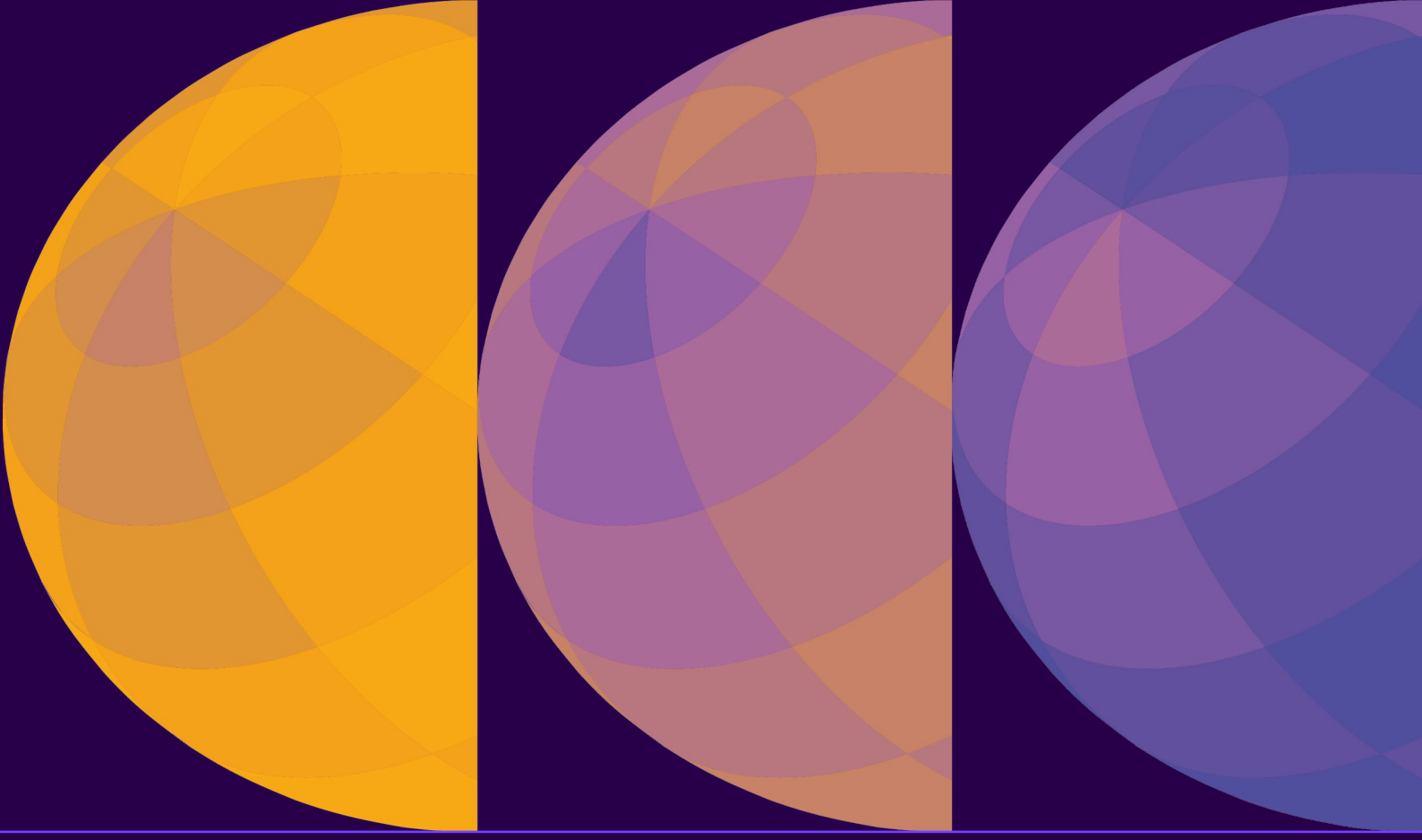

CCC Insights: Determining a pathway to Net Zero

January 2023

Climate Change Committee

Contents

Acknowledgements

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1. Introduction

Around 90% of global GDP is now covered by a Net Zero commitment, but the majority are not yet backed by credible delivery pathways.

As of 2022, most countries have made Net Zero commitments, in total covering around 90% of global GDP.[1] These require net emissions of greenhouse gases (GHGs), or in some cases carbon dioxide, to be reduced to zero by around mid-century or soon after – as required to stabilise global temperature. However, in many cases Net Zero targets are not yet backed by detailed pathways or clear interim targets on the path to Net Zero.

The UK set its Net Zero target in 2019, based on independent advice from the Climate Change Committee (CCC).[2] In 2020, the CCC published a detailed assessment of the UK's path to Net Zero in our Sixth Carbon Budget (covering years 2033-2037) report.[3] The UK Government followed this advice by setting the UK's Nationally Determined Contribution (NDC), a 68% reduction by 2030 relative to 1990 emissions, and legislating for the Sixth Carbon Budget at the level recommended by the Committee, which equates to a 78% reduction on 1990. The UK Government's Net Zero Strategy, which sets out the UK's plans for delivering on its emissions targets, was published in 2021 ahead of the UN COP26.[4]

This briefing explains the CCC's approach to recommending a pathway to Net Zero emissions by 2050 to the UK Government, as a guide for any institution seeking to determine a Net Zero pathway.

This briefing provides an overview of the approach taken by the CCC to determine its recommended pathway to Net Zero. It is intended to act as a guide for any Government or institution seeking to assess and determine pathways to Net Zero.

