Net Zero
Technical report

Committee on Climate Change
May 2019

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Contents

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Chapter 1: Introduction

This technical report accompanies the 'Net Zero'[1] advice report which is the Committee's recommendation to the UK Government and Devolved Administrations on the date for a net-zero emissions target in the UK and revised long-term targets in Scotland and Wales.

This introductory chapter is set out in four sections:

1. Aims and structure of this report

2. Assessing options for decarbonisation within each sector of the economy

3. Constructing economy-wide scenarios from individual options

4. Estimating the costs and benefits of a net-zero GHG emissions target

1. Aims and structure of this report

The conclusions in our advice report are supported by detailed analysis that has been carried out for each sector of the economy, plus consideration of F-gas emissions and greenhouse gas removals. The purpose of this technical report is to lay out that analysis.

England, Scotland, Wales and Northern Ireland each have an important role to play in delivering a UK net-zero emissions target. However, each devolved administration has a unique set of opportunities and challenges in achieving net-zero emissions, meaning that the combination of options will differ across the UK. We have therefore determined what each UK-wide scenario means for each devolved administration, as well as an assessment of whether and when each devolved administration could credibly achieve net-zero domestic emissions. This analysis is presented in Chapter 5 of the advice report, and compared to our previous scenarios for a maximum level of decarbonisation within Scotland and Wales in the appendix to this technical report.

The analysis is covered in the following chapters:

- Chapter 2: Power and hydrogen production
- Chapter 3: Buildings
- Chapter 4: Industry
- Chapter 5: Transport
- Chapter 6: Aviation and shipping
- Chapter 7: Agriculture, land use, land-use change and forestry
- Chapter 8: Waste
- Chapter 9: F-gas emissions
- Chapter 10: Greenhouse gas removals
- Technical appendix: Changes from previous scenarios for the UK, Scotland and Wales

[1] Referred to hereafter as the 'advice report'.

2. Assessing decarbonisation options within each sector of the economy

Chapters 1 to 9 each begin with a description of the current status of the sector: the level of emissions in 2017 (the latest available year of final emissions data; provisional data is now also available for 2018 and will be covered in the Committee's annual Progress Report to Parliament later this year) and how that has changed in recent years, including the contribution from low-carbon technologies.

We then break down the sector emissions into their separate sources, such as off-gas grid homes or HGVs, and present options for reducing those emissions to as low a level as possible by 2050. For this, we have drawn on an extensive evidence base which includes:

- Findings from our existing reports, notably our 2018 reports on biomass, hydrogen and land-use and our 2015 report on the level of the fifth carbon budget.[2]
- New research that we have recently commissioned on emissions sources which may be more difficult to decarbonise. The findings are summarised in Box 5.2 of the advice report and have been incorporated into the analysis presented in this report.
- Other studies published recently on alternative scenarios for achieving net-zero emissions. We present a review of these in Box 5.6 of the advice report, including how they compare with our approach.

In order to produce the economy-wide scenarios presented in the advice report, we have grouped the options in each sector by the level of challenge associated with their delivery. This aims to ensure that the level of effort is shared equally across all sectors. The categories are called 'Core', 'Further Ambition' and 'Speculative':

- **Core options** are those low-cost low-regret options that make sense under most strategies to meet the current 80% 2050 target. They also broadly reflect the Government's current level of ambition (but not necessarily policy commitment).
- **Further Ambition options** are more challenging and on current estimates are generally more expensive than the Core options.
- **Speculative options** currently have very low levels of technology readiness, very high costs, or significant barriers to public acceptability. It is very unlikely they would all become available.

For each devolved administration, we have identified which options are available, and at what scale. Our analytical approach involves three steps:

- Identify the set of possible Core, Further Ambition and Speculative options for the whole of the UK.
- Determine the extent to which these options can be applied for each source of emissions in each devolved administration, and the date at which this can be achieved.
- Allocate engineered removals to devolved administrations based on the amount of removals they could achieve with domestic effort.

This method enables us to determine what each UK-wide scenario means for each devolved administration, as well as assess the year in which each devolved administration could credibly

[2] CCC (2018) *Biomass in a low-carbon economy*. CCC (2018) *Hydrogen in a low-carbon economy*. CCC (2018) *Land use: reducing emissions and preparing for climate change*. CCC (2015) *Advice on the Fifth Carbon Budget*.

achieve net-zero domestic emissions. It is important to recognise that the different levels of emissions in 2050 in our scenarios reflect different opportunities to reduce emissions rather than any difference in ambition to pursue decarbonisation.

At a UK-wide level, the specific options are listed in each chapter, by category, together with a detailed discussion of the implications which include:

- **Delivery** actions that will be needed for each option, in relation to investment and financing, technical innovation, evolution of societal or individual behaviours and leadership by key actors.
- **Timings.** The timespan over which delivery should be possible. Factors taken into account include rates of stock turnover, timescales for the development and deployment of new technologies and infrastructure, and the timeline for formulation, development and implementation of policy.
- **Costs.** The costs associated with each individual option and in aggregate compared to a counterfactual with no action on cutting emissions. Implications for investment in infrastructure are also highlighted. Our method for estimating the costs is presented in Section 4.
- **Co-benefits.** The co-benefits of action to achieve net-zero emissions, such as those related to human health and the environment.
- **Challenge.** The scale of the challenge that each option presents in terms of, for example, new infrastructure that would be needed, the readiness of supply chains and any evolution of societal or individual behaviours that may need to occur.
- **Immediate priorities.** Actions that should be made a priority now, due to the length of time needed for implementation or the fact that they are a fundamental enabler of future options. One such example is the infrastructure required for carbon capture and storage.

3. Constructing economy-wide scenarios from individual options

The analysis of decarbonisation options by sector is brought together in the form of our economy-wide scenarios, which are presented in Chapter 5 of the advice report. They have been formed using a "bottom-up" approach which allows a detailed assessment of the options relevant to each source of emissions.

Our scenarios illustrate ways in which extensive decarbonisation of the UK economy could occur, by 2050. This allows us to demonstrate whether a net-zero emissions target by 2050 is plausible, in terms of both the actions required and the costs involved. In each sector chapter we also consider the earliest date at which each Further Ambition option could be delivered, to allow an assessment of the potential to decarbonise before 2050.

The starting point for the scenarios is a "baseline": emissions projections, to 2050, in the absence of future action on decarbonisation. The Core, Further Ambition and Speculative options from all sectors have been applied to this baseline, to explore the potential to achieve net-zero GHG emissions in the UK by 2050. These scenarios are presented in detail in Chapter 5 of the advice report. Although the baseline is an important element in our approach, it is generally not a strong determinant of emissions in the net-zero scenarios - where options exist to cut emissions to net-zero they are generally deployed in full, so a higher baseline means more deployment rather than significantly higher emissions.

Our scenarios represent decarbonisation across the entire economy but have been formed by looking at options for individual sources of emissions and considering the interactions. A "top-down" analysis could also be applied which, as the name suggests, would more directly treat the economy as an integrated system rather than being composed of individual parts. One technique for such an assessment would be through the use of energy system models, aiming to present a scenario for achieving a given emissions target at the lowest overall cost.

There are merits in both approaches and they should be seen as complementary rather than alternatives. However, we believe that the bottom-up approach is the crucial first step in understanding how a net-zero emissions economy can be achieved. New evidence is still emerging on the individual options and a solely top-down approach would not allow us to investigate how this new evidence can be targeted at the appropriate emissions sources.

