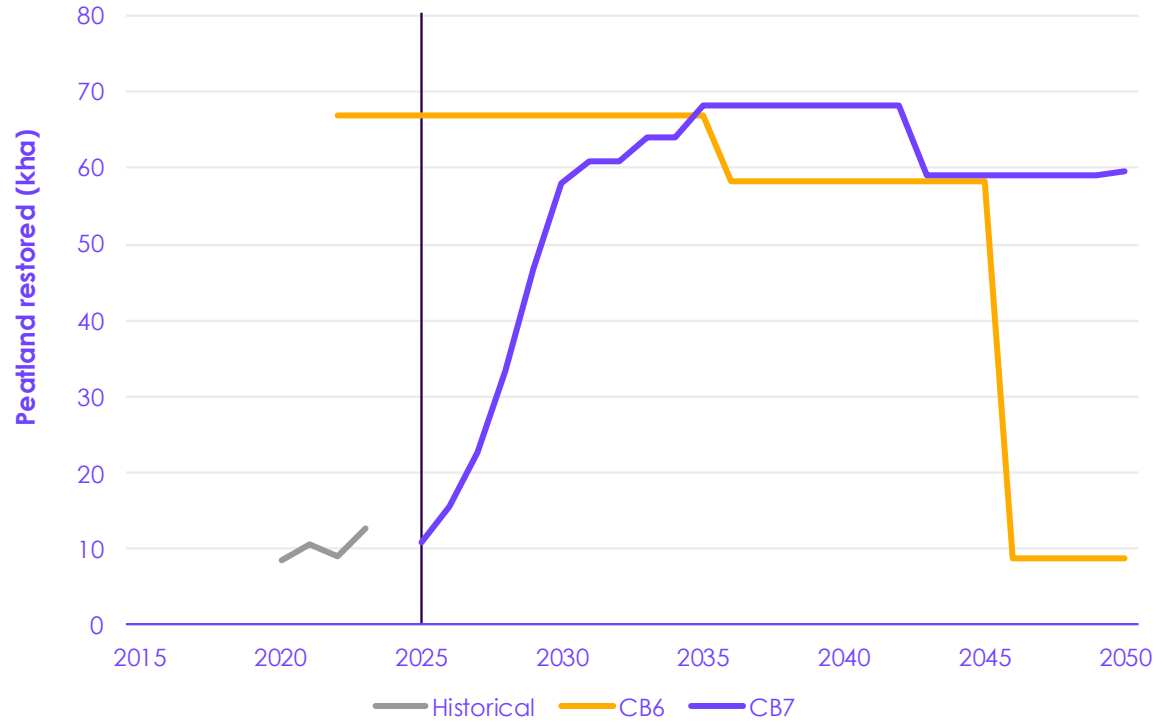
† This was adjusted to reflect logistical challenges in reaching this level, such as contractor capacity and accessibility of sites.

Figure 17.8 Key differences in deployment trajectories in the Balanced Pathway for land use compared to our Sixth Carbon Budget pathway

(a) New woodland creation per year



(b) Peatland restoration per year



Description: Deployment trajectories for woodland creation and peatland restoration increase from 2025, before both reach a plateau in the late 2030s. This differs from the Sixth Carbon Budget advice where a more stepped pathway was assumed.
Source: CCC analysis; Forest Research; Defra; Scottish Government; Welsh Government; DAERA.
Notes: Historical data aligns to that used to inform modelling for the Balanced Pathway, with more recent updates not reported here. Peatland restoration rates refer to action to rewet peat across the following starting land uses on organic soils – upland grassland, lowland grassland, lowland cropland and forested peat.

17.4 Uncertainties and sensitivity analysis

The land use sector is subject to a range of uncertainties, including how emissions in complex biological systems are quantified as well as challenges in determining the future upscaling of mitigation actions on the ground. See Chapter 5 for our general approach to uncertainty and contingency analysis, including descriptions of the methodology behind sensitivity tests that apply across multiple sectors.

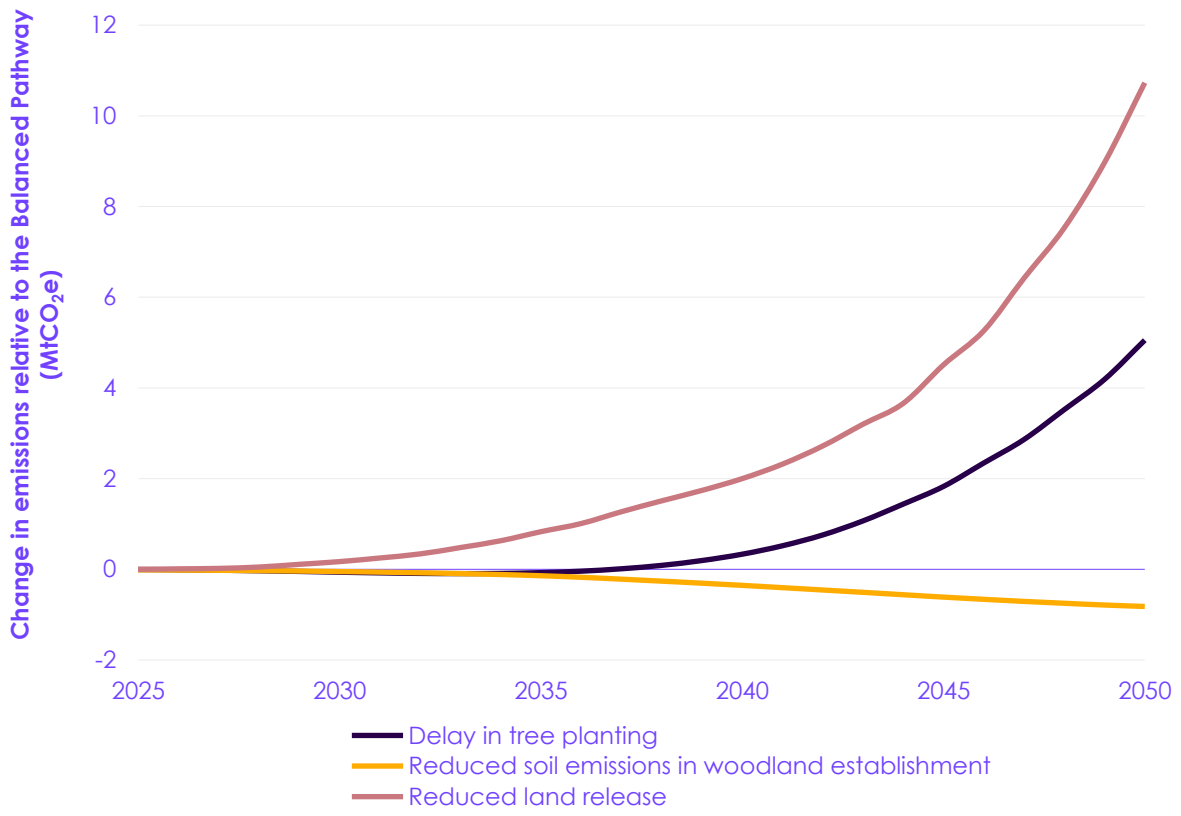
The key sensitivity tests that we have undertaken in the land use sector are shown in Table 17.2 and Figure 17.9.

Table 17.3
Key sensitivity tests for land use

Sensitivity test	Description	Impact on emissions in 2040		
		$MtCO_2e$	% of sector emissions	% of total emissions
Delay in woodland creation	A five-year delay in reaching the Seventh Carbon Budget woodland creation planting rates.	+0.3	-18%	+0%
Soil emissions from woodland establishment	Lower soil carbon emissions from the establishment of trees.	-0.4	+19%	-0%
Land not released from agriculture	Land is not made available for new measures that sequester carbon.	+2.0	-107%	+2%

Notes: By 2040, the land use sector is a small (but growing) net emissions sink. Therefore, the percentages of sector emissions are calculated relative to a small negative sector total – as a result, small absolute impacts have relatively large percentage values, and sensitivity tests that increase emissions have a negative percentage value.

Figure 17.9 Emissions impact of key sensitivity tests for land use



Description: Delays to upscaling tree planting rates and actions that release land increase emissions in the Balanced Pathway, especially over the 2040s, while actions to reduce soil emissions decrease emissions.
Source: CCC analysis.
Notes: The x-axis shows the difference in emissions compared to the land use Balanced Pathway.

17.4.1 Delay in woodland creation

While UK woodland creation rates have increased in recent years, they have not matched the ambition set out in our Sixth Carbon Budget advice. This sensitivity test seeks to quantify the impact of continued delay in deployment of this measure on future emission reduction by woodland creation.

- Current baseline planting rates are held for five years. Peak rates of woodland creation are achieved in 2041, rather than 2036.
  - We assume that the delay does not result in higher planting rates in later years, so overall the area of new woodland achieved is less.
- The species mix, density and allocation to different areas of the UK remain the same as in the Balanced Pathway.
- A delay in upscaling woodland creation rates results in an increase of emissions in the Balanced Pathway in 2040. However, due to the time lag newly established woodland take to achieve peak rates of sequestration, this impact is further amplified over the 2040s and by 2050, results in 5.1 $MtCO_2e$ less emissions reduction.

17.4.2 Soil emissions from woodland establishment

In the line with the GHG Inventory, the Balanced Pathway assumes carbon is lost from soils under new woodlands due to the disturbance of soils from planting and establishment of young trees. This is believed to be an overestimate, and with careful siting and planting techniques as promoted in current woodland grant schemes this carbon loss could be much reduced.

- Using the Woodland Carbon Code soil disturbance tables, we isolate and then apply a proportional reduction to soils emissions as represented in the Balanced Pathway. We estimate moving from a high disturbance to medium disturbance will result in a reduction of emissions from the soil of around 40%.
  - This is not presented as prescriptive and in practice would be site dependent and highly variable.
- It is estimated that reducing soil emission by this level could result in additional abatement of 0.35 and 0.82 $MtCO_2e$ in 2040 and 2050 respectively. A move to lower soil disturbance would deliver larger emissions savings although the range is currently uncertain.
- These results are uncertain and cautious but demonstrate the impact soil emissions can have, and low impact establishment techniques may reduce soil emissions further. This is currently being considered by DESNZ regarding its representation in the inventory and we will adjust our models accordingly.

17.4.3 Land not released from agriculture at scale expected

The Balanced Pathway for land is dependent on land being released from other uses such as agriculture and transitioned to new land uses that act to reduce emissions (for example, peatland restoration) or directly sequester carbon dioxide (for example, woodland creation). In this sensitivity we consider the impact of diet change on land release, and the impact to the land use sector if this land is not made available for a diversification in use.