Full details of the CCC approach can be found in the Methodology Report published alongside our UK Sixth Carbon Budget advice.[5]

Determining a sector-by-sector pathway to Net Zero is useful for understanding the pace of emissions reduction that can be achieved over time, as well as the choices, trade-offs, implications and constraints involved in the transition within each area of the economy. Such analysis can inform decision making on ambition and action to reduce emissions – such as setting appropriate targets (e.g. NDCs) and informing decarbonisation plans or Long-Term Strategies.

This briefing is structured as follows:

1. Methodology overview
2. A step-by-step guide to the methodology
3. Practicalities
4. Lessons learnt and reflections.

Box 1
CCC Insights Briefings

This briefing is a continuation of the eight Insights Briefings the CCC published in 2020 that document the work of the UK CCC under the UK Climate Change Act.[6] The CCC is the UK's independent advisory body on climate change mitigation and adaptation, tasked with providing regular advice to Government on emissions targets and adapting to a changing climate. The CCC publishes annual assessments of the UK Government's progress towards meeting these targets, biennial assessments of progress in adapting to climate change, and supporting analyses on key emerging issues. These briefings are intended as a practical guide to give insights on the CCC's work and learning over the fifteen years since its foundation in 2008.

The briefings in this series are:

- UK Climate Change Act
- The Climate Change Committee
- The UK's Net Zero target
- Advising on the level of the UK's carbon budgets
- Monitoring progress in reducing the UK's greenhouse gas emissions
- Conducting a climate change risk assessment
- Monitoring progress on adapting to climate change in the UK
- Past Climate Change Committee reports
- Determining a pathway to Net Zero

Source: CCC (2020) *Insights Briefings: Sharing the UK approach to addressing climate change.* https://www.theccc.org.uk/publication/insights-briefings-sharing-the-uk-approach-to-addressing-climate-change/

(a) Core principles of CCC approach

The CCC's approach was built upon six core principles including consistency with the latest climate change science and minimising the role of engineered greenhouse gas removals.

To inform our 2020 advice on the UK's pathway to Net Zero, we undertook a detailed modelling exercise to understand what the transition could involve.

Our approach was built upon the following core principles:

- **Pathways must be consistent with the latest science on climate change**. The International Panel on Climate Change's (IPPC) 2018 Special Report on Global Warming of 1.5°C improved the understanding of how future GHG emissions affect the climate. It also emphasised the need for near-term, rapid and sustained emissions reductions to minimise cumulative emissions and deliver the Paris Agreement temperature goals (Figure 2.1).

- **Pathways are designed to deliver Net Zero by 2050 at the latest**. This is the legal target set by the UK in 2019 under the Climate Change Act which covers all territorial greenhouse gas emissions plus the UK's share of international aviation and shipping emissions. The Committee's advice is that this should be delivered in the UK by domestic action without reliance on international carbon credits.

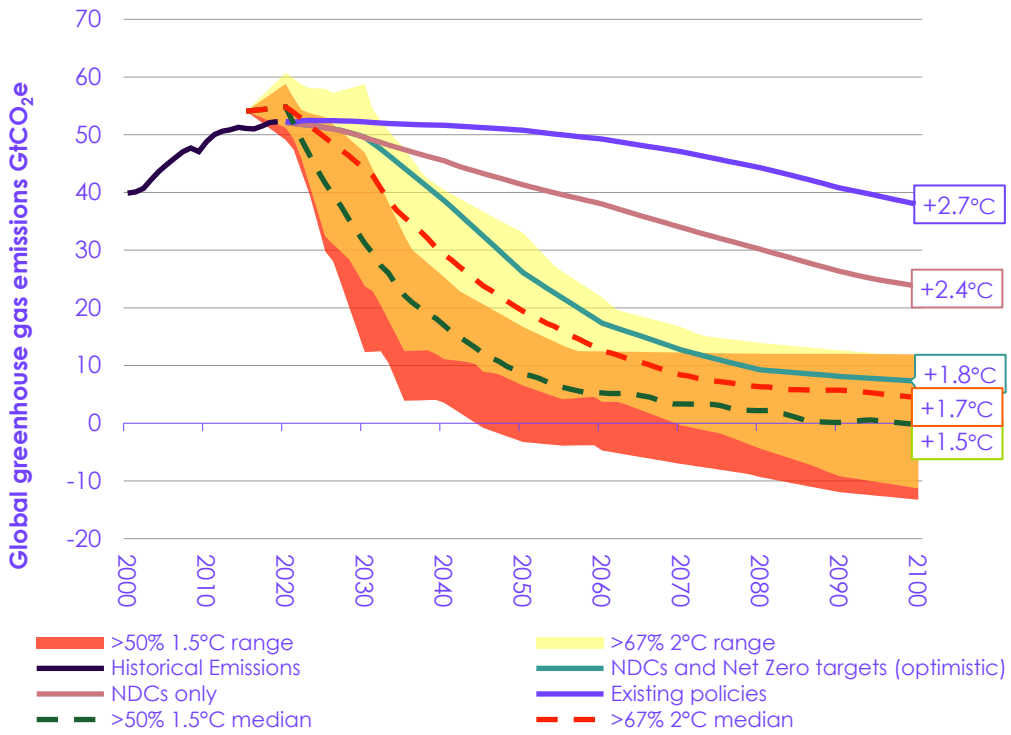
- **Pathways are built up through detailed sectoral analysis**. We looked at what the transition to Net Zero might involve for each source of the UK's emissions (e.g. transport, energy supply, industry) to have a more detailed understanding of what the choices, constraints and implications are for each sector as well as across the whole economy.