However, we have taken a number of steps to ensure that our scenarios represent a coherent picture at the economy-wide level:

- The residual emissions in each sector, after application of the decarbonisation options, have been carefully aggregated to obtain the level of total UK emissions in 2050. This includes ensuring that the decarbonisation of energy carriers that are used in multiple sectors (e.g. electricity, hydrogen) is accounted for once and once only.
- We have aggregated the demand for electricity and hydrogen across all sectors as a key input to our analysis of production and transportation of low-carbon electricity and hydrogen. That analysis uses (externally commissioned) modelling of the UK's electricity, natural gas, hydrogen and heat systems at both local district and national level. The model aims to minimise the total cost of long-term infrastructure and short-term operating cost (at an hourly resolution) whilst meeting carbon targets. The flexibility provided by different technologies and advanced demand control is also taken into account. This modelling allows us to identify the implications of uptake of electrification and hydrogen for construction of the necessary generation and storage facilities and networks to connect them to demands. This analysis is presented in Chapter 2 of this report.[3]
- We have also aggregated CO_2 capture requirements in all sectors to investigate the scale of storage required. This is presented in Chapter 5 of the advice report.
- We have considered the overall use of biomass so that it does not exceed limits that we judge could be sustainably-sourced and available to the UK in 2050. We have also drawn together how much biomass would be used in conjunction with CCS (BECCS) and hence the resulting volume of CO_2 that would be removed from the atmosphere. This is presented in Chapter 10 of this report on greenhouse gas removals.
- When calculating the costs of delivering the scenarios, the costs associated with decarbonising hydrogen have been allocated to the sectors which use it rather than those which supply it. For decarbonisation of electricity, the costs have been allocated to the end-use sectors only where additional electrification is required to deliver the option. Otherwise, costs are counted in the power sector. The costs of CCS have been counted only once, in each sector which requires CCS.
- We have drawn on findings from our extensive use of energy system models to date and incorporated them into this analysis.

[3] Further details on the modelling approach can be found in Imperial College (2018) *Alternative UK heat decarbonisation pathways.*

Managing uncertainties and risks in the transition to net-zero emissions

The key uncertainties, considered in detail in Chapter 5 of the advice report, are related to:

- Economic and demographic factors such as the growth rate of the economy, population growth and fuel prices.
- Social and behavioural factors that could influence future preferences.
- Costs, emissions reduction potential and development and deployment rates of low-carbon technologies.

The scale of uncertainty associated with determining a net-zero emissions target is large: the timescales involved are long and those affected could encompass all individuals and institutions in the UK. Therefore we have incorporated into our analysis a number of ways of treating uncertainty:

- We use a **conservative approach** so as to minimise the risk that the target we advise is not achievable, or only achievable at a much higher cost than our current estimate. We avoid an over-reliance on Speculative options and incorporate future anticipated changes in the emissions inventory (Box 5.1 of the advice report).
- We present **three net-zero emissions scenarios** rather than a single one, which rely on three different Speculative options. This reflects that there are potentially different ways to meet the target. Given the nature of the Speculative options, it is unlikely that all of these options will become available, but if a net-zero emissions target is to be met it is important that all three options are developed in the near-term.
- Our sector analyses generally identify **alternative** way to achieve the same emissions result. For example, more low-carbon heat could be provided by hydrogen or hybrid heat pumps and less by pure heat pumps. Whilst we have not set out specific alternative scenarios that reflect these possibilities, they indicate that there is a wide range of scenarios compatible with the emissions results in the scenarios we describe.
- **Transparency** about the main assumptions we have made, so that others can understand factors that have affected our result. A log of these assumptions is published alongside this report.
- A **review of strategies for achieving net-zero emissions** from other organisations, to challenge our own assumptions and incorporate these alternative views where appropriate. This is covered in Box 5.6 of the advice report.
- **Identification of the main uncertainties** that could affect our analysis, including an estimation of their effect on meeting the target late or not at all, or meeting it but at a higher cost.
- **Highlighting ways to manage the risk** that the future turns out less well than our scenario envisages. For example, keeping alternative ways to reduce emissions in play, until uncertainties can be reduced and the best strategy becomes clear.

4. Estimating the costs and benefits of a net-zero GHG emissions target

Chapter 7 of the advice report outlines a range of costs and benefits of achieving a net-zero emissions target in the UK, of which some could be quantified and some could not. These include additional costs of low-carbon systems relative to a high-carbon alternative (resource costs), potential economic impacts of these costs, as well as likely investment requirements. They also include a range of benefits, such as avoided climate damages and climate adaptation, benefits to human health and the environment, and potential economic benefits.

Resource costs

This technical report mainly addresses the **resource costs** of net-zero emissions scenarios across the economy. Resource costs are estimated by adding up costs and cost savings from carbon abatement measures and comparing them to costs in an alternative scenario: generally a hypothetical world with no climate action or climate damages.

For example, installing energy efficiency measures in homes (e.g. loft insulation, cavity wall insulation) has an upfront cost but reduces energy demand and emissions. There is an investment cost from installing the measures (e.g. labour costs, costs of building materials), followed by an ongoing stream of fuel and cost savings.

The total resource cost of the measure in 2050 will be the sum of its annualised capital costs plus in-year operating costs and cost savings (on the same basis - annualised capital cost savings and in-year operating cost savings). This exercise would be applied to all abatement measures in the economy to estimate total resource costs.

Resource costs presented in the sector-specific chapters of this report represent the in-year cost of all abatement measures that are in place in that year.

We also consider these costs relative to the costs that Parliament has already signed up to, in agreeing at least an 80% emission reduction target for the UK in 2050.

We often present these costs as a percentage of the projected GDP for the equivalent year, to provide context. But resource costs are not necessarily equivalent to GDP impacts. Complex dynamics will determine how resource costs and structural changes needed to achieve a net-zero emissions target feed into the rest of the economy, and these impacts will also depend on the mechanisms for delivering decarbonisation. Further details are presented in Chapter 7 of the advice report.

Chapter 2: Power and hydrogen production

Introduction and key messages

This chapter sets out the scenarios for the power sector that inform the Committee's advice on reviewing long-term emissions targets for the UK, Scotland and Wales. It also sets out our analysis of low-carbon hydrogen - the options for producing it and its role across the economy.

We find that emissions from the UK's electricity system can be reduced to almost zero whilst meeting increased electricity demands from the transport and heat sectors, potentially doubling the size of today's electricity system. Our findings in part reflect new research on the impact of heat pumps and electric vehicles on the UK's electricity system.

Reducing electricity emissions close to zero will require sustained and increased deployment of renewables and possibly nuclear power and the decarbonisation of back-up generation. Improvements in system flexibility - such as battery storage, interconnection and flexible demands - can help accommodate large volumes of variable renewables in the system at low cost. However some flexible power generation will continue to be required and will need to be decarbonised, probably via carbon capture and storage (CCS) and hydrogen.

Hydrogen (as either hydrogen or ammonia) can be used as a low-carbon fuel in the buildings, industrial, transport (including shipping) and power sectors. Producing hydrogen at low cost can be done with low emissions, by the development of advanced methane reformation facilities with CCS. Our hydrogen analysis draws mainly on our 2018 hydrogen report.[4]

The key messages from this chapter are:

- **Background.** Power sector emissions (which are almost all CO_2) come from burning coal and gas for electricity generation. The UK power sector was 15% of UK emissions in 2017 (73 $MtCO_2e$), 64% below 1990 levels. Supply of renewable power has grown rapidly in the last decade, and combined with nuclear, over half of UK electricity now comes from low-carbon sources. The UK currently produces a relatively small amount (27 TWh) of hydrogen, for non-energy uses and from high-carbon sources.
- **'Core' measures.** Renewables are cheaper than alternative forms of power generation in the UK and can be deployed at scale to meet increased electricity demand in 2050 - we therefore consider deep decarbonisation of electricity to be a Core measure. Alongside firm low-carbon power such as nuclear power and gas generation with CCS - which can reduce emissions more cheaply than the expected carbon price - emissions can be reduced by 97% compared to 1990 levels.
- **'Further Ambition' scenario.** Our 'Further Ambition' scenario meets a higher demand for electrification and deploys additional CCS and hydrogen infrastructure to decarbonise the remaining gas generation on the system, reducing emissions by 99% compared to 1990 levels. All hydrogen used in this scenario is assumed to come from low-carbon sources. That would require, for example, a fleet of methane reformation plant with CCS with a capacity comparable to the existing gas-fired electricity generation fleet.
- **Speculative options.** Alternative renewable technologies such as tidal and wave power that have not yet been commercially proven would add further options for decarbonisation of the power sector. Power sector emissions could be reduced further towards zero with

[4] CCC (2018) *Hydrogen in a low-carbon economy*.

increased carbon capture rates. Imports of low-carbon hydrogen might complement domestic production.