- This sensitivity is modelled by first estimating the proportion of land release that is due to diet change by land use types – cropland, grassland (temporary and permanent grassland), and rough grazing. From the mid-2030s around 70% of land release is driven by diet change. Other sources of land release (Chapter 9 agriculture) are assumed to continue.
- The proportional change in land area is then applied to the abatement reported in the Balanced Pathway. Emission reduction from land use that does not require land from agriculture (for example sustainable peatland management, management of existing woodlands) is excluded from these calculations.
- It is estimated that if land is not released for alternative uses this will result in an increase of emissions in 2040 from the land use sector. The impact is further exacerbated over the 2040s as the abatement offered by increased sequestration rates from tree growth is missed.
- This is a high-level approach to assessing the potential impact of reduced land release for new land-based measures and is intended to demonstrate the importance of the interaction between land and diet in the analysis.
  - For example, this analysis suggests the failure to release land would result in reduction by 48% of the expansion of new woodlands as advised in the Balanced Pathway.
  - However, in practice, the net impact on emissions will be highly dependent on what land use change measures are deployed and where.

- Lower rates of land release would have an impact on interactions between land use and other dependencies such as fuel supply and greenhouse gas removals. We have not assessed the impact of this in this sensitivity.

17.5 Contingencies in land use

Contingency actions are options to go further should emission reduction elsewhere in the land sector or wider economy go off track. See Chapter 5 for our general approach to contingency analysis.

The contingencies that we have modelled in the land use sector are shown in Table 17.4.

Table 17.4
Contingency option in land use

Contingency	Description	Potential average annual emissions savings ($MtCO_2e$, % of sector emissions)			
		2030	CB6	CB7	2050
Planting higher-yielding trees from 2035 onwards	From 2036 onwards, areas of YC16 conifer and YC6 broadleaves planted are assumed to increase yield class to YC18 and YC8 from 2036 onwards.				1.7 -6%

Source: CCC analysis.
Notes: We have blanked out cells where the contingency measure in question is estimated to deliver less than 0.3 MtCO2e in potential emissions savings, to focus on high-yield options.

17.5.1 Increased yield class of trees in new woodland

Yield class is the growth rate and productivity of trees, which in turn will influence the rate of carbon sequestration and timber output.

- This contingency relates to the creation of new woodlands. Annual rates of planting and the species mix of new woodland remain the same.
- We assume that from 2036 onwards, yield class of conifers reach YC18 and broadleaves reach YC8. These yield classes have been chosen following engagement with expert stakeholders.
  - Increases in yield class can potentially be achieved via improved silvicultural practices (for example selection of nursery stock, planting choice and location, and on-going management) and by innovation in plant breeding.
  - Recognising the forestry requires time to embed such improvements we assume it takes 10 years for this contingency to be established.
- Due to the deferred application of this contingency to the mid-2030s, there is little impact on emissions in the near-term. However, increasing yield class in new woodland from 2036 onwards is estimated increase net emissions reduction via increased sequestration rates by 0.06 $MtCO_2e$ annually over the Seventh Carbon Budget period, and by 1.7 $MtCO_2e$ in 2050.

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Chapter 18: Engineered removals

Introduction

There have been no engineered removals recorded to date in the UK via the engineered greenhouse gas (GHG) removal technologies within scope of this chapter. There are no engineered removals in the baseline.

The primary role of engineered removals in the Balanced Pathway is to offset residual emissions from sectors that cannot reach Net Zero emissions by themselves, particularly aviation.

- Specifically, as engineered removals send CO_2 to permanent geological storage, they are assumed to balance residual CO_2 emissions from fossil fuels.

- Land-based CO_2 removals, where CO_2 storage could be shorter term, are assumed to balance residual GHGs from agriculture and land use sources, a significant proportion of which are short-lived GHGs, including methane.

Technology options incorporated into our analysis are bioenergy with carbon capture and storage (BECCS), direct air carbon capture and storage (DACCS), enhanced weathering, and biochar. Across these subsectors, we draw on a combination of commissioned and in-house analysis. Assumptions are developed on the basis of expert stakeholder engagement and published literature.

18.1 Pathway assumptions and modelling for engineered removals

18.1.1 Modelling the Balanced Pathway for engineered removals

Overall modelling approach

Our engineered removals analysis is conducted largely independently for the three technology groups considered: BECCS, DACCS, and enhanced weathering and biochar.* This reflects the nature and role of the engineered removals sector: a set of largely independent industries for which a core part of the value generated is the climate benefit, even where there are associated co-products or co-benefits. See Chapter 1 for our general approach to pathway analysis.

The modelling approach differs across the three technology groups, using a range of commissioned analysis, in-house modelling, and assumption-based analysis based on peer-reviewed literature.

- BECCS modelling is integrated into the analysis of sectors that use biomass resources, namely electricity supply, fuel supply, waste and industry. Total BECCS is limited by available biomass supply.

* In the Balanced Pathway, enhanced weathering and biochar are grouped into a single subsector, reflecting uncertainty on their relative roles.

- DACCS analysis draws on commissioned consultancy research.[1] City Science examined the feasibility of DACCS deployment at scale in the UK, costs, and associated energy system implications. We draw on their analysis to develop a DACCS pathway which ensures economy-wide Net Zero in 2050, with a feasible scale-up to that point.

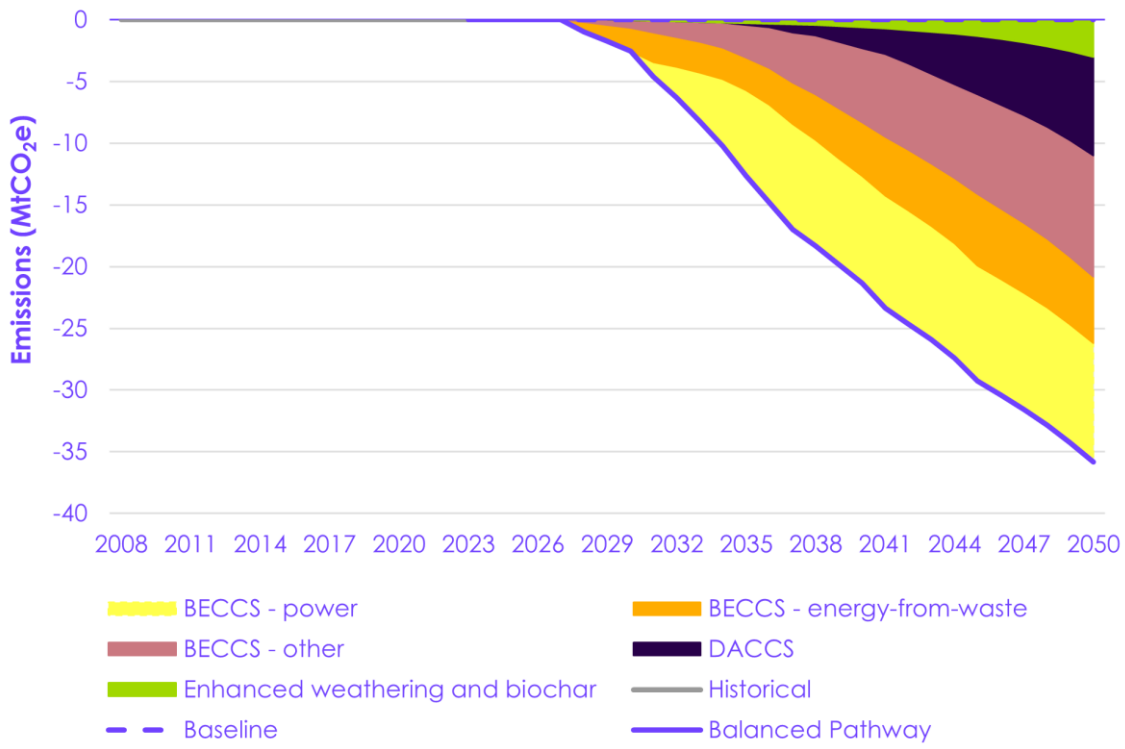
- The pathway for enhanced weathering and biochar is assumption-driven, drawing on evidence from recent peer-reviewed literature.

More speculative GHG removal approaches do not feature in the Balanced Pathway. Research is ongoing into carbon removal approaches such as ocean alkalinity, ocean fertilisation, and carbon-negative cement.[2] These were considered insufficiently developed, or judged to have too large potential negative co-impacts, for inclusion in the Balanced Pathway (see Chapter 1 for a wider discussion of our assessment approach to low-carbon technologies).

The Balanced Pathway for engineered removals

Engineered removals in the Balanced Pathway ramp up from 2028, with contributions first made by BECCS (across several sectors), then later from DACCS and enhanced weathering and biochar (Figure 18.1).

Figure 18.1 Sources of abatement in the Balanced Pathway for engineered removals



Description: Engineered removals scale up from zero currently to making a steadily growing contribution in the 2030s and 2040s, with the largest contributions from BECCS (across a range of sectors), followed by DACCS.
Source: CCC analysis.

The measures in our pathway

Table 18.1 summarises the measures in the engineered removals sector considered within our analysis, how these lead to negative emissions, and the key factors that influence their uptake. The

methodology used to develop the assumptions and analysis underpinning these is described in the rest of this chapter.

The factors underpinning the relative roles of DACCS and BECCS, and BECCS subsectors in turn, are described individually below. At a cross-sector level, BECCS deployment is driven by biomass and carbon capture and storage (CCS) availability. Within individual BECCS subsectors, each are allocated as much biomass as they require after application of cost-competitiveness and feasibility constraints, with BECCS hydrogen being assigned the residual (see Chapter 12). DACCS is then deployed to ensure Net Zero is reached in 2050, after accounting for other engineered removals, and subject to constraints described below.