- **Pathways are grounded by real world constraints**. Our pathway was built around practical realities of implementation, such as technology readiness and the need to build up skills and supply chains or develop supporting infrastructures. We also considered specific conditions within each nation (England, Scotland, Wales and Northern Ireland) of the UK.

- **Pathways minimise the role of engineered GHG removals (GGRs).** Our analysis prioritised known, cost-effective solutions involving technological and behaviour change. As these can be reliably implemented now, they reduce emissions sooner such that cumulative emissions – which determine the overall contribution to climate warming – are kept as low as possible. They also limit future over-reliance on more costly and/or less mature carbon dioxide removal technologies.

- **Pathways build in optionality and limit exposure to uncertainty**. A degree of uncertainty is inherent in developing scenarios across multiple decades. Our analysis takes a conservative approach to limit exposure to points of uncertainty, while at the same time using a range of scenarios to explore trade-offs and different degrees of optimism around potential solutions.

Figure 2.1 Temperature implications of global emissions pathways



Source: IPCC, Climate Action Tracker, CCC analysis.
Notes: The shaded ranges represent the upper and lower bounds of the scenarios that limit warming to a) 1.5°C with a >50% probability and b) 2°C with a >67% probability from the scenario database used by the IPCC Sixth Assessment Report. Ranges for median end of century warming are +1.9°C to +3°C for the NDCs only scenario (Climate Action Tracker '2030 Targets only' scenario). Aggregation of greenhouse gas emissions is done using the Global Warming Potential metric at time horizon of 100 years. Values from the IPCC 5th Assessment report are used, with a methane correction factor applied to Climate Action Tracker values which have been calculated using AR4 Global Warming Potential values with a 100-year time horizon. The Climate Action Tracker scenarios take into account NDCs and Net Zero pledges made by 09/11/22.

(b) Overview of key analytical steps

Understanding what Net Zero UK emissions in 2050 could look like was an essential starting point for the analysis.

In 2019 the CCC's Net Zero report assessed 2050 sectoral emissions in a single pathway. This found that some sectors achieve zero emissions by or before 2050, while others will have some residual emissions that require balancing by removals. This was valuable for the Sixth Carbon Budget pathway development as it identified the limits of decarbonisation.

This was valuable in later pathway development, as it identified the limits of decarbonisation in each sector and the approximate mix of solutions required to achieve this, as well as highlighting areas where further evidence and analysis was required. Earlier energy system optimisation modelling (using the TIMES framework) also provided insights into least-cost long-term pathways.

The CCC created a pathway to Net Zero and the UK's Sixth Carbon Budget through detailed sectoral modelling.

For the Sixth Carbon Budget pathways, we developed our analysis through detailed sectoral modelling. The analytical approach that we used to determine a pathway to Net Zero for the UK was broadly, for each sector:

- Establish a baseline of business as usual emissions and emitting activities (e.g. electricity use, vehicle-km, land use change) to compare against.
- Identify and prioritise options (technology and behaviour change) to reduce emissions, characterising their potential to scale up and their expected costs.
- Define scenarios to consider how far to deploy those options, testing different degrees of optimism, accounting for practical constraints and interactions/overlaps between options.
- Calculate the implications of the scenarios for emissions pathways, deployment trajectories, energy demand, costs and benefits. Iterate to refine options further.

In developing these scenarios we used some common key assumptions, for example for fossil fuel prices and GDP growth.

Pathways were produced for the UK, Scotland, Wales and Northern Ireland to determine the rate and achievable decarbonisation in each nation.

Pathways and other outputs were produced for the whole of UK, Scotland, Wales and Northern Ireland to account for different circumstances among the Devolved nations.* These pathways are based on specific factors that determine the rate and overall level of decarbonisation achievable in each nation. This includes:

- Different levels of activity and emissions in each sector today
- Existing land use, and opportunities for land-based removals
- Existing infrastructure
- Resources that could underpin the engineered removal of CO_2
- Existing policies

* The UK is made up of four nations – England, Wales, Scotland and Northern Ireland. The latter three have devolved Governments which lead on policies in some sectors e.g. agriculture, buildings and waste.

3. Methodology: Step by step

(a) Establishing a baseline

Establishing a baseline enables an estimation of the implications of the transition relative to a world that maintains current policies; the CCC used in-house analysis and government projections to create this.

We developed a baseline that broadly aimed to represent emissions and emitting activities that would occur under existing policies. The main purpose of this was to estimate the implications of the transition, relative to a world that maintains current policies.

Sector baselines were developed in-house or by using projections published by the UK Government.[7] These were created based on assumptions around future population and economic growth, fossil fuel demand, energy costs and planned or existing policies. Many of the energy projections are produced from econometric models, assuming a continuation of past relationships, while others use detailed sectoral models, such as the UK's National Transport Model, which have been developed for wider purposes. In some cases these were complimented by consideration of sector-specific assumptions, such as projections of car ownership.

Full details of our approach to establishing a baseline can be found on page 20 of our Methodology report.

(b) Identifying and prioritising options to reduce emissions

There is often a range of solutions available to achieve a specified outcome; to prioritise these solutions, the CCC considers six main factors including emissions savings potential and technology choice.

The CCC's advice on the Net Zero path is not policy prescriptive, meaning it does not seek to tell the Government exactly what policies to introduce to reduce emissions; rather, we focus on outcomes and examine a range of options to achieve these. In some areas the preferred solutions are clear (e.g. transitioning from petrol to electric cars), while in others we recommend keeping multiple options in play. Within each sector we prioritised solutions by considering:

- **Emissions savings**. How far a low-carbon option can reduce emissions compared to the high-carbon alternative. Options that partly reduce emissions may be valuable in the short run, but in the long run options must eliminate or at least deeply reduce emissions. Our analysis focuses on the need to reduce emissions rapidly to limit cumulative emissions of greenhouse gases. We also take care to filter out options that reduce UK territorial emissions but increase emissions globally (e.g. reducing production but not consumption of carbon-intensive products).