- **Costs and benefits.** A near zero-carbon power system costs about the same as a high carbon power system in 2050, whilst providing co-benefits which include improved air quality and low-carbon industrial opportunities. Although nuclear, CCS and hydrogen have higher costs, particularly for peak generation, that is outweighed by the cost savings from low-cost renewables and increased system flexibility. We count the costs of providing low-carbon hydrogen in the sectors that use it.
- **Delivery.** Continued rollout of low-carbon generation - using the policy instruments and principles set up under the UK's Electricity Market Reform programme - can decarbonise up to 95% of power generation. Decarbonising the remainder is likely to require low-carbon gas via a rollout of CCS and hydrogen infrastructure. Further market reforms are required to ensure that sufficient flexibility will be available and that the system will always be operable. Hydrogen requires a sustained programme of development, demonstration and then deployment, supported by a public engagement programme and prioritising low-regret opportunities, including low-carbon hydrogen production in at least one CCS cluster by 2030.

We set out our analysis in six sections:

1) Current and historical emissions from the power sector

2) Reducing emissions from the power sector

3) Scenarios for minimising emissions from the power sector

4) Costs and benefits of achieving very deep emissions reductions in the power sector

5) Delivering very deep emissions reductions in the power sector

6) Hydrogen production in a low-carbon economy

Table 2.1 summarises our scenarios for electricity, hydrogen and CCS.

Table 2.1 Summary of net-zero implications for energy system infrastructure

System-wide aggregation	Implications	Assessment of feasibility
Electricity use in 2050: 594 TWh (300 TWh in 2017)	• Generation required: 645 TWh • Peak demand: up to 150 GW • Generation capacity build rate: 9-12 GW p.a.	Requires increase in deployment of baseload and variable low-carbon power, and development of CCS and hydrogen infrastructure.
Hydrogen use in 2050: 270 TWh (27 TWh in 2017)	• Production capacity in 2050: 29 GW of advanced methane reformation plant and 6-17 GW of electrolyser capacity (depending on load factor). • Production capacity build rate: 2-3 GW p.a.	Requires low-carbon hydrogen production at scale from advanced methane reformation, as well as some electrolysis. Will also require hydrogen gas grids, or alternative transportation infrastructure, and development of CCS infrastructure.
Carbon captured and stored in 2050: 176 $MtCO_2$ (0 in 2017)	CCS infrastructure required for decarbonisation across the economy: • Hydrogen production: 46 Mt • Power generation: 57 Mt • BECCS: 35 Mt • Industry: 24 Mt • Biofuel production: 9 Mt	Requires CCS transportation and storage infrastructure at scale by the 2030s.

Source: CCC analysis.
Notes: Methane reformation is assumed produce 0.8 units of hydrogen per unit of natural gas input (80% efficiency) and capture 95% of process CO_2. Electrolysers are assumed to produce 0.74 units of hydrogen per unit of electricity input (74% efficiency), and run at load factors of 30-90%. Estimates for CCS in power and hydrogen should be considered upper bounds.

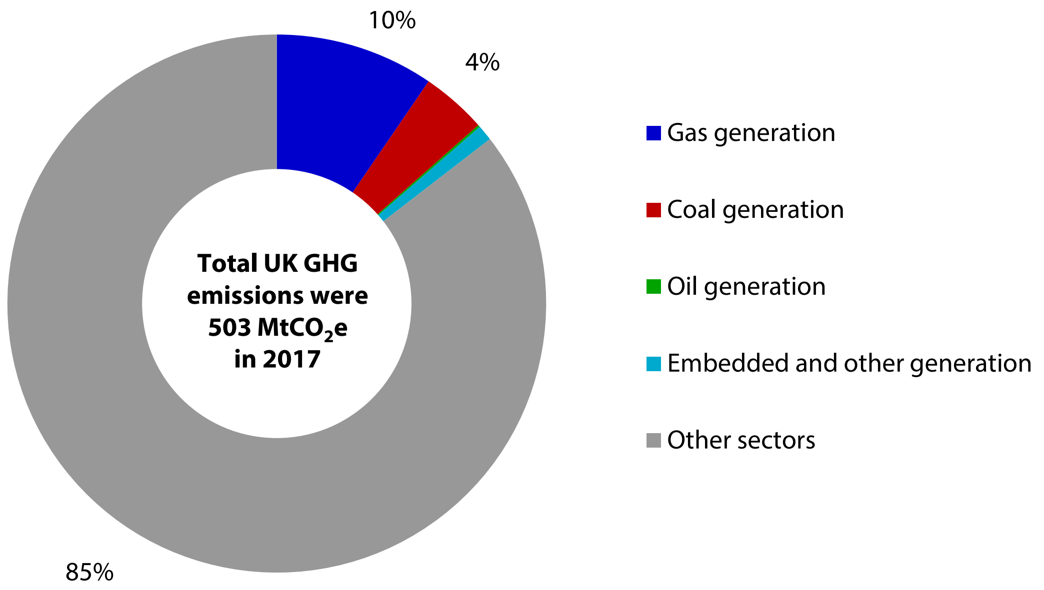
1. Current and historical emissions from the power sector

Greenhouse gas emissions from the power sector were 73 $MtCO_2e$ in 2017, 15% of the UK total (Figure 2.1)

- Power sector emissions come from burning coal and gas for electricity generation.
- Over 99% of GHG emissions in power are from CO_2, with 0.9% of emissions from N_2O and CH_4, mostly from biomass, municipal solid waste and coal power.[5]

Emissions have fallen by 64% from 1990 levels (Figure 2.2). That largely reflects a transition away from coal generation towards renewable and gas generation, and improved energy efficiency.

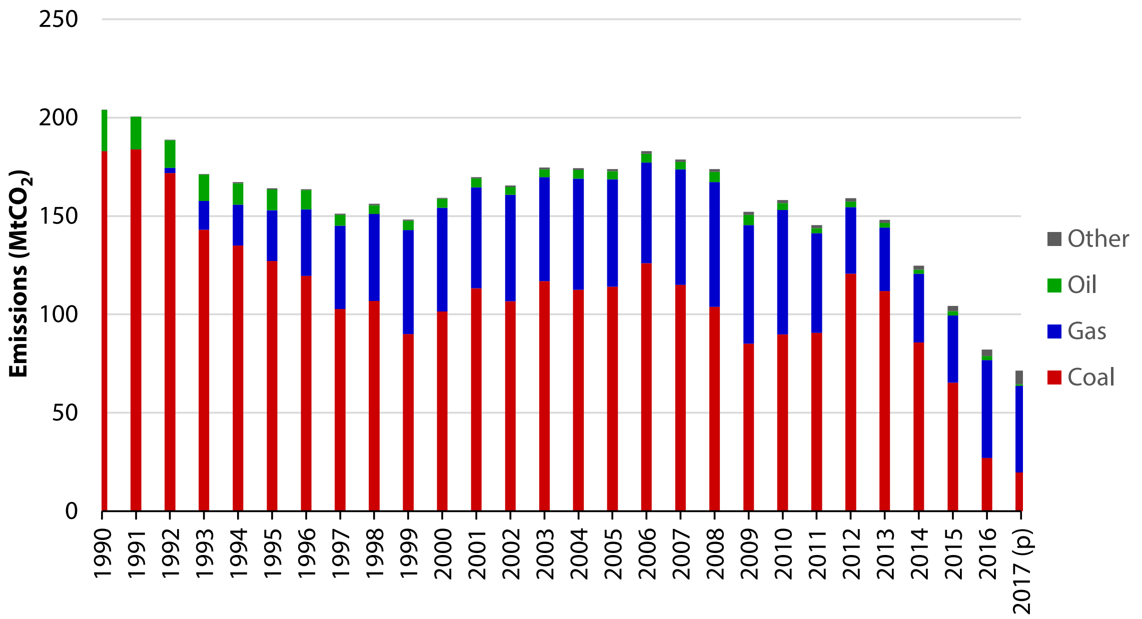
Figure 2.1. Current CO_2 emissions from the power sector (2017)



Source: CCC analysis based on: BEIS (2018) *UK Greenhouse Gas Emissions 1990-2017* and BEIS (2018) *Energy Trends: Table 5.1*.
Notes: Estimates of emissions from coal and gas generation are based on generation from Major Power Producers in BEIS (2018) *Energy Trends: Table 5.1*. Embedded and other generation includes municipal solid waste plants.