Table 18.1
Measures considered within our modelling for engineered removals

Decarbonisation measure	How does this measure influence emissions in our modelling?	What are the key factors that affect uptake in our modelling?
BECCS power	The combustion of biomass for electricity generation with CCS applied. By capturing biogenic CO_2 and sending it to permanent storage, it is a net negative emissions process.	Capacity scales up to an assumed maximum deployment level of 1.3 GW. CCS is added from 2031, in line with feasible retrofit timelines applied to existing unabated biomass generation capacity.
BECCS energy from waste	The application of CCS to the biogenic portion of energy from waste. In practice the biogenic and non-biogenic waste is mixed in energy from waste plants, but they are separate for accounting purposes. By capturing biogenic CO_2 and sending it to permanent storage, it is a net negative emissions process.	Removals derive from CCS being applied over time to energy from waste facilities burning biogenic waste. Key drivers of the resulting energy from waste BECCS pathway include total volumes of residual biogenic waste, a near-elimination of biodegradable waste sent to landfill from 2028, and the elimination of nearly all waste streams to landfill from 2045.
BECCS biofuels	A group of technologies that apply CCS to biofuel production processes. It includes the production of aviation biofuels, biomethane, biodiesel, and bio-liquefied petroleum gas (bio-LPG). By capturing biogenic CO_2 and sending it to permanent storage, it is a net negative emissions process.	Biofuel plants for each fuel are built in line with sectoral demand and biomass availability. Over time they apply CCS (retrofit at first, then at initial plant construction), resulting in BECCS removals. CCS retrofit is applied from 2028 for aviation biofuels, from 2031 for other biofuels.
BECCS hydrogen	The application of CCS to the process of biomass gasification to produce hydrogen. By capturing biogenic CO_2 and sending it to permanent storage, it is a net negative emissions process.	Deployment is included to maintain technology optionality. After total biomass supply is set and other biomass use sectors demands met, this measure makes up the residual.
BECCS industry	The application of CCS to the combustion or processing of biomass in industrial processes. By capturing biogenic CO_2 and sending it to permanent storage, it is a net negative emissions process.	Least-cost modelling determines the deployment of biomass and CCS at industrial sites. When these are applied concurrently, BECCS removals are produced.
Liquid DACCS	The extraction of CO_2 directly from the atmosphere using liquid solvents and sending it to permanent storage.	Total DACCS is driven by the need to reach Net Zero in 2050, subject to scale-up feasibility constraints. Liquid is assumed

		to account for half of DACCS deployment to maintain technology optionality.
Solid DACCS	The extraction of CO_2 directly from the atmosphere using solid sorbents and sending it to permanent storage.	Total DACCS is driven by the need to reach Net Zero in 2050, subject to scale-up feasibility constraints. Solid is assumed to account for half of DACCS deployment to maintain technology optionality.
Enhanced weathering and biochar	Enhanced weathering is the removal of CO_2 from the atmosphere and sending it to permanent water-based storage through accelerating natural rock weathering processes. Biochar as a removal involves processing biogenic waste materials to create a stable carbon-rich substance for application to soils, resulting in land-based storage.	The pathway is assumption-driven, aligning with the lower end of potentials in the literature.

Source: CCC analysis.
Notes: We also model direct air capture (DAC) for synthetic fuel production for aviation and shipping, using liquid and solid DAC technologies. These are not included in the table above as the process does not reduce or remove emissions itself. See Chapters 11 and 15 for a discussion of the use of synthetic fuels as abatement measures.

Given the lack of deployment at scale to date, uncertainties in the engineered removals sector are very large. One implication of this, borne out in the Balanced Pathway, is the value in having a portfolio approach to the sector. While our analysis illustrates a single pathway for DACCS, BECCS, and enhanced weathering and biochar, there is scope for one or more of the measures to deploy at a different scale to the Balanced Pathway if, for example, the feasibility or cost of another measure proves different to current assumptions.

Residual sector emissions are an additional uncertainty for permanent engineered removals, as well as aviation and shipping synthetic fuel uptake. See Chapter 11 for more on aviation emissions uncertainty and sensitivity analysis.

18.1.2 CO_2 capture and storage

BECCS and DACCS rely on capturing CO_2 and sending it to permanent geological storage. The efficacy of both the capture and storage processes is well-evidenced.

- CO_2 capture at point-source has been in operation for several decades. Historically this has been primarily for CO_2 usage applications (for example, food and drink production), but also for dedicated storage. In Norway more than 20 $MtCO_2e$ has been injected into geological storage since 1996.[3] CO_2 capture processes employed in DACCS technologies are largely an evolution of point-source capture and other industrial processes.[4] Several developers have proven their technical efficacy with independent verification.[5]

- The effective permanence (10,000 years or more) of CO_2 storage in properly selected geological strata is supported by a wide body of evidence, including the Intergovernmental Panel on Climate Change (IPCC) and International Energy Agency (IEA).[6;7]

18.1.3 BECCS

BECCS is the burning or converting of a biomass resource in a process with CCS applied. By capturing biogenic CO_2, which is taken up from the atmosphere as plants grow, burning or converting it, and sending it to permanent geological storage, BECCS is a net negative emission

process.* BECCS can be applied in several sectors: in the Balanced Pathway it features in the electricity supply, industry, waste, and fuel supply sectors.

There has been no deployment of BECCS in the UK to date. A pilot project has demonstrated CO_2 capture on a biomass power plant, without sending it to storage.[8] Internationally, there are two BECCS projects currently operating in the United States, and several other demonstrator and at-scale projects operating or under development globally, including a demonstrator operating in Japan and a 0.8 $MtCO_2e$/year capacity plant in Sweden scheduled to begin operation in 2026.[9;10;11]

BECCS processes differ across sectors:

- In some sectors, such as industry, bioenergy may replace a fossil fuel in a combustion process, and applying CCS provides an additional abatement option. In the electricity supply and energy from waste sectors, unabated biomass combustion is already used to generate heat or electricity. The addition of CCS turns this into a net negative emission process.

- In other sectors, such as hydrogen and biofuel production, biomass is used as feedstock, and the application of CCS to capture process emissions results in a net negative emission process.

- In all cases, BECCS processes produce a valuable energy or fuel output alongside the CO_2 removal, ensuring maximum value is generated by the available biomass resource. In our analysis, removals from BECCS are counted in the engineered removals sector, while the service BECCS processes provide are reflected in the biomass use sectors.

In the Balanced Pathway, deployment is driven by technological feasibility and cost assessments of the abatement options available in sectors that use biomass, subject to a 'best use' allocation of limited biomass resources (see Chapter 12). By 2050, almost all the bio-resource used in our pathway is with CCS (BECCS). The majority of uses with CCS are likely to be in power, hydrogen, and aviation biofuel production and at remaining energy from waste facilities, although there are other uses with similar overall GHG savings that may be deployed as well.

This section summarises the modelling approach for BECCS in each sector. Further detail can be found in relevant biomass use sector chapters.

- **Electricity supply.** In the power sector, we assume deployment of BECCS is largely tied to existing unabated biomass power capacity. This reflects that unabated biomass generation is not part of a least-cost decarbonised electricity system, so should be converted to operate with CCS. The costs of CCS retrofit are also likely to be lower than costs of new build.[12] This retrofit assumption is not prescriptive: the same level of power BECCS removals could plausibly be generated through new-build plants. The key elements of the power BECCS analysis are as follows:

  - A deployment pathway is developed based on a judgement of feasible timelines to deliver CCS retrofit to existing biomass plants. We assume 2032 as the substantive start year of power BECCS operations, with a small scale up in 2031. Capacity scales up to an assumed maximum deployment level of 1.3 GW.

  - Biomass feedstock supply reflects this analytical assumption: plants would either operate on domestically produced biomass, or imports, which in our pathway decline

* In line with existing international biomass accounting rules, we assume negative emissions are counted at the point of capture.

at the rate of expansion of the domestic supply, to meet demand, producing the net position described in Chapter 12.

  - This power BECCS deployment pathway is integrated into the wider power sector modelling done by AFRY (see Chapter 10).

  - CO_2 capture rates are assumed to increase from 90% in 2030, to 92% in 2040, and 95% by 2050 (see Section 1.7.2).

  - We assume large-scale unabated biomass runs at low load factors between the conclusion of their existing subsidy support in 2027 and the retrofit of CCS, beginning in 2031. This is in line with a recent Government announcement of new support for low load factor operation between 2027 and 2031.[13] Unabated biomass generation is phased out by 2037. Power BECCS is expected to run inflexibly due to its relatively high capital-intensity and the value of the removals it provides alongside the electricity.

  - Costs of power BECCS are based on assumptions and outputs from AFRY (Chapter 10). Capex, including for CCS, accounts for under 15% of total costs over 2025-2050. Opex accounts for over 85% of total costs over 2025-2050, including biomass feedstock costs which are based on long run variable costs (LRVCs).* The LRVCs are held constant over time at 2.9 p/kWh for domestic biomass and ranging from 4.9 p/kWh in 2031 (the first year of power BECCS deployment) to 6.5 p/kWh in 2040 and 5.3 p/kWh in 2050 for imported biomass.

- **Fuel supply.** Fuel supply sectors – production of biofuels, biomethane and hydrogen with CCS applications – are modelled through in-house analysis. The key elements are summarised below.

  - BECCS biofuels includes the production of aviation biofuels, biomethane, biodiesel, and bio-LPG. CCS is applied to biofuel production, including for conventional biofuels (biodiesel) and for aviation biojet fuels, providing a source of BECCS. Conventional biofuels are phased out as the transport sector electrifies over time, meaning these resources are increasingly used for biojet production with CCS over the period to 2050.

  - For BECCS biomethane – upgraded biogas for use in the gas grid – we assume that by 2035, half of biogas upgrading facilities are able to connect to a CO_2 network, so contribute to negative emissions. The volume of biomethane injected into the gas grid declines as cross-economy gas demand falls to 2050.

  - BECCS hydrogen is included with a view to maintain technology optionality, given uncertainty in hydrogen production costs (see Chapter 12). Deployment is determined by the level of residual biomass after other sector demands have been met.

  - CO_2 capture rates of 75% in 2030, rising to 90% in 2050, are assumed for BECCS biofuels and biomethane. BECCS hydrogen achieves 90% capture rates across all years, aligning with DESNZ analysis.[14]

  - Costs are applied to each deployment profile, based on Energy System Catapult's ESME model estimates of capex and opex for bioenergy fuel production routes.[15] In cases where only unabated or abated fuel production costs are available, the ratio of 'with CCS' to 'without CCS' costs from bio-synthetic natural gas from the same ESME dataset is applied, to account for CCS retrofit costs and efficiency losses. This amounts to an uplift to capex and fixed opex of 120% in 2020, falling linearly to 109% in 2050.

* Long-run variable costs include the components of the retail price that represent costs to society as a whole, and vary according to the level of consumption. It does not include transfer payments, such as taxes.

  - Across BECCS fuel supply measures, capex accounts for 23% of cumulative costs over 2025-2050, including plant and CCS construction, and opex accounts for 77%, driven by biomass feedstock demands. The resulting weighted average abatement cost across BECCS fuel supply sectors ranges between £645/tCO_2e in 2030 to £381/tCO_2e in 2040 and £420/tCO_2e in 2050.*

- **Energy from waste.** Energy from waste is modelled using a combination of in-house analysis and energy system modelling commissioned from consultants AFRY. In-house analysis developed projections for waste arisings from biogenic and non-biogenic sources. The energy system modelling applied CCS to energy from waste plants in line with CCS cluster timelines, with assumed CO_2 capture rates of 90% until 2040, and 95% from 2041 onwards. When CCS is applied to a given level of energy from waste capacity, the CO_2 captured from the biogenic share of waste in that year is reported as BECCS. Key drivers of the resulting energy from waste BECCS pathway include total volumes of residual biogenic waste, a near-elimination of biodegradable waste sent to landfill from 2028, and the elimination of nearly all waste streams to landfill from 2045. See Chapter 13 for further detail and underlying assumptions.