- **Wider benefits of action.** More broadly, we consider benefits of action to tackle climate change for society more widely, including health benefits (e.g. through healthier diets, more active lifestyles, improved air quality). For example, we include improvements to energy efficiency that are targeted at low-income households and are needed to meet the UK's targets on fuel poverty.

- **Costs**. We estimate the unit cost (or benefit) per tonne of emissions reduction associated with measures to reduce emissions.

  - We aim to consider the full 'system costs', for example including not just the cost premium for an electric vehicle compared to an equivalent petrol or diesel vehicle, but also the required charging network, low-carbon electricity and the cost savings from not using petrol or diesel.

  - We make conservative assumptions on the scope for costs to fall over time with deployment, both in the UK and internationally. We used carbon values (see Glossary) to compare the relative cost of different abatement options and the timing of their deployment becoming more cost-effective.

- **Dynamics.** When considering 'dynamic' cost-effectiveness (i.e. reaching Net Zero by 2050 at overall least cost), early action is required in numerous areas to secure a greater contribution by 2050, even if the carbon values do not by themselves indicate that deployment is cost-effective at that time. Examples of this include developing supporting infrastructure and supply chains over time; the stock-turnover cycles of capital in particular sectors; and time taken for biological growth in the land use sector.

- **Deployment timing and technology choice**. Our general approach, following the Paris Agreement, is to adopt the highest possible ambition for deployment. This is to deploy low-carbon options as soon as realistically possible while recognising real-world constraints such as the time to build up skills and supply chains. We consider the lifetimes of existing assets such as boilers or cars, and generally seek to limit early capital scrappage, which can be more costly, add to emissions and/or imply stop-start investment programmes. Where there are choices in the technologies that might be applied (such as low-carbon hydrogen or carbon capture, utilisation and storage) we assess their relative deployment timing according to real-world constraints, such as asset lifetimes and the requirement for new training and skills to be established, along with their relative costs.

- **Optionality**. Where it is not yet possible to identify a clearly favoured solution, we identify a range of alternative options to deliver the desired outcome and the required actions to keep these options open. For example, deep decarbonisation of manufacturing is likely to require a range of different low-carbon technologies including electrification, low-carbon hydrogen and carbon capture, utilisation and storage. We recommend actions to develop and test the application of all these technologies to varying degrees to ensure that the approach taken to decarbonisation is more robust to uncertainties over the success of different solutions.

Across most sectors a common order of preference emerged, with demand reduction solutions coming first.

In practice, the set of solutions tended to result in choices in the following order of preference:

1. **Demand reduction** – can we do less of a carbon-intensive activity without making people worse off?
2. **Improved efficiency** – can we maintain the same level of activity with less waste?
3. **Electrification** – can we use low-carbon electricity to power the activity instead of fossil fuels?
4. **Hydrogen** – if the energy use cannot be electrified, can we use low-carbon hydrogen instead?
5. **Carbon capture** – if we can't avoid emissions, can we capture them and store them safely?
6. **Removals** – for any remaining emissions, we need to remove an equivalent amount from the atmosphere to meet Net Zero.

Full details of our approach to identifying and prioritising abatement options can be found on pages 18-19 of the CCC's Methodology report. Implementation within sectors is detailed in the sector chapters of that report.

(c) Sectoral interactions

To create a holistic analysis, we overlayed sectoral models with a whole economy analysis to understand sectoral interactions and resource allocation.

While the analysis is undertaken at a sectoral level, it is important to consider interactions between sectors.

We overlayed the sectoral level models with a cross-economy analysis (Figure 3.2) to define and consider interactions between sectors and the most appropriate allocation of energy and resources, such as:

- Trade-offs around using land to grow food, produce bioenergy or sequester carbon.
- Interactions between energy demand from end-use sectors and prioritisation of low-carbon energy supply from different sources where:
  - **Low-carbon hydrogen** is prioritised for energy end-uses where electrification is not expected to be feasible, based on the insights and conclusions from the CCC's 2018 hydrogen review;[8]
  - **Low-carbon electricity** is prioritised for reducing unabated fossil electricity generation and to meet new demands where it is used with high efficiency, such as in heat pumps and electric vehicles.

Some iteration is likely to be necessary to ensure that the analysis is self-consistent. For example, ensuring that the level and cost of energy supply accords with the level and assumed cost of meeting energy demands, or ensuring that assumptions on agricultural production and land availability for afforestation do not exceed the available land area.

Use of whole system models (e.g. TIMES), which characterise some of the links between sectors, can be useful early in the process to provide an initial guide to key interactions. This can be useful as a starting point, even if the intention is to undertake more detailed sectoral analysis subsequently.

(d) Defining exploratory scenarios

We created a central, 'Balanced Net Zero Pathway', using four exploratory scenarios, which was designed to provide choice and flexibility to decision makers.

A key aspect of our approach was the use of scenarios to explore a range of choices and uncertainties around the potential path to Net Zero (Figures 3.1 and 3.2). We initially constructed three 'exploratory' scenarios that reach Net Zero by 2050. One scenario is more conservative, while the other two are more optimistic either on developments regarding behavioural change or improvements in technology costs and performance:

- **'Headwinds':** our most conservative scenario whilst still meeting Net Zero by 2050. Deployment of low-carbon technology and behaviour change among society were assumed to be relatively more difficult, resulting in a greater dependency on large-scale deployment of low-carbon hydrogen and carbon capture.