[5] As over 99% of power sector emissions are from CO_2, this chapter focuses on CO_2 emissions. Non-CO_2 emissions in our Further Ambition scenario are 0.02 $MtCO_2e$ from CH_4 and 0.03 $MtCO_2e$ from N_2O.

Figure 2.2. Emissions from the power sector since 1990



Source: CCC analysis based on BEIS (2018) *UK Greenhouse Gas Emissions 1990-2017* and BEIS (2018) *Energy Trends: Table 5.1*.
Notes: 'Other' includes emissions from municipal solid waste.

2. Reducing emissions from the power sector

(a) The current role of low-carbon sources

In 2017, 52% of electricity was supplied from low-carbon sources, up from 23% in 1990:

- 21% of electricity generation was from nuclear power
- 19% was from variable renewable sources such as wind and solar
- 11% was supplied by bioenergy (9%) and hydro power (2%)
- The remaining 48% was supplied by fossil-fuelled power generation (41% gas, 7% coal)

The majority of the UK's 9 GW of nuclear power plants are set to retire by the early 2030s, limiting the pace of power decarbonisation over this period. Without these nuclear reactors, low-carbon electricity generation would have been just 33% in 2017 (100 TWh, of 300 TWh total generation). Without additional low-carbon generation, it is likely that existing gas-fired power plants will make up the shortfall in electricity generation, increasing emissions.

(b) Potential to increase low-carbon sources to 2030

Existing Government commitments, such as the phase-out of coal power, and contracts for new low-carbon generation will increase the share of low-carbon generation from 52% in 2017 (155 TWh) to 57% in 2030 (210 TWh), whilst demand increases:

- In 2018 the Government confirmed its intention to phase out coal power – the most carbon-intensive form of large-scale electricity generation - from the UK's electricity system by the end of 2025.

- Electricity demand in our scenarios would increase by 12%, from uptake of 12.5 million electric vehicles and 2 million heat pumps, partially offset by energy efficiency improvements.
- Contracts for renewables and the new nuclear plant at Hinkley Point are set to increase low-carbon generation by 69 TWh and increasing low-carbon generation to 46% by 2030 (compared to the 33% share if retiring nuclear plants were not replaced).
- Additional funding and auction rounds have been announced for low-carbon technologies to come online during the 2020s, which could increase overall low-carbon generation by an additional 43 TWh, to 57% by 2030 (210 TWh). The next auction round commences in May 2019, with plans for subsequent auctions every 2 years, as part of a commitment to support 30 GW of offshore wind by 2030.

The Committee's power scenarios[6] for 2030 suggest low-carbon power can reach 75-85% of overall generation, at minimal additional cost to consumers, if any. This is above the 57% that has been committed and likely to require contracting for additional low-carbon generation to come online during the 2020s.

- Our 2018 Progress Report to Parliament recommended that, in addition to current commitments, a further 50-60 TWh of low-carbon generation would need to be contracted to come online by 2030, in order to reduce emissions to below 100 gCO_2/kWh (75% low-carbon generation).
- Some scenarios considered that more rapid progress with low-carbon deployment could reduce the emissions intensity to 50 gCO_2/kWh (85% low-carbon generation).
- There is a large pipeline of onshore and offshore wind, and solar PV projects that could deploy over this time period, without subsidy, but would likely still require a Government contract.
  - It is unlikely that this generation will come forward at scale without Government backed contracts, which de-risk investments and reduce project costs.
  - So-called 'merchant' renewables - projects that don't rely on a Government backed contract - will likely be limited in volume and are considered highly unlikely for offshore wind.[7]
- Further new build nuclear plants and CCS power plants could also fill the shortfall in low-carbon generation over this period.

Emissions in a low-carbon power sector in 2030 - reaching 50-100 gCO_2/kWh - would be 18-34 $MtCO_2$ in 2030.

(c) Electrification and efficiency

Electricity consumption in the UK was 300 TWh in 2017. 36% of consumption was in the residential sector, with the remainder used by businesses (34%) and industry (31%). For most households, the majority of electricity consumption is from appliance use (71%), lighting (16%), cooking (7%) and water heating (6%).[8]

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[6] CCC (2018) *Progress Report to Parliament.*
[7] See, for example, Arup (2018) *Cost of Capital Benefits of Revenue Stabilisation via a Contract for Difference.*
[8] BEIS (2018) *Energy Consumption in the UK (Table 3.02).*

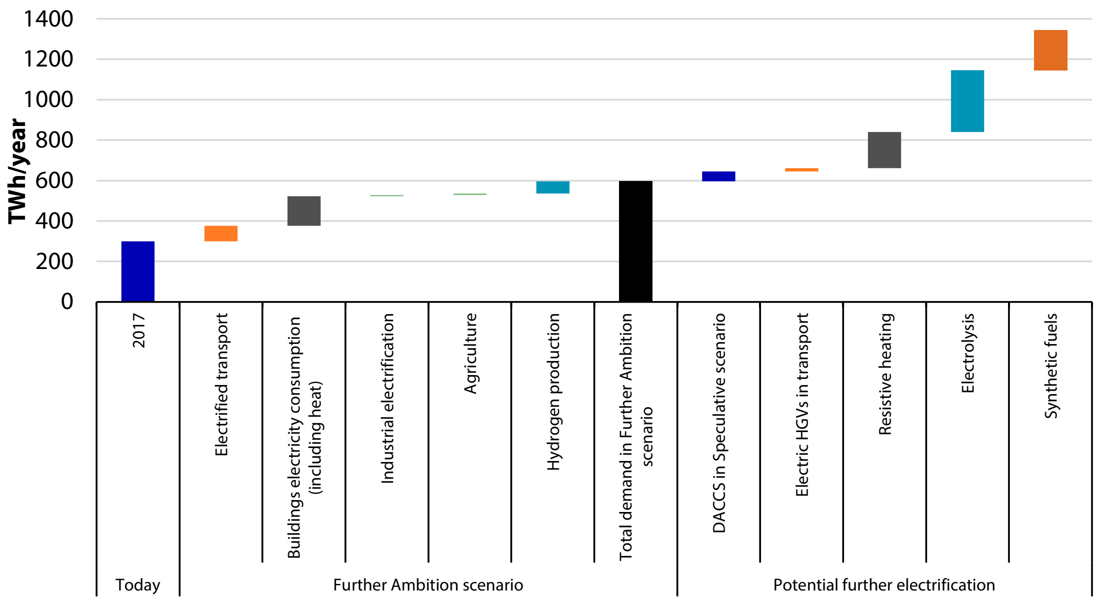
UK electricity demand has been falling in recent years as improvements in the efficiency of lights and appliances has more than offset the effects of increasing population and economic activity. We expect those trends to continue as more lights are switched to LEDs (which are seven times more efficient than incandescent bulbs and almost twice as efficient as CFLs), and with the continued rise of mobile computing (which is more efficient than fixed mains-powered computers) and continued improvements in appliance efficiency. Without new electricity demands we would expect demand to fall by 20% to 2050, to 240 TWh.