- **Industry.** Industry is modelled using the Net Zero Industry Pathways model (NZIP2), which selects cost-effective decarbonisation options for industrial sites. NZIP2 applies bioenergy and CCS as individual measures but does not calculate the CO_2 removals that arise when these measures are combined. We therefore calculate these BECCS removals in an off-model adjustment. Sites with implied BECCS processes are in the cement or chemicals subsectors. See Chapter 8 for further detail on NZIP2.

- **CO_2 transport and storage.** CO_2 transport and storage costs of £39–42/tCO_2e are applied in line with principles in Section 1.7.2. An additional £10/tCO_2e is applied to CO_2 captured in Northern Ireland to reflect the estimated cost of shipping CO_2 to the UK's HyNet cluster.

18.1.4 DACCS

DACCS is a group of technologies designed to extract CO_2 directly from the atmosphere through chemical and physical methods, and permanently store it in geological formations. DACCS involves gas separation technologies that generally fall into one of three categories:

- **Liquid DACCS.** This approach involves CO_2 absorption by liquid solutions, such as potassium hydroxide. It generally requires high temperature process heat. The most advanced methods, such as those pursued by Carbon Engineering in North America, are assessed to have a technology readiness level (TRL) of 6–7 by City Science and 6 by the International Energy Agency (IEA).[16;17]

- **Solid DACCS.** This approach involves CO_2 adsorption by solid sorbents, such as amine functionalised materials. It generally requires low temperature process heat. The most advanced methods, such as those pursued by Climeworks in Iceland, are assessed to have a TRL of 8–9 by City Science and a TRL of 7 by the IEA.[18;19]

- **Membrane separation.** This approach involves physical separation of CO_2 from air through materials such as an ion exchange membrane. Although theoretically possible with low temperature requirements, it is currently assessed to have a low TRL of 3–4 and is therefore not included in our modelling.[20;21]

There are no DACCS facilities currently operating or publicly planned at scale in the UK. The most advanced development is a demonstrator direct air capture (DAC) project planned using waste

* The weighted average abatement costs across BECCS fuel supply mask a range of measure-specific abatement costs. In some cases, these are higher than the central carbon value in 2050; however, they do not incorporate the value of energy or fuel produced in the BECCS process.

heat from the proposed Sizewell C nuclear power plant.[22] This is not expected to link directly to CO_2 storage, and it is unclear when operation is expected to begin.

Globally, there are now several small-scale DACCS plants that are operational or under construction.

- Climeworks have a 4 $ktCO_2e$ per year capacity facility called Orca which has been operational since 2021, and a 36 $ktCO_2e$ capacity facility called Mammoth which began operations in 2024, both in Iceland.[23;24] These use solid DAC technology.[25]

- Carbon Engineering and 1PointFive are developing a 0.5 $MtCO_2e$ per year capacity facility called STRATOS, which is under construction in Texas, United States, and due to start operations in 2025.[26] This uses liquid DAC technology.[27]

- The IEA is tracking projects accounting for a total of over 60 $MtCO_2e$ per year of DAC capacity that are under some form of consideration worldwide as of 2024. Of these, 0.5 $MtCO_2e$ capacity is under construction, 2 $MtCO_2e$ capacity is considered at 'advanced development' stage, and 61 $MtCO_2e$ capacity is at concept and feasibility stage.[28] What proportion of these will proceed to operation is uncertain.

- The Global CCS Institute also tracks DAC projects, and as of December 2024 reports a total of 20 plants either operational (the two Climeworks plants referenced above, plus small-scale plants in California and Oklahoma), in construction (one plant each in Oman and United States), or in development.[29]

As a CO_2 removal approach, DACCS does not directly displace high-carbon processes. Nor does it provide any significant accompanying service (such as energy production) or co-benefit, though it does benefit from a relatively low land use footprint compared to other GGR options.

- Solid DACCS is currently higher cost due to higher capex requirements. It operates at lower temperatures with potential heat provision by heat pumps or waste heat.

- Liquid DACCS is currently lower cost and relies on high temperature process heat which we assume in our modelling to be provided by natural gas. The emissions associated with the gas combustion are mostly captured within the DACCS process, with the small remaining amount offset by additional DACCS removals. Liquid DACCS also requires electricity, but at a lower rate than solid DACCS.

In the Balanced Pathway, DAC capacity features in two forms. DACCS, including CO_2 storage, is a GHG removal technology – its deployment leads to negative emissions. DAC (without storage, hereafter referred to as "DAC–feedstock") is also used as a source of CO_2 feedstock required to produce synthetic fuels for aviation and shipping.

- Demands for CO_2 feedstock from the shipping and aviation sectors are outputs of their respective sector and fuel supply modelling. In aviation, the relative role of synthetic fuels and engineered removal offsets, including DACCS, is uncertain and will influence deployment of DAC–feedstock and DACCS respectively. We assume a contribution from both to maintain technology optionality. See Chapters 11, 12 and 15 for details.

- The dual use of DAC capacity may create both synergies and trade-offs. The opportunity for DAC developers to sell captured CO_2 to synthetic fuel producers may allow them to begin project development and plant operation before CO_2 storage infrastructure is fully developed, offering an early route to market. Conversely, there are likely to be significant constraints, particularly in the form of energy infrastructure, for which DAC capacity would be competing between those capturing CO_2 for storage and those capturing for feedstock.

- In the Balanced Pathway, we assume the CO_2 feedstock required for synthetic fuel production is provided by DAC. In practice, CO_2 feedstock could be biogenic point-source or direct from atmospheric sources. An alternative assumption would not materially change our analysis as using biogenic point-source CO_2 would reduce the amount of CO_2 being removed through BECCS, and require an equivalent amount of additional DACCS removals to account for that.

Deployment modelling

Figure 18.2 illustrates the structure of our modelling of DACCS deployment in the Balanced Pathway. The key steps in are as follows:

- **2050 residual emissions.** Removals from DACCS in 2050 are set such that they balance residual emissions from other sectors, after removals from BECCS, enhanced weathering, and biochar are considered, and subject to scale-up feasibility constraints. This illustrates DACCS' primary role in the Balanced Pathway: to ensure the UK reaches Net Zero by 2050.

- **Scale-up pathway.** A pathway to scale up DACCS to the 2050 level is developed subject to several considerations and constraints:

  - DAC deployment (for both removals and production of CO_2 feedstock) is assumed to begin in 2035, reflecting several factors.* Global DAC development is progressing, with several small plants operational and several large-scale projects now under development, as discussed above. In the UK there are no large-scale projects publicly under development, though several UK-based companies are developing DAC technologies and are involved in plant development.[30;31] The policy landscape and supporting infrastructure are also progressing. In particular, UK CCS policy development is relatively advanced in an international context. By 2030, we assume four CCS clusters are operational, providing CO_2 transport and storage infrastructure to which DACCS plants could connect.

  - Total DAC capacity is assumed to scale up in line with a maximum feasible deployment scenario modelled by our consultants (Box 18.1).[32] The constraint is applied at the level of annual capacity additions of solid and liquid DAC respectively. This implies tightly constrained scale-up in the 2030s, before a gap opens between the Balanced Pathway and the maximum feasible scenario in the 2040s, when electrical grid infrastructure in particular, is less constrained. The constraint from the 'standard' scenario for maximum feasible deployment is applied to total DAC capacity, including capacity for both removals and CO_2 feedstock (see above), given the two processes are assumed to use the same DAC plants.

  - We assume equal shares of solid and liquid DAC capacity across both DACCS and DAC–feedstock. There is large uncertainty in DACCS costs: while estimates put liquid DACCS at lower initial cost, research suggests solid DACCS has greater potential for cost reductions due to its more modular nature, and by 2050 their cost ranges overlap.[33;34] An equal split acknowledges the uncertainty inherent in these early-stage technologies, while reflecting optionality.

- **Impacts analysis.** Resulting pathways for DACCS and DAC–feedstock are inputted into an impacts model developed by City Science. For the given levels of solid and liquid DACCS and DAC–feedstock capacity, the model outputs implications for costs (capex, opex, and abatement costs), and electricity and gas demands. Key assumptions used by the model

* Although DAC becomes substantively available in 2035, synthetic fuels in the shipping sector begin to be used in 2033 due to the model smoothing results between five-yearly time-steps.

are presented in Table 18.2 and summarised here; a full discussion of the assumptions can be found in City Science (2025).[35]

  - Capex accounts for 52% of total costs over 2025-2050. Capex reflects the engineering, procurement, and construction work required to build a DAC plant, with optimism bias applied. Capex is modelled as occurring in the two years preceding the first year of operation. As a result, capex scales down in 2049 and is zero in 2050, as no further DACCS capacity is needed to deliver Net Zero.

  - Opex accounts for 48% of total costs of 2025-2050. Energy costs account for approximately half of core DAC opex (slightly more for liquid DACCS, slightly less for solid DACCS). Energy unit cost assumptions align with other sectors, using LRVCs for industrial sectors. Non-energy opex includes spending on labour, materials (including solvents and sorbents), and water demand.

  - CO_2 transport and storage costs of £42/tCO_2e are added in line with principles in Section 1.7.2.

  - Resulting DACCS removal costs in the Balanced Pathway reach £328/tCO_2e for solid and £242/tCO_2e for liquid, for new units in 2050. This is below the central carbon value of £409/tCO_2e in 2050 (Figure 18.4), though in earlier years costs are above the carbon value. That DACCS is scaled up even when costs are above the carbon value reflects a dynamic cost effectiveness, to ensure sufficient ramp-up to deliver Net Zero (see Section 1.5.1). These costs mask wide uncertainty ranges, explored further in City Science (2025).