- **Widespread Engagement:** higher optimism about the extent of societal and behaviour change possible to reduce demand for carbon-intensive activities and increase uptake of low-carbon solutions.

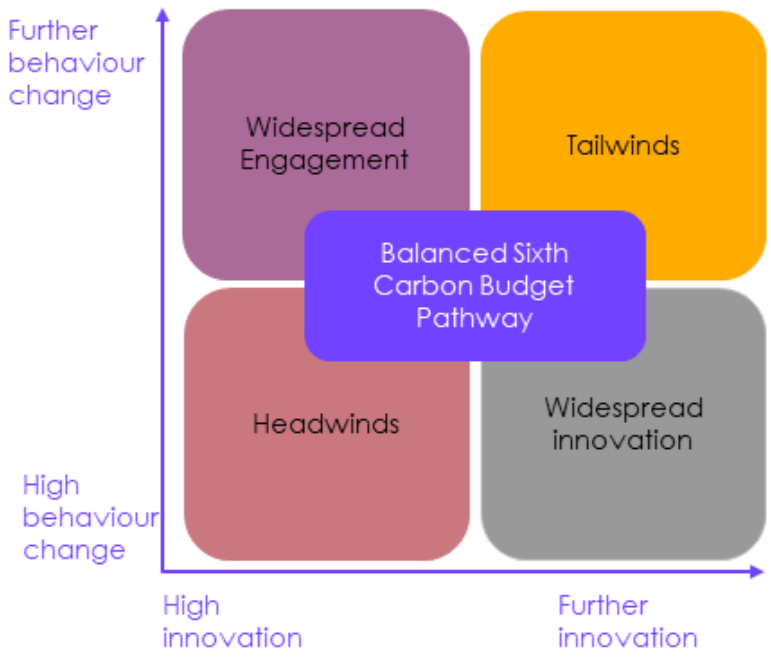
- **Widespread Innovation:** higher optimism about potential cost reductions in low-carbon technologies alongside efficiency improvements. This leads to wider deployment of renewables and engineered GHG removals, and lower demand for energy and resources.

A fourth exploratory scenario ('**Tailwinds**') was then constructed, which assumes success on innovation and societal and behavioural change. This scenario represents the limit of our assessment of what might be feasible based on current evidence and achieves Net Zero earlier than the others.

We then constructed the '**Balanced Net Zero Pathway**', as a central pathway that reaches Net Zero by 2050. It was designed to drive progress through the 2020s, while creating options in a way that gives flexibility to respond to changing circumstances. This is the pathway on which the recommendations for the UK's NDC and the legislated Sixth Carbon Budget were based.

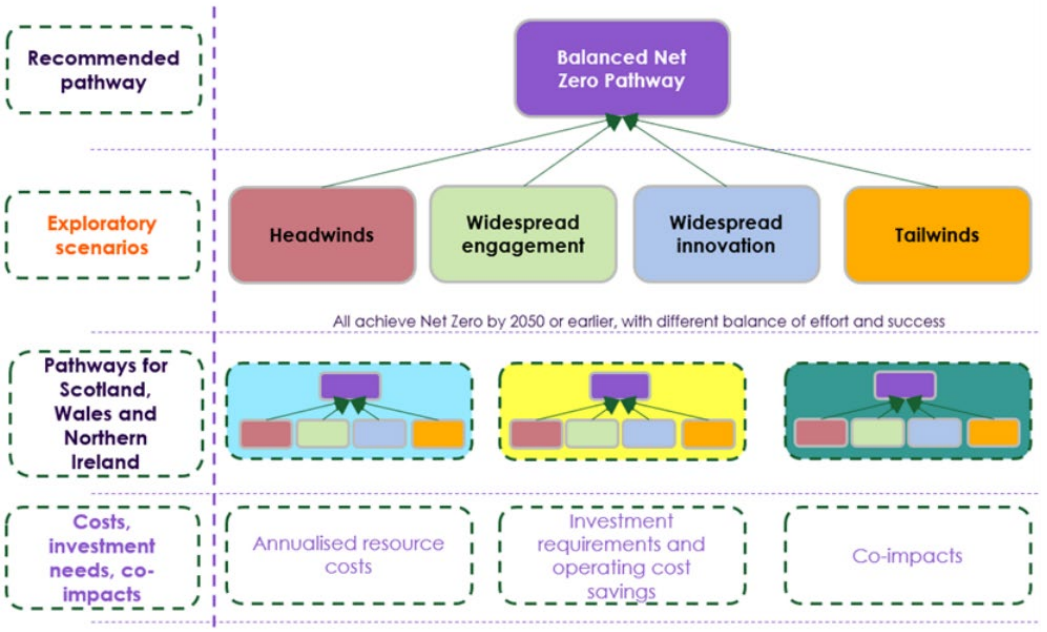
Full details of our scenario methodology can be found on pages 13-16 of the CCC Methodology report.

Figure 3.1 Sixth Carbon Budget scenarios matrix



Source: CCC

Figure 3.2 Scenario framework for Sixth Carbon Budget analysis



Source: CCC

(e) Calculating outputs

When producing outputs, we consider the costs and benefits of different options, as well as issues such as energy security and fairness.

We considered the costs and benefits of different options to reduce emissions when developing our sectoral models and analysis. These considerations, as well as the impacts on issues such as energy security, affordability and fairness informed our overall assessment of suitable pathways to Net Zero.