However, our scenarios in the other chapters of this report emphasise electrification as a key route to reducing emissions. Our scenarios therefore involve an increasing level of electrification as ambition increases (Figure 2.3):

- **Core:** Cars, vans, some industrial processes and some heat is electrified. These add around 200 TWh to demand, which reaches a total demand of just over 500 TWh in 2050.
- **Further Ambition:** More industrial processes and the majority of buildings heat is decarbonised through electrification (with some hydrogen) along with more vehicles, and increased electricity supplied for hydrogen production. Total demand roughly doubles to just under 600 TWh in 2050.
- **Speculative:** Further options that we consider speculative would add more electricity demand. For example, 25 $MtCO_2$ of removals from direct air capture (see Chapter 10) would add 50 TWh. Producing hydrogen solely via electrolysis could add 305 TWh.

Previous modelling for the CCC which looked at uptake of low-carbon heat and transport suggested electricity demand could more than double, to 750 TWh/year in 2050.[9]

Figure 2.3. Potential new electricity demands from 2017 to 2050



Source: CCC analysis.
Notes: Electric HGVs in transport are hydrogen fuelled vehicles switching to electricity.

[9] Imperial College (2018) *Analysis of alternative heat decarbonisation pathways.*

These scenarios assume that most of the UK's heating systems switch to electric heat pumps, but we recognise that hydrogen could play a larger role. If the heating in our scenarios were switched to hydrogen rather than heat pumps, electricity demand could be 90 TWh lower, but hydrogen production would have to be correspondingly higher (270 TWh).

It is possible that electricity demand could be higher than what is considered in our scenarios:

- Our scenarios assume that HGVs largely switch to hydrogen fuel by 2050. However, we note that electrification could also be an option – if used for all HGV segments electricity demand would be higher by around 20 TWh.
- Our scenarios assume that where heat is electrified it is done efficiently through heat pumps - which can produce more than three units of heat per unit of electricity - rather than resistive or immersion heating (which only produce one unit). If heat were electrified using resistive heating, electricity demand would be 180 TWh higher.
- Our scenarios assume that hydrogen production at scale is done via gas-reforming with CCS rather than electrolysis. If all hydrogen in our scenarios were produced via electrolysis this would increase electricity generation by over 305 TWh.
- Production of synthetic fuels for aviation using electrolytic hydrogen, and carbon dioxide produced in the UK could require 200 TWh of additional power generation in 2050.

Total electricity *demand* in the Core and Further Ambition scenarios is 511 TWh and 594 TWh, requiring *generation* of 554 and 645 TWh respectively in 2050.[10]

(d) Options for reducing emissions further

Reducing emissions towards net-zero will require continued deployment of renewables and possibly nuclear power and other low-carbon sources such as carbon capture and storage and hydrogen[11], along with avoiding emissions by improving energy efficiency or reducing demand.

The Committee commissioned an updated review of the deployment potential of low-carbon power technologies in the UK for this report.[12] These options offer the opportunity to expand low-carbon power generation many times over if needed.

Renewables

The UK has extensive wind and solar resources, which can enable a major expansion of renewable power at low cost.

- Our updated resource estimates, in line with other assessments, suggest potential for 29-96 of GW of onshore wind, 145-615 GW of solar power and 95-245 GW of offshore wind in the UK.[13]
- Public and environmental acceptability, as well as cost, will likely determine the appropriate mix of onshore and offshore renewable technologies.

[10] Electricity system losses - largely transporting electricity along networks - are assumed to be 8.5% in our analysis, based on the 2013-2017 average in BEIS (2018) *Energy Trends Table 5.5*.
[11] Hydrogen in the power sector is used to refer to hydrogen energy carriers in general, so can include ammonia.
[12] Vivid Economics and Imperial College (2019) *Accelerated electrification and the GB electricity system.*
[13] See CCC (2015) *Power sector scenarios for the Fifth Carbon Budget* and Vivid Economics and Imperial College (2019) *Accelerated electrification and the GB electricity system*.

- Offshore wind farms also face siting restrictions, such as seabed depth, and avoiding areas sensitive to wildlife (including bird migration routes), fishing and shipping routes, and military zones. However should deployment of onshore renewables on UK land be restricted, it is likely that additional offshore wind generation could compensate.
  - Our updated review suggests a technical deployment potential for up to 245 GW of fixed offshore wind in UK waters. However a more detailed, and co-ordinated review of the practical deployment potential - which considers the potential energy requirements, ecological constraints and military and shipping needs of the UK's waters - could reduce this figure significantly.
  - Our Further Ambition scenario (see section 3 (a)) involves up to 75 GW by 2050. That would require up to 7,500 turbines and could take up as little as 1-2% (around 9,000 km^2) of the UK's seabed.
    - There are currently around 2000 turbines in UK waters with an average capacity of 4 MW, a total of 8 GW. This wind fleet will need to be repowered by 2050, with the expectation that newer, larger turbines would replace them, at significantly lower cost.
    - Offshore wind turbines of 10-15 MW are being developed and are expected to have much higher productivity (from load factors of under 40% to over 58%).[14]
    - At an average size of 10 MW, a fleet of 7,500 turbines could provide 75 GW of capacity and around 370 TWh of generation.
  - The Crown Estate for England and Wales has already leased around 8,600 km^2 of seabed, equivalent to around 1% of the UK's seabed, and is considering a further leasing round. Crown Estate Scotland has leased an additional 2,800 km^2.
  - Floating wind turbines would increase the potential for deployment in deeper waters.

The UK has 8 GW of offshore wind now. The Government is committed to supporting the deployment of 30 GW of offshore wind by 2030. Deploying up to 75 GW of offshore wind in our scenarios could require at least the same capacity being installed again between 2030 and 2050 plus repowering of the existing fleet.

Historical deployment rates suggest this sort of deployment should not be a major issue.

- Deployment rates of up to 4 GW/year of offshore wind could be needed (including repowering existing sites). A further 1 GW/year of onshore wind and up to 4 GW/year of solar are deployed in our Further Ambition scenario.
- This represents an increase on recent levels for offshore wind, but not for onshore wind or solar. The UK has deployed an average of 1.7 GW/year of offshore wind, over 2 GW/year of onshore wind, and 4 GW/year of solar PV between 2012 and 2017.
- Deployment of offshore wind at up to 4 GW/year is more than double historical deployment rates. However, the offshore wind market has already scaled up from almost no deployment a decade ago. Furthermore the UK is an ever smaller share of a growing offshore wind market, suggesting increased deployment could be managed. However the increasing size of

[14] See BEIS (2019) *Draft Allocation Framework for the Third Allocation Round*, which estimated load factors for offshore wind at 58.4%.

offshore turbines and foundations may indicate a need to scale up UK based production facilities.

We are therefore confident that the levels of renewables deployment in our scenarios are achievable and that more should be possible if needed and desirable.

Whether higher deployment is desirable may depend on limits relating to intermittency:

- The variability of weather means there will be limits to the utilisation of renewables such as wind and solar, which are currently the lowest cost option for power sector decarbonisation. Our scenarios for 2030 and 2050 see variable renewables providing 50-75% of overall electrical energy production, and are contingent on system flexibility improving.
- Improvements in system flexibility can come from increased deployment of battery storage, interconnection and fast-response gas plant as well as demand-side management and improvements in system operation.

Further penetration could be possible, but will depend on system flexibility (Box 2.1).