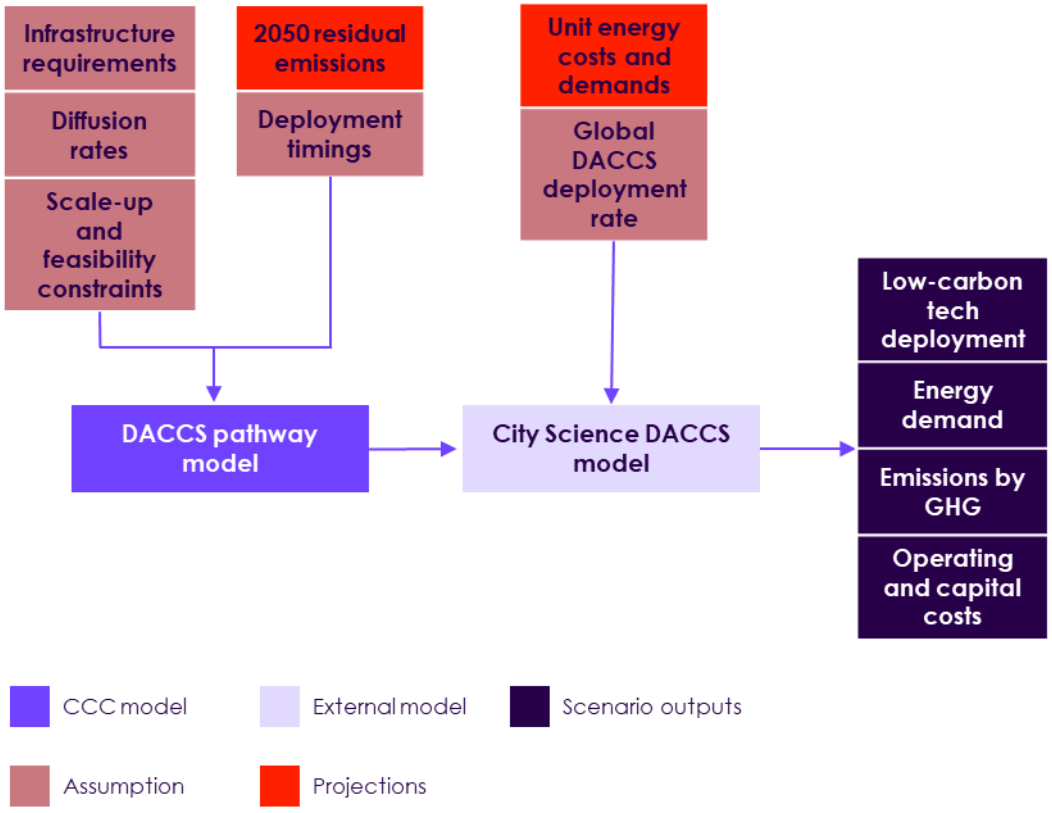
- **DACCS siting.** Given CO_2 transport and storage infrastructure requirements, DACCS is highly likely to be situated in CCS clusters.

  - In the Balanced Pathway in 2050, to reflect expected co-location with CCS clusters, 62.5% of DACCS is located in England (reflecting the East Coast and Viking clusters and a 50% share of the cross-England-Wales border HyNet cluster), 25% in Scotland (reflecting the Scottish cluster), and 12.5% in Wales (reflecting 50% of the HyNet cluster). Scotland has natural advantages that favour development of engineered removals via DACCS, notably abundant renewable electricity generation, particularly from wind. These factors, as well as Scotland's earlier Net Zero target, are likely to encourage a faster scale up of DACCS in Scotland. We assume Scotland scales up to maximum DACCS capacity by 2045, five years ahead of the UK as a whole reaching maximum DACCS capacity.

  - In the Balanced Pathway, there is no DACCS located in Northern Ireland, as there are no plans for a CCS cluster to be located there. In the Northern Ireland Net Zero Pathway, discussed in our Northern Ireland Fourth Carbon Budget advice report, we assume 3 MtCO_2e DACCS removals is located in Northern Ireland by 2050, to ensure Northern Ireland's Net Zero target is met.

- **DAC–feedstock siting.** Siting of DAC–feedstock capacity is assumed to follow each UK nation's synthetic fuel demands from aviation and shipping (see Chapter 12). As set in Box 7.7.1 of our Seventh Carbon Budget advice report, future clarification of international accounting rules may merit revision of assumptions on synthetic fuel production siting.

Figure 18.2 Modelling schematic for DACCS



Description: Our DACCS pathway outputs are based on our deployment model and a model developed as part of a research project into the impacts of DACCS.
Source: CCC analysis.
Notes: BECCS, DACCS, and enhanced weathering and biochar are modelled independently. Modelling schematics for biomass use sectors are presented in those sectors' respective chapters of this report. A modelling schematic for bioenergy allocation is presented in Chapter 12. Enhanced weathering and biochar are not presented in schematic form as the pathway is entirely assumption-driven, as set out in Section 18.1.5.

Table 18.2 summarises the key assumptions underpinning the Balanced Pathway for DACCS.

Table 18.2
Key assumptions in the Balanced Pathway for DACCS

Variable	Technology	Assumption	Notes
Global DACCS capacity ($MtCO_2e$)	All	2030: 1.6 2050: 142.9	Higher global deployment is associated with lower cost in the UK. Scenarios are created based on a range of diffusion rates, at the top end broadly aligning with a 1.5°C global scenario. These global scenarios imply UK DACCS capacity in the Balanced Pathway accounting for 1%, 6% (for the scenario used in the Balanced Pathway) and 45% of global capacity in 2050.
DAC – annual deployment constraint ($MtCO_2e$)	All	2030: 0.9 2035: 0.4 2040: 0.9 2050: 2.1	City Science analysis (see Box 18.1). Figures relate to gross capture capacity across solid and liquid technologies. 2030 is the assumed first year of deployment and the level in 2030 reflects the possibility of two initial 0.5 $MtCO_2e$ nameplate capacity plants. The subsequent trajectory is smoothed, while projects would likely be 'lumpy' in practice. The deployment

			constraint is applied to the combined DACCS and DAC–feedstock pathway.
Heat source	Liquid	Natural gas	Emissions from natural gas are largely captured within the DACCS process. Hydrogen could also be used, but supply will be scarce and expected costs higher than natural gas.
	Solid	Electricity (industrial heat pump)	This could also be provided by waste heat from industrial processes, but availability (particularly in locations where DACCS is most likely to be situated) is likely to be limited.
Capacity factor	Liquid	90%	Based on City Science expert judgement.
	Solid	87.5%	
Capex learning rate	Liquid	8%	Based on recent literature and City Science expert judgement.[36]
	Solid	12%	

Source: CCC analysis; City Science (2025) *Assessing the feasibility for large-scale DACCS in the UK*.
Notes: Assumptions shown relate to those used in the Balanced Pathway; for some variables alternative assumptions are considered as sensitivities in City Science (2025).

Box 18.1
Direct air capture – maximum feasible deployment scenarios

City Science's detailed feasibility assessment of DACCS deployment in the UK considers a series of feasibility factors across three areas: construction, supporting infrastructure, and operation. In each case, they develop a 'ceiling' approach, simulating a high level of DACCS deployment, based on high deployment scenarios in the literature, to quantify potential demand for each factor, which is then compared to an assumed maximum non-constraining level.

The maximum non-constraining level is generally set as a share of current or projected demand for the factor, based on City Science's expert judgement. A red-amber-green rating is assigned depending on the extent to which a constraint is or is not breached by the 'ceiling' level of deployment. Constraints are developed independently, not reflecting CCC analysis or outputs for relevant sectors, such as electricity supply. Electricity grid constraints, for example, are developed based on NESO Future Energy System Scenarios (2023).[37]

Across the three areas, key constraints are identified as follows. A full explanation can be found in City Science (2025).

- Construction factors are found to be relatively unconstraining, with green assigned to the construction workforce and to aluminium demand for liquid DACCS, and amber ratings assigned to concrete demand for liquid DACCS and solid DACCS under a 'ceiling' rate of deployment.* Amber is assigned to steel and aluminium demand under a high requirement solid DACCS scenario only. The steel manufacturing workforce is also given an amber rating (assessed across both technology types).
- Supporting infrastructure factors are assessed as red (highly constraining) in the short term for CO_2 transport and storage capacity for both technologies, and for electrical grid connection for solid DACCS. This improves to amber for both factors in the medium term, and to green for CO_2 transport and storage in the longer term.
- Operational factors are found to be most constraining. Electricity demand for solid DACCS, solvent supply for liquid DACCS, and sorbent supply for solid DACCS are all assigned red ratings.

Based on these feasibility factor assessments, combined with assumed maximum diffusion rates derived from the literature, City Science then develops several maximum feasible deployment scenarios. The key features of each scenario are summarised below.

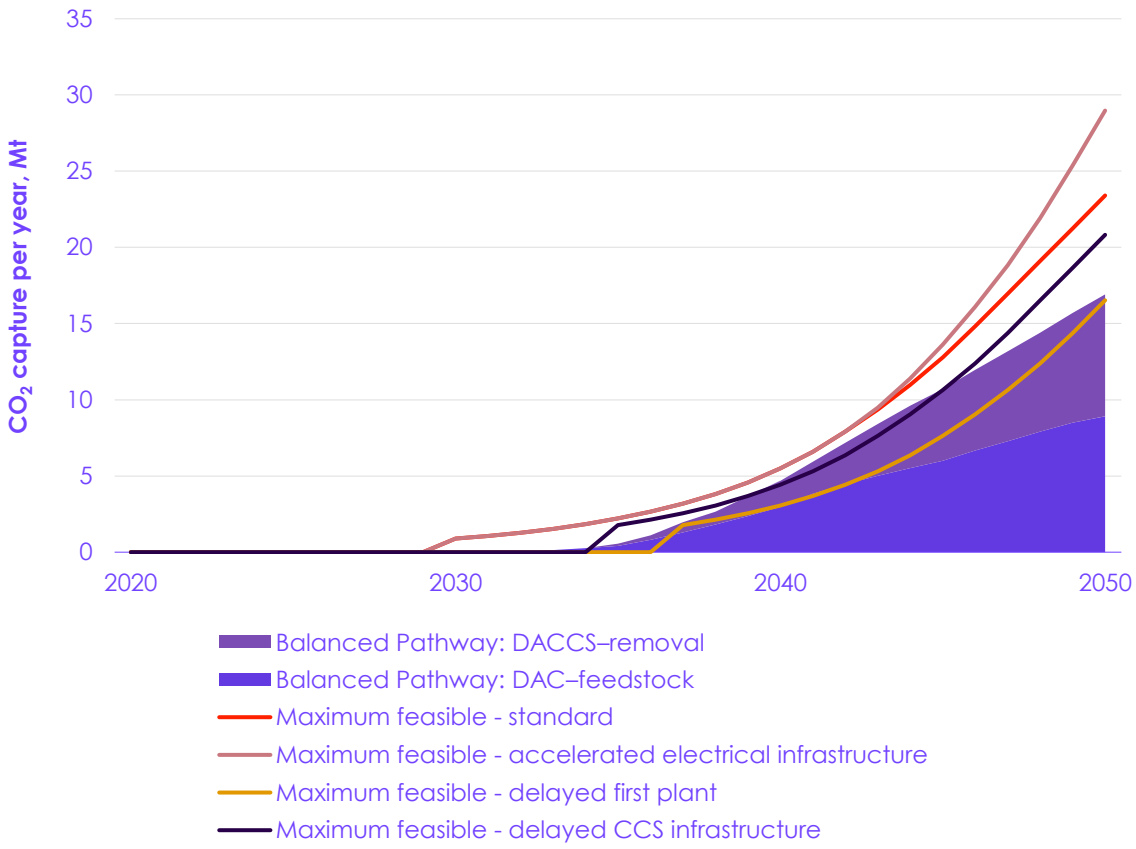
- **Standard.** CO_2 transport and storage infrastructure is available from 2030, maximum starting capacities are 0.5 $MtCO_2e$ for both solid and liquid DACCS, a 20% diffusion rate is assumed, and solid DACCS requires new electrical grid infrastructure. In this scenario, the electrical connection limit, at which point the annual deployment rate is constrained, is reached in 2047 for liquid DACCS, and 2042 for solid DACCS (with its larger grid connection requirement).
- **Delayed CCS infrastructure.** A five-year delay is applied to the availability of CO_2 transport and storage infrastructure compared to the standard scenario, implying availability from 2035. The scenario assumes that with global deployment progressing in the meantime, the first plants could now be 1 $MtCO_2e$ capacity for both solid and liquid technologies.
- **Delayed first plant.** The first DACCS plant is not built until 2037. The scenario assumes that with global deployment progressing in the meantime, the first plants could now be 1 $MtCO_2e$ capacity for both solid and liquid technologies.
- **Accelerated electrical infrastructure.** The electrical constraint is not as stringent, meaning that both the solid and liquid technologies can build out quicker, with limits now being hit in 2045 and 2050 respectively.