- **Recorded results.** For each action to reduce emissions, CCC analysts recorded a range of results including: the unit abatement cost in £/tCO_2e, abatement of each GHG in each year, energy consumption and total capital and operational costs in each year. These were then aggregated up to the sectoral and economy-wide levels. Energy consumption outputs by sector were used as an input to the assessment of the size, emissions and cost of energy supplies.

- **Capital expenditure over time.** In developing our pathways for the Sixth Carbon Budget, for the first time we estimated the capital expenditure over time in each sector pathway. This enabled costs to be broken down, with increased capital expenditure separated from changes in operating expenditure.

- **Avoiding double counting.** To aggregate these to an economy-wide level we adjusted the sectoral results to ensure that all energy supply costs were counted only once. This avoided double-counting, for example of capital expenditure for electricity generation and as operating costs in the charging of electric vehicles.

Full details of our costing methodology can be found on pages 25-30 of the CCC Methodology report.

4. Practicalities

(a) Structuring the team and process

It took 15 months to complete the analysis and publish the report, but the process built on previous Net Zero target analysis and research publications.

The CCC team for the Sixth Carbon Budget consisted of around 20 analysts, including managers and the central analytical team that brought the analysis together. The larger sectors in terms of the emissions (buildings, industry, surface transport, land use/agriculture, energy supply) typically had two analysts each, while less resource was devoted to the smaller sectors (aviation, shipping, waste, F-gases). The analytical process and write-up took around 15 months, from September 2019 to December 2020.

The process built on previous CCC analysis and publications, most importantly the May 2019 publication that recommended the Net Zero target. Key publications in late 2018, which fed into both the advice on both Net Zero and the Sixth Carbon Budget, looked at three key areas – land use,[9] biomass[10] and hydrogen[11] – where increased ambition might be feasible compared to previous assessments and/or the high level of complexity required a detailed assessment of interacting components.

This laid the groundwork for the pathway analysis by exploring different approaches to decarbonisation and setting out principles for how some of the most complex areas can best contribute to Net Zero. This meant that the analysis could be undertaken at a sectoral level with a broad understanding of the roles of different solutions and likely interactions between them.

The analysis was created with input from stakeholders and expert external advisory groups, as well as the invaluable and regular insight, oversight, challenge and direction from the CCC's expert Committee.

The CCC's independent Committee of experts provided regular insight, oversight, challenge and direction to ensure the analysis was well founded, comprehensive and rigorous. For the Sixth Carbon Budget advice, this was done through monthly Committee meetings, together with smaller meetings with Committee 'champions' for particular areas, which went into more analytical detail. The Committee inputted on the design of the scenarios, the approach to and results of the analysis and the overall framing of the advice.

As part of the process for the advice on the Sixth Carbon Budget we issued a Call for Evidence, which included specific questions to collect evidence from stakeholders. As well as using this evidence as an input to our analysis and advice, we published a summary of responses on our website.

We also commissioned three expert advisory groups, which brought together external expertise in areas of interest: policy, finance and the health co-impacts of action to reduce GHG gas emissions.

A key aspect of the CCC's work is transparency, which means that we publish inputs and supporting documents whenever possible. We published the above documents, as well as reports on commissioned research and a detailed dataset, on our website.[12] More information on the CCC's internal structure can be found in our second insights briefing online.[13]

(a) Data and evidence used to inform our analysis

We use a wide range of data sources as analysis inputs, some of which are highlighted below. We draw on official datasets as far as possible, but also make use of additional data from reliable third parties or sometimes commission new research where there is a particular data gap.

A detailed data explorer covering many of the inputs, assumptions and outputs from our analysis for the Sixth Carbon Budget can be found on our website.[14] All Sixth Carbon Budget materials are on our website too.[15]

Whole-economy inputs:

- Energy-cost projections (official data – complimented by our own analysis)
- Carbon-values (official data)
- GDP projections (official data)
- Population projections (official data)
- Historical emissions (official data)
- Global warming potential of GHGs (from the IPCC)

Sectoral inputs – generally considered relative to the baseline:

- Technology costs and opportunities to reduce emissions
- Energy and land-use emissions intensity
- Asset/technology deployment rates and lifetimes
- Various sector specific inputs. For example, data on UK housing stock, land-use, transport demand, and recycling rates derived from sector specific research and engagement with these sectors.

(b) Models and commissioned research

We used in-house analysis, commissioned research, stakeholder engagement and expert advisory groups to develop sector decarbonisation options.

The CCC uses a combination of in-house analysis, commissioned research, stakeholder engagement and expert advisory groups to understand and develop decarbonisation options for each sector.

Some sector models were developed in-house by the CCC's analytical team using bespoke spreadsheet tools, sometimes complemented by external analysis for specific aspects.

In other cases, such as decarbonisation of industry and residential buildings, a large modelling exercise was commissioned and the resultant model handed over to the CCC.

The research commissioned for the Sixth Carbon Budget advice included:

- Deep-decarbonisation pathways for UK industry
- Trajectories for residential heat decarbonisation
- Costs, efficiencies and roll-out trajectories for zero-emission heavy goods vehicles, buses and coaches

- Updated quantification of the impact of future land use scenarios to 2050 and beyond
- Non-CO_2 abatement in the UK agricultural sector by 2050
- Macroeconomic modelling on the economic impact of the Sixth Carbon Budget
- Unpacking leadership-driven global scenarios towards the Paris Agreement

Box 2
The UK citizens' Climate Assembly

In June 2019, six Select Committees of the UK Parliament's House of Commons called a citizens' assembly to understand public preferences on how the UK should tackle climate change because of the impact these decisions will have on people's lives. A Select Committee is a group of Members of Parliament from different political parties that examines policy issues, holds the Government to account and makes proposals for new policies and laws.