Nuclear and CCS

'Firm' power is production which can be scheduled with confidence well in advance and may continue to play an important role in the UK's power sector. 'Mid-merit' power is provided by power stations who are able to flexibly adjust their output over short periods of time (e.g. under an hour). Power system modelling suggests that deployment of firm and mid-merit low-carbon power will continue to be important and can usefully complement variable renewable power, particularly if heat is electrified.[15]

Nuclear power and gas or bioenergy power stations fitted with CCS could provide firm and mid-merit low-carbon power, with significant deployment potential.

- The ETI has identified potential for up to 35 GW of nuclear capacity on existing nuclear sites in the UK. The total could be higher if Small Modular Reactors can also be deployed on non-nuclear sites.[16]
- CO_2 storage potential is not considered a binding constraint on CCS deployment in the UK, with total storage capacity estimated at 78 Gt (equivalent to over 150 $MtCO_2$ per year, which could support 50 GW of gas CCS plant running all year, for 500 years).[17]
- As well as in application to gas-fired power stations we consider potential use of CCS in combination with bioenergy. Deployment of bioenergy with CCS in the UK is contingent on sourcing sustainable sources of biomass. The Committee's 2018 report, Biomass in a low-carbon economy, identified scope for 45 TWh of potential BECCS generation in power.[18] The same review suggested the UK could potentially be a hub for negative emissions from BECCS, due to the level of available geological CO_2 storage in the UK, increasing potential power generation from BECCS to 200 TWh.

Deployment of firm and mid-merit capacity in line with our scenarios should be possible:

[15] See, for example, Imperial College (2018) *Analysis of alternative heat decarbonisation pathways*; Ofgem (2018) *The role of baseload*; Zappa et al. (2019) *Is a 100% renewable European power system feasible by 2050?*
[16] ETI (2015) *The role for nuclear within a low-carbon energy system*.
[17] Energy Technologies Institute (2016) *Strategic UK CCS Storage Appraisal*.
[18] CCC (2018) *Biomass in a low-carbon economy*.

- Our Further Ambition scenario includes addition of 1-2 GW/year of firm power plant in addition to 1-2 GW/year of mid-merit plant (which we assume would be CCS).
- Large buildouts of similar capacity have precedent in the UK, with 3 GW/year of coal capacity being built in the 1960s and 1970s and up to up to 3GW/year of gas plant in the 1990s.
- Similarly, neighbouring European countries have achieved sustained build outs of large power plant fleets, such as France's 5 GW/year rollout of nuclear power in the 1980s.

Our scenarios therefore represent a plausible, but more sustained, build out of firm power capacity. Alongside variable renewables this would bring low-carbon power up to 85-95% by 2050.

Costs

Renewables are cheaper than alternative forms of power generation in the UK and can be deployed at scale to meet increased electricity demand in 2050, even when accounting for the impacts of their intermittency. Non-intermittent low-carbon technologies are also expected to be cost effective.

- Building large-scale wind and solar power plants is cheaper than building and running new gas plant, and could be cheaper than running existing gas plant between now and 2050, when accounting for the costs of carbon. Estimates suggest a gas plant built in 2020 would cost on average £70/MWh over its lifetime (including £20/MWh of carbon costs), compared to £50-70/MWh for building wind and solar. [19] By 2050 we expect renewables to cost less than a gas plant, without including a carbon price (Table 2.2).
- Although variable renewables increase system requirements for capacity, balancing and backup plant and new transmission networks, studies suggest that high penetrations of renewables can be managed in the UK's electricity system, and that adding more renewables can continue to decrease the overall costs of the energy system, up to very high penetrations.[20]
- Non-intermittent low-carbon plant such as nuclear power or gas or bioenergy plant with CCS are more expensive than renewables, but have lower system impacts. Latest estimates suggest nuclear and CCS could cost £70-80/MWh for deployment in the second half of the 2020s (Table 2.2). Operating a CCS plant to provide more flexible and responsive output could increase overall operating costs. We've assumed that this could add £30/MWh to the costs of CCS plant operating in mid-merit mode.
- Intermittent renewables would be cost-effective without a carbon price. Nuclear and gas CCS would need a carbon price of around £40-80/tCO_2 when operating throughout the year. Gas CCS at mid-merit or peak would need a carbon price of £115-120/tCO_2 to be cost-effective.

[19] All cost numbers in this chapter are in £2018.
[20] See for example, Imperial College (2018) *Analysis of alternative heat decarbonisation pathways*, which modelled variable renewable penetrations of 57-74%, and Aurora Energy Research (2018) *System cost impacts of renewables*, which modelled penetrations of renewables of over 80%.

Table 2.2. Costs of low-carbon generation technologies				
£/MWh	**2020 £/MWh**	**2025-2030 £/MWh**	**2050 £/MWh**	**Abatement cost £/tCO_2**
Gas plant (excluding carbon price)	50[1]	55[1]	56[2] (39-66)	-
Renewables (wind, solar)	50-70[3]	50-70[3]	40-50[4]	-6
Firm low-carbon power (nuclear, gas CCS)	-	70-80[5]	70-80[5]	50
Mid-merit gas CCS	-	-	108[2]	115-120
BECCS	-	173[2]	205[2]	125-158

Sources:
1) BEIS (2016) *Electricity Generation Costs (converted to £2018).*
2) CCC Analysis based on Wood Group (2018) *Assessing the Cost Reduction Potential and Competitiveness of Novel (Next Generation) UK Carbon Capture Technology*. Higher BECCS costs in 2050 reflect an increase in cost of imports.
3) Renewables costs based on Baringa (2017) *An analysis of the potential outcome of a further 'Pot 1' CfD auction in GB*, Solar Trade Association (2018) *Cost reduction potential for UK large-scale PV* and BEIS (2016).
4) CCC Analysis based on Imperial College (2018) *Analysis of alternative heat decarbonisation pathways*.
5) Nuclear and CCS costs based on Wood Group (2018) *Assessing the Cost Reduction Potential and Competitiveness of Novel (Next Generation) UK Carbon Capture Technology*, and BEIS (2018) *Nuclear sector deal*.
Notes: All cost numbers in this chapter are in £2018. Costs are levelised costs for projects commissioning in that year. Abatement costs for renewables include payments for capacity.

In aggregate, given cost savings expected from renewables, large-scale deployment of low-carbon power generation technologies can decarbonise the power sector to very low emissions at little additional cost to an alternative, high-carbon power sector.

(e) Challenges in avoiding all emissions from the power sector

Peak, back-up and mid-merit generation

Alongside building further low-carbon capacity, a particular challenge for the power sector is decarbonisation of peaking and back-up generation, and to some extent mid-merit generation. This role is currently largely provided by gas power stations, which can flexibly vary their output over a short period of time.

Decarbonising 'mid-merit' gas generation will require the deployment of carbon capture and storage technology to capture emissions from gas CCS plant, or hydrogen gas plant.

- Both these options require transport and storage infrastructure for CCS[21], and potentially hydrogen, which is not currently deployed at scale in the UK. This can provide the majority of the remaining 5-15% of generation in our scenarios.
- The ability to flexibly adjust output over short periods of time will need to be built into the design of plant (and its contract and business model), a factor of particular significance in respect of CCS intended to have that capability.

Decarbonising emissions from peak demand will require a storable low-carbon fuel, such as hydrogen, as a backup source of generation for periods when electricity demand is high and/or renewable generation is low. Emissions from back-up power generation may be low in an average year, but could be higher in years with extreme cold weather periods (Box 2.3).

Peak power generation can be largely decarbonised by burning hydrogen or ammonia in gas turbines or engines, provided these low-carbon fuels can be transported to, and stored at, power stations.

- If relevant parts, or all, of UK gas networks are converted to hydrogen, power stations should be able to access and store low-carbon fuels for peak periods.[22]
- In the absence of widespread hydrogen networks, plants could locate close to hydrogen production or import facilities, or hydrogen could be transported to sites via road or rail.

Residual emissions from carbon capture and storage

Carbon capture and storage plants are not expected to capture 100% of emissions. Low capture rates could lead to large residual emissions, particularly in scenarios where CCS makes up a large proportion of generation. Our scenarios assume capture rates achieve 95%. It is important therefore for CCS policy to encourage high capture rates and for industry to deliver, otherwise the role for CCS would have to be limited.