Figure 18.3 presents the four maximum feasible deployment scenarios alongside the Balanced Pathway for DACCS and DAC–feedstock. We use the Standard scenario in our Balanced Pathway and explore the impacts of the accelerated electrical infrastructure scenario in our contingency analysis.

Source: City Science (2025) *Assessing the feasibility for large-scale DACCS deployment in the UK.*

* Two assessments of the solid technology requirements were provided (low and high) as there is uncertainty in its design.

Figure 18.3 Direct air capture capacity in the Balanced Pathway compared to maximum feasible deployment



Description: The maximum feasible deployment of direct air capture capacity grows steadily across a range of scenarios, beginning between 2030 and 2037 and reaching 17–29 $MtCO_2e$ by 2050. The combined level of DACCS–removal and DAC–feedstock in the Balanced Pathway remains below the standard maximum feasible scenario.
Source: CCC analysis; City Science (2025) *Assessing the feasibility for large-scale DACCS deployment in the UK.*
Notes: 'DAC–feedstock' refers to direct air capture capacity dedicated to producing CO_2 feedstock for the production of synthetic fuels for aviation and shipping. This CO_2 capture does not result in a GHG removal. 'DACCS–removal' refers to DACCS capacity used for producing CO_2 for permanent storage, resulting in a GHG removal. 'Maximum feasible deployment' refers to the scenario developed by City Science, which models the maximum level of direct air capture capacity it would be feasible to deploy over time in the UK under assumed constraints. City Science's 'Standard' scenario is used in the Balanced Pathway, converted from gross capacity to net capture levels for consistency with the Balanced Pathway metrics. See City Science's report for further detail and underpinning assumptions.

18.1.5 Enhanced weathering and biochar

Enhanced weathering and biochar are a set of removals approaches to capturing atmospheric CO_2 through natural processes and storing it in land and ocean systems. Enhanced weathering involves speeding up the natural process of rock weathering through grinding and spreading silicate rocks, such as basalt, on land to accelerate its reaction with CO_2 in the atmosphere to form bicarbonates. These bicarbonates are gradually washed via rivers into the sea where the carbon is stored for centuries or more.[38;39] Biochar as a removal involves processing biogenic waste materials which have removed atmospheric carbon, heating these wastes in the absence of oxygen to form a stable carbon-rich biochar, which is resistant to breaking down and can be spread onto and integrated into soils.[40;41]

- Enhanced weathering is already occurring globally at a small scale, with an estimated 0.03 $MtCO_2e$ removed in 2023. This is taking place primarily in Australia, Canada, India, and the UK (albeit not officially recorded in GHG inventories).[42] UK-based company UNDO is developing enhanced weathering techniques and research, and have 40 $ktCO_2e$ removals issued on voluntary carbon markets, as of May 2025 (with the majority yet to be delivered).[43]

The publicly-funded Greenhouse Gas Removal Demonstrators (GGR-D) programme is also exploring enhanced weathering deployment in a UK context.[44]

- Biochar is currently the largest form of CO_2 removal globally outside of land-based CO_2 removal (defined as afforestation/reforestation and forest management, peatland and coastal wetland restoration, and soil carbon sequestration), with an estimated 0.79 $MtCO_2e$ per year as of 2023, with a notably wide geographic spread compared to some other removals approaches.[45] Interest in biochar as a CO_2 removal approach has grown steadily in recent years, with significant research, innovation, and financing activities.[46] UK-based company A Healthier Earth is developing a biochar production facility in the UK, targeting production equivalent to 17 $ktCO_2e$ removals.[47] GGR-D is exploring biochar deployment in a UK context, with field trials at arable and grassland sites, railway embankments, and forestry sites.[48]

Other than the small-scale trials referenced above, there have been no CO_2 removals from enhanced weathering or biochar recorded to date in the UK. However, there is growing evidence of the CO_2 removal potential these approaches represent. Modelling assessments of the potential for CO_2 removal from enhanced weathering in the UK range from 3 $MtCO_2e$ to around 30 $MtCO_2e$ in 2050.[49] Assessments of the potential for CO_2 removal from biochar in the UK are between zero (given potential competition for feedstocks) and 20 $MtCO_2e$ in 2050.[50;51;52]

Due to the large uncertainty range around potential CO_2 removal from these approaches, we group enhanced weathering and biochar into a single abatement measure in the Balanced Pathway. Their inclusion reflects the developments in recent years in demonstrating the potential role they could play, while their grouping into a single measure acknowledges the uncertainty in the relative size of the contribution from each approach.

Currently IPCC accounting approaches include no guidance on the inclusion of enhanced weathering and limited guidance on the inclusion of biochar in national GHG inventories. The IPCC's Task Force on National Greenhouse Gas Inventories will develop updated guidance in the coming years, which we assume to be operational in time for the deployment of these approaches in our pathway.[53]

Deployment of enhanced weathering and biochar in the Balanced Pathway adopts the following steps:

- **Assumption-driven approach.** The CO_2 removal pathway is determined independently of other economic or energy variables. Based on the literature discussed above – substantial potentials but high levels of uncertainty – we assume a small CO_2 removal contribution from enhanced weathering and biochar, reaching 3 $MtCO_2e$ in 2050.

- **Pathway.** We assume deployment and removals begin at very low levels in 2030, allowing for continuing development of the approaches, including the necessary monitoring, reporting and verification frameworks, in the next five years. Between 2030 and 2050 we assume an accelerating scale-up pathway.

- **Siting.** Given uncertainty in the types of land that these measures could be applied to, we distribute removals from enhanced weathering and biochar across the nations of the UK according to their share of the combination of temporary grassland, cropland, and rough grazing land. These are the land types where active trials are underway for enhanced weathering; biochar is being trialled on a wider set of land types.[54;55] By 2050 this results in 50% of the CO_2 removal taking place in England, 45% in Scotland, 4% in Wales, and 2% in Northern Ireland.

The peer-reviewed literature provides more comprehensive and functional estimates of the CO_2 removal potential and wider implications in the UK for enhanced weathering than for biochar. We

therefore apply estimates for costs and resource requirements for enhanced weathering to the combined subsector. This ensured a conservative approach:

- Net energy demands for biochar production are uncertain. It may be possible to extract energy from the pyrolysis process, with some analyses suggesting approximately net zero energy demand. This should imply a lower energy intensity per unit of CO_2 removal for biochar than for enhanced weathering.

- Where cost estimates for biochar do exist, they are generally in line with or below those that exist for enhanced weathering. Analysis for the Government, drawing on modelling also referenced by the Royal Society and Royal Academy of Engineering, quotes £16–149/tCO_2e for biochar in 2030, with a central estimate of £83/tCO_2e (2023 prices).[56;57] The Royal Society and Royal Academy of Engineering also note that if the energy released during biochar production processes could be profitably used, the carbon removal could be achieved at a positive net financial return.[58] Costs for enhanced weathering are estimated in the same analysis for the Government at £45–448/tCO_2e in 2030, with a central estimate of £247/tCO_2e (2023 prices).[59] CO_2 removal credits are available at a market price of £130/tCO_2e for biochar and £250/tCO_2e for enhanced weathering (2023 prices).[60;61]

Kantzas et al (2022) provides the most comprehensive assessment to date of the costs and energy requirements of enhanced weathering in the UK, while being broadly consistent with other sources referenced above.[62] We use this paper as the basis for our cost and energy demand assumptions for the enhanced weathering and biochar subsector, the key details of which are set out below. Cost variables are converted to 2023 prices.

- Abatement costs are £157/tCO_2e in 2030, falling to £95/tCO_2e in 2050, reflecting increasing CO_2 removal with successive rock dust application in their modelling, among other factors. This abatement cost pathway is derived from the 'S1_Med_p8010' and 'S1_Med_p80100' scenarios, reflecting the low levels of deployment and uncertainty in expected dust particle sizes that may be used.* These abatement costs fall below the central carbon value in all years of deployment (for example, £409/tCO_2e in 2050 – Figure 18.4).

- Capex is £3.14 per tonne of rock, which covers assets required for mining and grinding rock dust. We assume the same machinery is used for spreading rock dust as would be for fertilizer, requiring no additional capex. This implies total capex of £135 million over 2030–2050, with capacity assumed to expand every five years for the demands of the subsequent five-year period. Assets are assumed to have 25-year lifetimes.

- Operating expenditure is £10.39 per tonne of rock, which covers mining, grinding, and rock dust spreading operations. This implies total opex of £1,774 million over 2030–2050.

- Electricity demand is derived by applying the average TWh per unit of MtCO_2 from the S1 scenarios to our CO_2 removal pathway. This implies 0.02 TWh in 2030, rising to 0.76 TWh in 2050.

- Demand for rock is not explicitly modelled. In the S1 low deployment scenarios presented by Kantzas et al (2022), to which the Balanced Pathway aligns closely, and on which the costings were based, no additional rock extraction capacity is needed compared to existing levels.