108 participants were selected from throughout the UK, bringing together people from different backgrounds, age groups, and viewpoints to form a representative sample of the UK's population to consider how the UK can meet its Net Zero target by 2050.

The outcomes of their discussions were presented to the six Select Committees in September 2020. The Assembly provided an unprecedented opportunity for the public to contribute to the UK climate change debate, and to inform action taken by Government and Parliament.

The CCC helped to facilitate discussions with the Climate Assembly and used findings from their deliberations to inform choices in our scenarios, particularly those related to behaviour change.

Source: Climate Assembly (2020) The path to net zero, Climate Assembly UK full report. https://www.climateassembly.uk/report/

5. Key lessons and reflections

Based on the CCC's experience and other national and international analyses, there are several common lessons emerging from Net Zero pathways analysis.

This briefing note has sought to summarise the CCC's approach to developing its advice on the UK's pathway to Net Zero, which was specifically chosen with the UK's national circumstances in mind (Box 3). There are other tools and methods that can be used to model energy transitions and emissions reduction pathways. Countries and institutions around the world will want to take an approach that is appropriate to their own circumstances and needs.

However, based on our experience, there are several key lessons that we believe are broadly applicable across different contexts, and that we find reflected in other national and international Net Zero pathways:[16]

- **Rapid emissions cuts.** All pathways will require rapid emissions cuts from the mid-2020s to remain consistent with achieving the Paris temperature goals. Effort from all sectors of the economy and application of a broad range of emission reduction technologies and solutions will be required.

- **Low carbon electricity and electrification.** Decarbonising and expanding electricity generation (predominantly with low-cost renewables) underpins efforts to decarbonise energy-related emissions elsewhere in the economy (surface transport, buildings, industry). Energy efficiency can offer immediate emissions savings, while low-carbon hydrogen will be increasingly important to reduce energy emissions. For example, in electricity generation to back up the high-renewables system and across energy end-uses where electrification is not feasible.

- **Net Zero and public engagement.** Public engagement is vital to achieving Net Zero and should be a key focus for any credible pathway analysis and climate plan. Public engagement underpins measures to reduce demand from high-carbon activities and the adoption of low-carbon technologies, as well as wider acceptance of new approaches to cut emissions such as CCS.

- **Necessity of GHG removals.** It is unlikely that emissions in every sector will be able to reduce to zero, so GHG removals will be needed. Priority should be given to preservation and expansion of natural carbon sinks and although engineered removals technology are likely to be needed in the future, their planned use should be minimised, with cuts to emissions prioritised.

- **Sector-level analysis is recommended.** For a more granular understanding of the real-world constraints and implications of the transition, a degree of sector-level analysis is recommended. This is particularly helpful for informing implementation plans and determining the timing of deployment of different emissions saving measures across the economy. Communication of these timings (e.g. phase-out dates of high-carbon technologies) is a key output of the analysis.

- **Whole-system optimisation models.** Models such as TIMES are a useful tool for informing Net Zero pathways. They can help to understand the interactions between the energy and resource demands of different sectors of the economy and in prioritising some high-level actions (e.g. best use of finite biomass supplies, priority areas for hydrogen use). System-level modelling can complement detailed sectoral modelling or provide a high-level alternative to it.

- **Scenario analysis can be useful in informing decision making.** Ideally, scenarios should explore uncertainties and/or choices on the multi-decade decarbonisation path. The analysis can be designed to be outcome-focused rather than policy prescriptive, meaning it can be applied through different policy instruments or in different policy settings. For example, from more market driven economies to more centrally managed economies. Developing economies may need to specifically consider challenges around access to finance and funding.

- **Importance of stakeholder engagement.** Engaging external groups with deep sectoral knowledge and expertise from across society throughout the analytical process helps build acceptance of, and confidence in, the final recommendations. If possible, giving time for stakeholder feedback is invaluable for improving analysis and identifying potential gaps.

Analysis of decarbonisation pathways can provide a rich and detailed guide to the changes required and the necessary choices on the path to Net Zero. However, assessment of pathways is not an end in itself, but a guide to the action that must be taken. No analysis will be completely correct, but it only needs to be good enough to provide policy makers with the information to act. Although the future is uncertain, taking action to reduce emissions will help to create options for future pathways, while failing to act will close them off.

Box 3
The UK's national circumstances

The CCC advised a front-loaded pathway to Net Zero based on the UK's national circumstances. In 2021 UK GHG emissions were 447 $MtCO_2e$, including the UK's share of international aviation and shipping emissions – this is 47% below 1990 levels.