Networks

Decarbonising the UK's electricity system whilst meeting additional electricity demands will place increasing burdens on the UK's electricity networks, requiring investment in transmission and distribution networks and making use of increased interconnection to other countries. Upgrades will be particularly important to accommodate new demands from electric vehicles and heat pumps at the distribution network level.

- Transmission network capacity will need to keep pace with developments on generation (e.g. large-scale offshore wind) and interconnections, and with the need to ensure that peak demand can be met reliably in all areas on still days as well as on windy days. Transmission investment is largely dependent on the location of new generating assets, with increased costs for renewables far from centres of demand. The costs of additional transmission

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[21] Hydrogen production via methane reformation is seen as the leading hydrogen production option in the UK, but would require CCS technology and infrastructure in order to make this low-carbon. See CCC (2018) *Hydrogen in a low-carbon economy*.

[22] Uncertainty remains around the costs, feasibility and safety of converting gas networks to hydrogen. See CCC (2018) *Hydrogen in a low-carbon economy*.

investment represent just 2% of total electricity system costs in our Further Ambition scenario.[23]

- Given anticipated uptake of electric vehicles and full and/or hybrid heat pumps, electricity demand will rise in most areas. Recent work for the Committee shows that the cost of upgrading distribution network capacity is relatively insensitive to the size of the capacity increase, provided it is well-managed, as most of the cost is in the civil works rather than the equipment (e.g. larger cables) (Box 2.2).
  – It is essential, therefore, that when grid capacity is increased, this is to a sufficient level to avoid having to upgrade the capacity again prior to 2050.
  – A relatively large expansion in capacity is likely to have low regrets, 'future-proofing' the network to enable greater electrification if necessary and/or enabling demand to respond more readily to variations in low-carbon electricity supply.
- Building long-distance high voltage interconnectors to other countries can also help share electricity system resources, and improve system flexibility.

[23] The Transmission Operator, National Grid, produces a 10 year forecast, reviewing onshore transmission needs, see National Grid (2018) *Network Options Assessment*. The costs of offshore transmission for offshore wind farms are borne by the project developers.

Box 2.1. Electricity system flexibility

Electricity systems need to match electricity supply to electricity demand in real-time. As more weather-dependent sources of electricity supply come online, matching supply to demand can become more challenging. Separately, new electrified demands from electric vehicles and heat pumps can offer opportunities to make use of variable renewable supply. Both would benefit from increased system flexibility.

Increasing renewable deployment can have four major system impacts:

- **Meeting peak demand.** There may be periods where electricity demand is high and renewable output is low, meaning backup capacity may need to be installed, to ensure demand can be met at all times.
- **Balancing and reserve.** Plant may need to be held in reserve to balance short-term variations in renewable output or changes in electricity demand.
- **Making use of generation.** There may be periods where renewable output exceeds demand. If this output can't be used it would effectively be wasted, and have no value.
- **Networks.** Renewables - such as wind in Scotland, or in the North Sea - may be located far from where electricity is needed. Additional investments in electricity networks could be required to transport this electricity.

Market reforms are underway to reduce barriers to entry for flexibility providers in the UK's electricity markets. This will allow for further deployment for demand-side management, battery storage, interconnection and flexible gas generation that can help integrate variable renewable resources into the UK's electricity system. Improvements in system flexibility have potential to bring electricity system costs down by £3-8 billion/year by 2030 and £16 billion/year by 2050. New electricity demands - such as electric vehicles and heat pumps - can help reduce overall system costs, provided they make use of 'smart' charging (see Box 2.2). There is also potential for electric vehicles to provide electricity back to the grid at times of high demand, reducing the need for extra storage or back-up capacity.

Provided system flexibility continues to improve, evidence suggests that renewables can be accommodated at costs of £10/MWh at penetrations of around 40% and £20/MWh or more at penetrations of 50% or above (compared to a wind farm at say £50/MWh). Penetration beyond these levels is contingent on being able to make use of renewable generation. The marginal costs of increasing renewable generation from the same source will increase over time, implying a high, but real, limit to the deployment of renewables within the UK's electricity system.

A technical annex is published alongside this report, summarising the challenges that are likely to arise at higher levels of renewable penetration.

Source: Imperial College for the CCC (2015) *Value of flexibility in a decarbonised grid and system externalities of low-carbon generation technologies*; Imperial College for the CCC (2018) *Analysis of alternative heat decarbonisation pathways.*
Notes: See CCC (2017) *Progress Report to Parliament* for further information on the importance of system flexibility, and barriers to deployment.

(f) The strengthened evidence base used in this report

In this report, we have drawn on the evidence published in and alongside recent CCC reports – including advice on the Fifth Carbon Budget and reviews of Hydrogen, Biomass and Heat, as well as a technical note on intermittency published alongside this report.[24]

- Modelling conducted for the Committee's hydrogen report suggested that gas has a role to play in power sector decarbonisation, as a complement and backup to large volumes of variable and baseload low-carbon generation. This conclusion is similar to that by others (see below).
- The same modelling also considered the impacts of transport and heat electrification on the power sector, noting that significant investments in new low-carbon power generation, back-up gas plant and electricity networks will need to be made in order to satisfy these new demands.[25]
- The Committee's hydrogen review provided new evidence on the potential use of hydrogen fuels for power generation, suggesting that further research was required into the feasibility of hydrogen use in gas turbines for power generation. This included considering whether new gas-fired plants in the UK could be made 'hydrogen-ready'.
- Previous CCC reports have provided evidence that the costs of integrating variable renewables into electricity systems are manageable, and increasing system flexibility can help accommodate high levels of variable low-carbon generation. [26] This report is accompanied by a technical annex which summarises and advances this analysis.
- The Committee's 2018 biomass report recommended BECCS as a source of greenhouse-gas removals and low-carbon electricity, with the potential to provide up to 45 TWh/annum of electricity generation.[27]

We have also commissioned and undertaken new analysis for this report (Box 2.2).

- Work by Vivid Economics and Imperial College has considered the energy system implications of accelerated uptake of electric vehicles and hybrid heat pumps, compared to the fifth carbon budget Central scenario, with a focus on network implications.
- They concluded that network upgrades in the 2020s should be able to accommodate future uptake of electric vehicles, and potentially electrified heat. Oversizing these upgrades to accommodate future upgrades represents a small proportion of overall costs. Additionally, deploying system flexibility (such as demand-side management, and battery storage) is key to minimising the network cost upgrades required for new electricity demands.

Our findings and assumptions are in line with those of other recent literature:

- Several analyses have considered the future of the UK power sector, and consider that combined shares of up to 75-95% of firm and variable low-carbon electricity is technically

[24] CCC (2015) *The Fifth Carbon Budget*; CCC (2018) *Hydrogen in a low-carbon economy*; CCC (2018) *Biomass in a low-carbon economy*; CCC (2016) *Next Steps for UK Heat Policy*.
[25] Imperial College (2018) *Analysis of alternative heat decarbonisation pathways.*
[26] CCC (2015) *Power Sector Scenarios for the Fifth Carbon Budget*, and CCC (2017 and 2018) *Progress Report to Parliament*.
[27] CCC (2018) *Biomass in a low-carbon economy (Figure 5.9).*

possible, delivering electricity to consumers without compromising on the reliability of the electricity system.[28]

- The same studies suggest the remaining 5-25% of power involves some gas-based power generation, as a cost-effective complement and backup to baseload and variable low-carbon sources of power.

We reflect this new evidence along with our existing evidence base in our scenarios in section 3.