There may be several benefits and risks associated with enhanced weathering and biochar approaches. We did not quantify these in our analysis, but note developing literature.

* Scenarios are described in terms of their rock extraction scenario (S1 = low, S2 = medium, S3 = high), their rock dust size as defined by the size under which 80% of particles are (p8010 = 80% are less than 10 µm, p80100 = 80% are less than 100 µm) and their uncertainty approach (Med = central, Low = low estimate, High = high estimate).

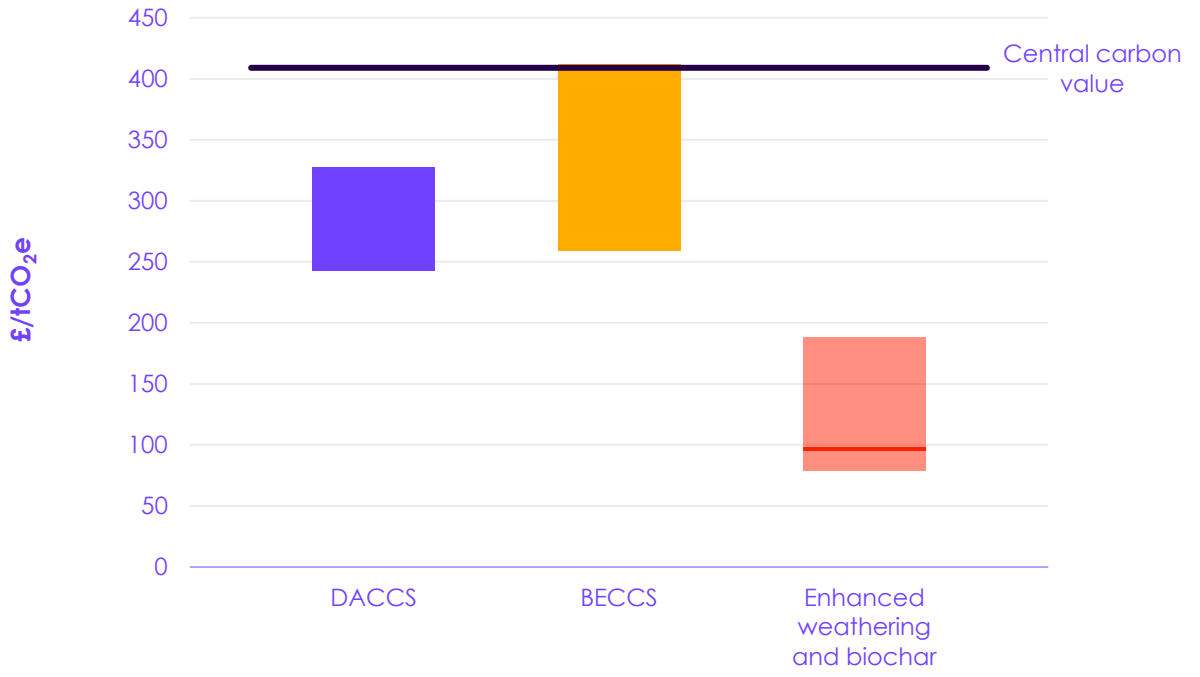
- **Uncertain CO_2 removal quantities and durability.** Studies suggest that the efficiency of CO_2 removal from enhanced weathering depends on the size of rock dust applied, soil types, and climatic conditions such as rainfall levels and temperature.[63;64;65;66] Permanence of CO_2 storage may be affected by similar variables, as well as the possibility for CO_2 leakage in the process of CO_2 transport to rivers and the ocean.[67;68] Similarly, the efficiency of biochar for CO_2 removal is found to depend on feedstock type and production techniques, though modelling suggests the stability of the removal should be high.[69;70;71;72]

- **Possible impacts to soil health, crop yields and wider ecosystems.** The application of both enhanced weathering rock dust and biochar have the potential to improve soil health and increase crop yields, though evidence from field trials is mixed, implying likely dependence on the land and soil types in question, among other factors.[73;74;75;76] There may also be wider impacts on ecosystems, with studies suggesting potential positive and negative effects.[77;78]

- **Implications for air quality.** Enhanced weathering rock dust may have negative health impacts if inhaled regularly over long periods, though this should be avoidable with careful spreading practices and safety equipment.[79;80] Biochar production may have local air quality implications, likely dependent on feedstock choices and production processes. These will need to be managed.[81]

These potential co-impacts highlight the need for continued development of robust monitoring, reporting, and verification processes for enhanced weathering and biochar, alongside other engineered removals approaches. They also support the approach taken in the Balanced Pathway to limit enhanced weathering and biochar deployment to the low end of estimated CO_2 removal potential.

Figure 18.4 Engineered removals abatement costs per tonne of CO_2 removed in 2050



Description: Engineered removals costs in the Balanced Pathway in 2050 are generally high and have wide uncertainty ranges, though tend to fall below the central carbon value, indicating that they are cost-effective for society to undertake.
Source: CCC analysis; City Science (2025) *Assessing the feasibility for large-scale DACCS deployment in the UK;* Kantzas, E., P. et al (2022) *Substantial carbon drawdown potential from enhanced rock weathering in the United Kingdom.*
Notes: The abatement cost is shown for a new unit in each year. The range shown for DACCS represents the central cost scenarios for liquid and solid DACCS respectively; the full high to low range across technologies is larger (see City Science (2025)). The range for BECCS represents the cost of BECCS across grouped sectors (calculated as weighted averages within those groups), with BECCS energy-from-waste at the low end and BECCS fuel supply at the high end; it does not reflect the full range of individual BECCS measures. BECCS abatement costs do not reflect the value of the energy or fuel produced in the BECCS process and are therefore not directly comparable to a carbon credit generated from these activities. Alignment at the top end of the BECCS cost range with the central carbon value is by chance, not by analytical design. The range for enhanced weathering and biochar reflects costs for enhanced weathering only (as discussed in Section 18.1.5) and represents the range across scenarios presented in Kantzas et al (2022); the Balanced Pathway cost is illustrated by the solid line within the range.

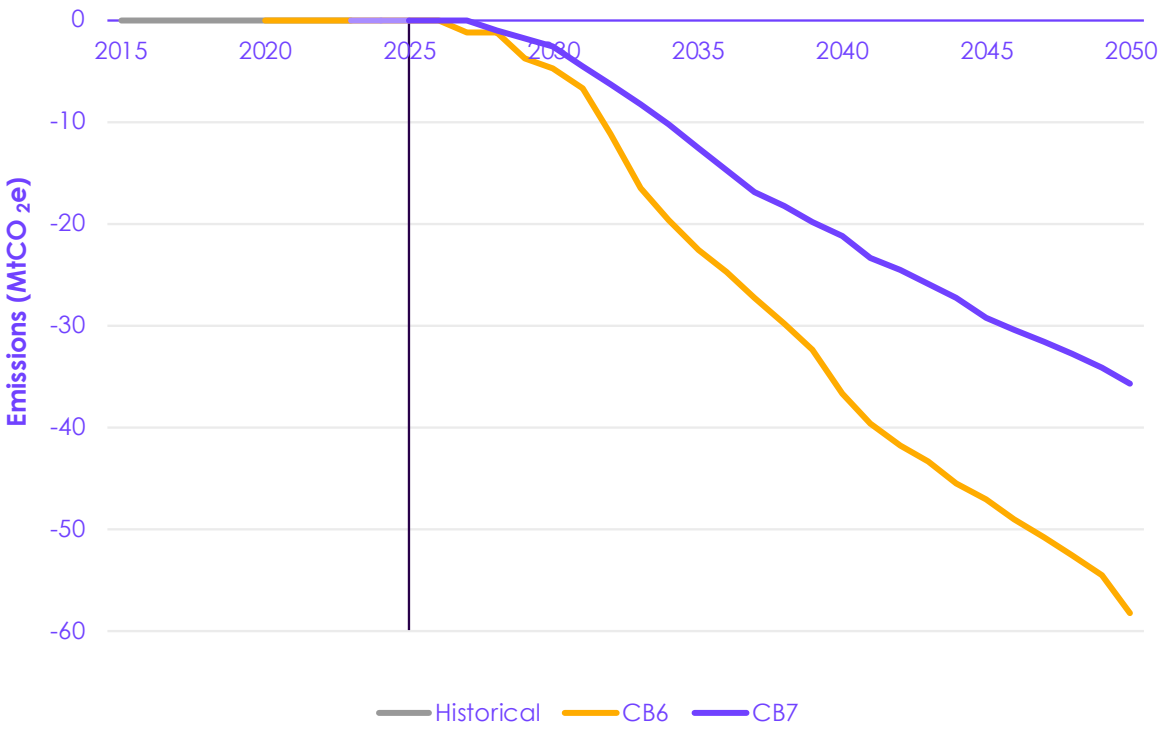
18.2 Changes since our Sixth Carbon Budget advice

18.2.1 Comparison with our Sixth Carbon Budget pathway

There are several differences between our Balanced Pathway for engineered removals and the pathway assumed in our Sixth Carbon Budget advice.* In total, engineered removals make a smaller contribution across all years (Figure 18.5). This reflects a lower level of engineered removals required to deliver Net Zero in 2050, driven by changes in emissions accounting (see Section 7.1.4 of the Seventh Carbon Budget advice report). Such updates to accounting methodologies are an important source of uncertainty in our analysis, as discussed in Chapter 5.

* All comparisons in this section compare the Balanced Pathway in this advice with the Balanced Net Zero Pathway in our Sixth Carbon Budget. Our Sixth Carbon Budget advice also included four other exploratory pathways, which are not discussed here. Data for those pathways can be found in our Sixth Carbon Budget advice.

Figure 18.5 The Balanced Pathway for engineered removals compared to our Sixth Carbon Budget advice



Description: The contribution from engineered removals is smaller in all years in the Seventh Carbon Budget (CB7) Balanced Pathway compared to the Sixth Carbon Budget (CB6) pathway.
Source: CCC analysis.

18.2.2 Key pathway differences compared to our Sixth Carbon Budget advice

There are several key areas in which the deployment rates, measures included, or underlying assumptions in our updated Balanced Pathway have been revised since publication of our Sixth Carbon Budget advice in 2020. These include:

- **DACCS.** Our Balanced Pathway contains slightly more DACCS than in our Sixth Carbon Budget advice.
  - DACCS deployment is assumed to begin in 2040 in the Sixth Carbon Budget pathway. In our Balanced Pathway, it now begins in 2035. The rationale for this start date is set out in Section 18.1.4.
  - DACCS costs are around 80% higher in the Balanced Pathway compared to the Sixth Carbon Budget pathway. This is the result of up-to-date modelling using detailed UK-specific assumptions, as set out in Section 18.1.4.
- **BECCS.** Total BECCS levels are lower in our Seventh Carbon Budget pathway due to lower biomass supply, reflecting limited progress in tree planting, lower estimates of forest residue availability, and our Balanced Pathway assuming a transition away from imported biomass.
  - BECCS deployment in the electricity supply sector began in 2027 in the Sixth Carbon Budget pathway. In our Balanced Pathway, it now begins substantively in 2032, with a small scale-up in 2031.