Emissions reductions varied across sectors in the decade before 2019, with the largest reduction seen in electricity supply due to the roll out of renewables and phasing down of coal generation. Surface transport is now the largest emitting sector in the UK. For more information on UK sectoral emissions trends, see the CCC's 2022 Progress Report.[17]

Other relevant contextual circumstances:

- The UK has the 5th largest economy in the world (on basis of GDP) and is primarily a service-based economy. The UK is a highly market-driven economy with a fully privatised energy market.
- Economic, energy and social policy is largely reserved to the UK Government, but Scotland, Wales and Northern Ireland all have devolved powers particularly in areas such as regional transport, planning and agricultural policy. The Climate Change Act (2008) provides an overarching legal framework for reducing emissions and adapting to climate change cross the UK.
- In 1990 (the base year of the UK's emissions targets) coal power generated just under 80% of the UK's electricity. In 2021, coal power supplied 2% of the UK's electricity, while gas provided about 40%. Natural gas (largely from the UK's North Sea with minimal Russian imports) is also used extensively for both heating and cooking in UK homes and businesses, while UK buildings have overall relatively poor energy efficiency.
- Low-carbon power generated close to 60% of the UK's electricity in 2021. Nuclear power has provided around 20% of electricity since the 1980's, while generation from renewables, in particular wind power, has rapidly increased since 2010 as costs have fallen. The UK is considered to have among the best wind-power potential in the world.
- The majority of UK land is used for agriculture, specifically grassland for grazing. There is large capacity for geological CO_2 storage situated beneath the UK seabed, which in combination with the skills and experience of the UK's oil and gas industry makes carbon capture and storage more feasible.
- The UK has relatively high per-capita aviation demand and per capita car ownership (~0.6 cars per person) with most car journeys being very short (<20km).
- UK consumption emissions reduced 30% between 1990 and 2020.

Source: World Bank (2022) *GDP indicator*; CCC (2022) *Progress in reducing emissions: 2022 Report to Parliament*, DEFRA (2021) *Food Security Report.*

Endnotes

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[2] Climate Change Committee (2019) *Net Zero Advice Report,* https://www.theccc.org.uk/publication/net-zero-the-uks-contribution-to-stopping-global-warming/

[3] Climate Change Committee (2020), *Sixth Carbon Budget Advice Report,* https://www.theccc.org.uk/publication/sixth-carbon-budget/. This advice was previewed in the Committee's 2020 letter *Advice on the UK's 2030 Nationally Determined Contribution*.

[4] UK Government (2021) *Net Zero Strategy,* https://www.gov.uk/government/publications/net-zero-strategy

[5] Climate Change Committee (2021) *Sixth Carbon Budget Methodology Report,* https://www.theccc.org.uk/wp-content/uploads/2020/12/The-Sixth-Carbon-Budget-Methodology-Report.pdf

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[7] UK Government (2021), *Energy and Emissions Projections* https://www.gov.uk/government/collections/energy-and-emissions-projections

[8] Climate Change Committee (2018), *Hydrogen in a low-carbon economy* https://www.theccc.org.uk/publication/hydrogen-in-a-low-carbon-economy/

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[12] Climate Change Committee (2020) *Sixth Carbon Budget,* https://www.theccc.org.uk/publication/sixth-carbon-budget/

[13] Climate Change Committee (2020) *CCC Insights Briefing 2, The Climate Change Committee,* https://www.theccc.org.uk/wp-content/uploads/2020/10/CCC-Insights-Briefing-2-The-Climate-Change-Committee.pdf

[14] Climate Change Committee (2020) *Sixth Carbon Budget,* https://www.theccc.org.uk/publication/sixth-carbon-budget/#supporting-information-charts-and-data

[15] Climate Change Committee (2020) *Sixth Carbon Budget,* https://www.theccc.org.uk/publication/sixth-carbon-budget/

[16] International Energy Agency (2021) *Net Zero 2050 Roadmap*, https://www.iea.org/reports/net-zero-by-2050

[17] Climate Change Committee (2022) *Progress in reducing emissions: 2022 Report to Parliament,* https://www.theccc.org.uk/publication/2022-progress-report-to-parliament/

Annualised resource costs: The annualised costs estimated by the CCC are composed of capital investment costs (e.g. for new low-carbon technologies or industries), operating costs (e.g. for low-carbon fuels) and financing costs (the cost of capital – representing the cost of borrowing the money to finance the capital investments in the scenarios). These costs are intended to include the direct cost of building and installing low-carbon technologies, and operating them over the course of their lifetimes. The costs are then annualised over the lifetime of the technology to give an average annual cost. These resource cost estimates do not include the impacts of taxes or other transfers.

Baselines: To determine the costs of decarbonisation we constructed an additional scenario, which estimates what future emissions in the UK could be for each sector to 2050, if no further climate action is taken beyond today. Emissions and energy demands are produced for this baseline, so we can then estimate the change between the baseline and our scenarios.

Sector baselines are based on the Energy and Emissions Projections 'Reference Policies' scenario produced by the Department of Business Energy and Industrial Strategy and complemented by CCC internal analysis. Typically, these baselines will ensure that currently funded low-carbon policies are taken into account (e.g. renewables with Government-backed contracts that have been deployed, or are expected to be deployed in the 2020s) but will not take into account unfunded policies or proposals, or significant additional uptake of low-carbon technologies from today.

Capital investment: The additional in-year gross capital investment costs of building a low-carbon economy, compared to the investment in a counterfactual world with no further climate action (the 'baseline', as outline above).

Carbon values: Typically expressed in £/tCO_2e, can be used to represent a monetary value for reductions in emissions, and are useful to compare against the abatement costs of technologies and behaviours in our scenarios.

Calculating levelised abatement costs: Costs are smoothed over the lifetime of the technology to give a levelised cost per tonne of GHG emissions abated (£/tCO_2e). The CCC uses a Net Present Value (NPV) method to calculate the levelised costs of an abatement measure. This calculates a stream of annual costs over the lifetime of a technology, and discounts future costs. These costs are then divided by the total avoided emissions ('abatement') over the lifetime of the asset, which is also discounted.

£/tCO_2e = Net present cost of measure / Total discounted lifetime abatement

This step does not change overall costs of the transition, but rather smooths the costs of abatement over the technology lifetime.

CCC Insights: Determining a pathway to Net Zero
January 2023

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