  - BECCS in other sectors (particularly energy from waste) begins in 2028 in the Balanced Pathway, whereas in the Sixth Carbon Budget pathway this varied between 2025 for industry and 2040 for the substantive start of energy from waste. The rationale for these start dates is set out in Section 18.1.3.

  - BECCS costs are generally higher in the Balanced Pathway than in the Sixth Carbon Budget pathway, reflecting several factors:

    - Biomass LRVCs are higher: 2.9 p/kWh for domestic biomass and 4.9–6.5 p/kWh for imported biomass in the Balanced Pathway, compared to 2.5 p/kWh for domestic biomass and 3.6 p/kWh for imported biomass in the Sixth Carbon Budget pathway.*

      - CO_2 transport and storage are higher: £39–42/tCO_2e (depending on the sector) in the Balanced Pathway, compared to £15/tCO_2e (2019 prices) in the Sixth Carbon Budget Balanced Pathway, reflecting an updated assumption source and the inclusion of optimism bias in our updated analysis.

- **Enhanced weathering and biochar.** For the first time, our Balanced Pathway includes a contribution from enhanced weathering and biochar. The rational for their inclusion is set out in Section 18.1.5.

18.3 Contingencies in engineered removals

The measures included in the engineered removals sector are, at present, only tested and demonstrated at relatively small scales. Their costs are uncertain and generally estimated to be high. Given the uncertainty associated with each measure, there is a case for considering optionality between them, as well as the potential for any of them to go further in isolation. This logic can also be applied to account for faster or slower progress compared to plans in other sectors. See Chapter 5 for our general approach to contingency analysis.

In this section we consider the potential for additional DACCS as a contingency for slower deployment in other areas, and how greater biomass imports could allow for higher BECCS deployment.

- As well as the options for engineered removal technologies to go further than their contributions in the Balanced Pathway, in Box 6.1 of our Seventh Carbon Budget advice report we explore a scenario with no contribution from BECCS in electricity supply. We note that such a scenario would leave shortfalls in emissions and electricity supply.

  - An emissions shortfall could be made up by using the biomass in other BECCS applications to generate alternative engineered removals, or contingency actions from other sectors.

  - The electricity supply shortfall could be made up by nuclear, gas CCS, or hydrogen generation. Such a scenario would present its own challenges and reduce the scope for contingency actions to make up for shortfalls elsewhere.

* Sixth Carbon Budget costs are updated to 2023 prices for consistency.

Table 18.3
Contingency options in engineered removals

Contingency	Description	Potential average annual emissions savings ($MtCO_2e$, % of sector emissions)			
		2030	CB6	CB7	2050
Increased DACCS deployment	This contingency relaxes constraints on the electricity infrastructure required for DACCS, on the share of synthetic fuels produced in the UK, on the assumption that solid and liquid DACCS account for equal shares of total capacity, and applies the constraint to cumulative rather than annual capacity additions.			2.0 -9%	15.6 -44%
Less reduction in bio imports, allowing more BECCS H_2	More biomass imports, allowing more BECCS hydrogen and displacing blue hydrogen production.		0.8	1.5	1.5

Source: CCC analysis.
Notes: We have blanked out cells where the contingency measure in question is estimated to deliver less than 0.3 $MtCO_2e$ in potential emissions savings, to focus on high-yield options. The percentage of sector emissions metric is not shown for the BECCS hydrogen contingency as it cuts across two sectors: engineered removals and fuel supply.

18.3.1 Increased DACCS deployment

The primary role for DACCS in the Balanced Pathway is to offset residual emissions, after other engineered removals are accounted for, and ensure the UK reaches Net Zero by 2050. Following this approach, additional DACCS could be used to make up for a shortfall in other sectors. However, DACCS deployment is not limitless: as well as high and uncertain future costs, DACCS deployment is subject to constraints on the feasibility of its build out. We consider this contingency as follows:

- City Science developed maximum feasible deployment scenarios for DACCS capacity in the UK (Box 18.1 and Figure 18.3). In developing the Balanced Pathway, we use their standard scenario, ensuring that annual capacity additions of total DAC capacity (including both DACCS and DAC–feedstock) does not exceed the maximum feasible rate, as described in Section 18.1.4. We also assume a 50:50 split between solid and liquid DACCS.

- In the Balanced Pathway, we assume all synthetic fuels used in the aviation and shipping sectors are produced in the UK, given uncertainty in existing accounting guidelines (see Box 7.7.1 of our Seventh Carbon Budget advice report). DAC–feedstock accounts for 57% of cumulative CO_2 captured by DAC over 2025-2050, and is therefore a large factor constraining the level of DACCS removals, given the DAC constraint applies to the sum of the two.

- To explore how additional DACCS could be deployed, we relax several constraints.

  – Instead of the standard scenario for maximum feasible deployment, we use the accelerated electrical infrastructure scenario. This scenario assumes that limits on the level of DAC capacity that can get an electricity grid connection are higher than in the standard case.

  – Rather than assuming all synthetic fuels are produced in the UK, we assume that around 40% is imported. Under current accounting guidelines, it is not clear where

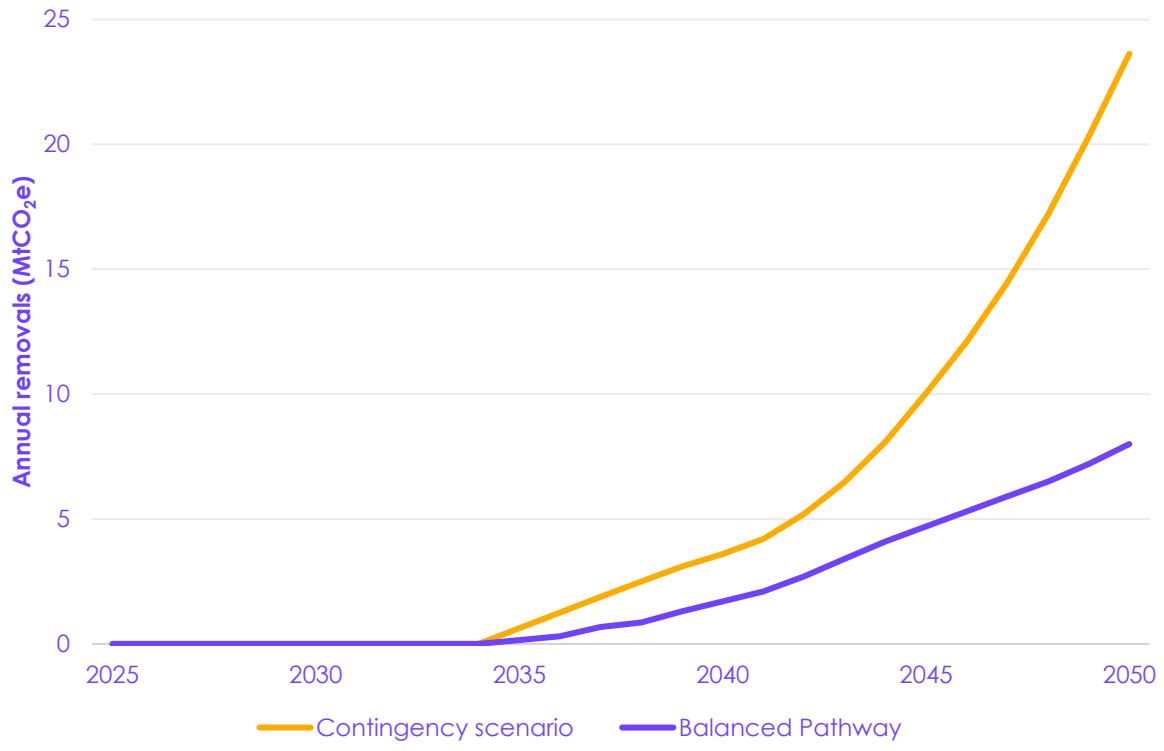
captured carbon should be counted, and therefore whether imported synthetic fuels should be considered low carbon at the point of use. It is possible these rules are clarified in future, facilitating international trade in these fuels. This assumption reflects that possibility, with 40% chosen as an illustrative share.

  - The assumption of a 50:50 split between solid and liquid DACCS, which served to limit liquid DACCS some way below its individual maximum feasible rate of deployment in the Balanced Pathway. The contingency pathway has liquid DACCS providing 58% total capacity in 2050 and solid providing 42%.

  - Rather than applying the maximum feasibility constraint to annual capacity additions, we apply it to cumulative capacity. City Science assess it is technically feasible to commence deployment in 2030, before the start in the Balanced Pathway and contingency pathway. Therefore, it is possible that deployment starting in line with the Balanced Pathway might catch up to meet the cumulative technically feasible maximum over the period to 2050.

- The contingency pathway is shown in Figure 18.6 and scenario results are summarised in Table 18.3. The scenario results in an average of 2 $MtCO_2e$ per year additional removals over the period of the Seventh Carbon Budget and 15.6 $MtCO_2e$ additional removals in 2050.

Figure 18.6 CO_2 removals from DACCS in the Balanced Pathway and contingency scenario



Description: CO_2 removals from DACCS in the contingency scenario are higher than the Balanced Pathway in all years, with the gap growing fastest in the 2040s
Source: CCC analysis; City Science (2025) *Assessing the feasibility for large-scale DACCS deployment in the UK.*

18.3.2 Less reduction in BECCS imports

We also consider increasing the deployment of engineered removals to allow more biomass imports than assumed in the Balanced Pathway. This allows for additional removals from BECCS, which we explore through the increased production of BECCS hydrogen.

We consider an additional 5 TWh of biomass imports in 2040 – a nearly 30% increase on the total bioenergy imports of 17.5 TWh in 2040 and implying a slower imports phase-down. This allows 10% of blue hydrogen production to be displaced by BECCS hydrogen, enabling an additional 1.4 $MtCO_2e$ of removals and a saving of 0.1 $MtCO_2e$ from reduced blue hydrogen production in both 2040 and 2050 compared to the Balanced Pathway. This slower reduction in biomass imports would need to be considered in the context of robust biomass sustainability criteria (see Section 7.7 of our Seventh Carbon Budget advice report).

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Methodology report – UK, Northern Ireland, Wales, and Scotland carbon budget advice

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