[28] See, for example, European Commission (2018) *2050 long-term strategy;* Aurora Energy Research (2018) *System cost impacts of renewables;* Bloomberg (2018) *New Energy Outlook;* Energy Transitions Commission (2017) *Low-cost, low-carbon power systems;* Eurelectric (2018) *Decarbonisation pathways.*

Box 2.2. New research on the challenges associated with accelerated electrification

Deployment of hybrid heat pumps and electric vehicles (EVs) are key options for decarbonisation of buildings and transportation. We commissioned Vivid Economics and Imperial College to consider the impacts on the UK's electricity system of a rapid rollout of these technologies, with the required electricity generation met by low cost renewables. Specifically, they investigated the feasibility of:

- Accommodating accelerated electrification at manageable cost;
- Carrying out the necessary reinforcements to distribution networks; and
- Deploying the necessary generation capacity and demand response needed to accommodate accelerated electrification.

They concluded that adding electricity demand for 10 million hybrid heat pumps and an additional 15 million EVs by 2035 can be done at low cost:

- Electric vehicles and hybrid heat pumps are inherently flexible and are unlikely to increase the cost of electricity. If this demand is met by renewables, the cost of electricity could decrease.
- Provided they are used efficiently, hybrid heat pumps could deliver carbon savings almost as large as electric heat pumps, but with significantly lower impact on the cost of electricity.
- 'Smart' charging of electric vehicles could see 80% of vehicles charging in non-peak periods, avoiding significant costs.
- Significant new renewable generation capacity is needed to accommodate rapid uptake of electric vehicles and hybrid heat pumps. Over the period to 2035, up to 35 GW onshore wind, 45 GW offshore wind and 54 GW solar PV could be needed. Further deployment is likely to be needed over the period to 2050. The UK's onshore wind, offshore wind and solar PV resource are likely to be more than adequate to deliver an expanded and decarbonised electricity system to 2050.

Furthermore, they concluded that significant network upgrades will be required to meet these new demands. Deployment of these networks will need to take place at scale in the 2020s, and should reflect that oversizing these networks to meet future electricity demands is a 'low-regrets' option:

- Significant network reinforcements could be needed to accommodate rapid uptake of electric vehicles and hybrid heat pumps. Overall, rapid uptake of electric vehicles and hybrid heat pumps could increase the costs of maintaining and reinforcing distribution networks by up to 40% by 2035. However, distribution costs would still account for less than 10% of electricity system costs.
- Network reinforcements are costly and disruptive. Further, the costs of over-sizing network infrastructure are very low, as cable capacity accounts for just 8-10% of upgrade costs. As a result, future-proofing investments by over-sizing network infrastructure is a very low-regrets option, and could avoid up to £34 billion of network expenditure.
- Uncertainty over electric vehicle and heat pump uptake is a major challenge to accurately projecting network investment needs. The RIIO price control framework should be flexible enough to allow distribution network operators to respond to emerging evidence on future uptake, even during a single price control period.
- Batteries and demand response can reduce the need for distribution network reinforcement. The RIIO price control framework should continue to incentivise distribution network operators to reduce total expenditure (TOTEX) and make use of these solutions where possible.

Source: Vivid Economics and Imperial College (2018) *Accelerated electrification and the GB electricity system.*

3. Scenarios for minimising emissions from the power sector

Our scenarios for electricity production are based on whole energy system modelling, which meets real time requirements for electricity production and demand in a decarbonised energy system.[29] We consider emissions from energy production to be positive emissions only, with any negative emissions from greenhouse gas removals counted elsewhere in the economy (see Chapter 10).

We first set out the scenarios and then consider how quickly scenarios with emissions close to zero could be delivered.

(a) Scenarios for cutting emissions towards zero

In this section we summarise the options to reduce emissions. We split these into 'Core', 'Further Ambition', and 'Speculative' options that were outlined in Chapter 5 of the CCC's (2019) Net Zero advice report.

- **Core options** are those low-cost low-regret options that make sense under most strategies to meet the current 80% 2050 target. For most the Government has already made commitments or begun to develop policies (although in many cases these need to be strengthened).
- **Further Ambition options** are more challenging and/or more expensive than the Core options, but are all likely to be needed to meet a net-zero target.
- **Speculative options** currently have very low levels of technology readiness, very high costs, or significant barriers to public acceptability. It is very unlikely they would all become available. Some of these options would be required to reach net-zero GHG emissions domestically.

Figure 2.4 shows how these options would reduce emissions from the power sector.

Core scenario

In the Core scenario, over 95% of electricity generation (which grows as transport and heat electrify) is provided by renewables, nuclear power and CCS, given their relative cost-effectiveness.

- Meeting new demands can largely be done by building 1-2 GW of firm low-carbon power capacity, and 5-8 GW of variable renewables per year. This can provide 615 TWh of power generation in 2050 (95% of generation), and would leave residual CCS emissions of around 2 $MtCO_2$ (rather than around 180 $MtCO_2$ if it was all provided by unabated gas-fired generation).
- The falling costs of renewables mean that this mixture of firm and variable power has an average cost of around £60/MWh in 2050. This is in line with the expected cost of unabated gas generation (before a carbon price is applied), and therefore involves limited additional cost. For comparison, average wholesale electricity prices in 2018 were £57/MWh.[30]

[29] See Imperial College (2018) *Analysis of alternative heat decarbonisation pathways*. The CCC's analysis is based on the 'Hybrid 10 Mt' scenario which includes widespread electrification of surface transport via electric vehicles, and of heat in buildings, via hybrid heat pumps.
[30] Aurora Energy Research (2019) *EOS platform*.

- The Core scenario in 2050 would require a significant fleet of gas-fired plant operating at mid-merit. This could be partly decarbonised by capturing its emissions, using CCS, or burning a low-carbon fuel such as hydrogen.
  – Modelling by Imperial College (2018) for the Committee suggests a need for 16-43 GW of mid-merit gas plants, operating in over 50% of hours (but individually at load factors of 20-25%) providing 5-15% of generation. If met by unabated gas plants this would result in 9 $MtCO_2$ of emissions.
  – This represents a decrease in mid-merit generation compared to today, due to large volumes of firm and variable low-carbon power being on the system, increased interconnection to other countries, and use of hybrid heat pumps to avoid the need for electricity to provide peak heat requirements (which could double overall generation from mid-merit plant).
  – Our Core scenario decarbonises half of this generation, requiring up to 8-22 GW of low-carbon mid-merit plant. This implies building up to 0.4-1 GW/year of CCS power stations between 2030 and 2050 and reduces emissions to less than 5 $MtCO_2$/year.
  – Latest estimates for CCS plants suggest abatement costs of £80-120/tCO_2, with the higher end of the range reflecting lower load factors.
- In the Core scenario, generation from backup plant using unabated gas plants for electricity generation during peak periods incur emissions of around 0.3 $MtCO_2$.

Emissions in the Core scenario would be around 7 $MtCO_2$ (2 $MtCO_2$ of residual emissions from CCS plants and 5 $MtCO_2$ of emissions from unabated gas plant). This implies a carbon intensity a little over 10 gCO_2/kWh. The average abatement cost would be £17/tCO_2.

Further Ambition options for cutting power emissions to 2050

Our 'Further Ambition' options would reduce emissions close to zero, whilst meeting increased electricity demand. That could be needed to deliver the UK's existing 2050 target and will almost certainly be needed for a net-zero target.

- Further electrification in the Further Ambition scenario could add an additional 83 TWh of power demand, requiring 90 TWh of power generation.
- Increased deployment of CCS plant in the Further Ambition scenario - from 0.5-1 GW/year to 1-2 GW/year between 2030 and 2050 - could see emissions from mid-merit power reducing towards zero by 2050, at abatement costs of £115-120/tCO_2.
- Particularly for mid-merit plants operating at lower load factors (and possibly for all), it may be more cost-effective to produce hydrogen separately using CCS and to use that as a fuel for electricity generation, rather than to build dedicated CCS power plants. That would also allow peak and back-up generation to be decarbonised (Box 2.3).

Emissions in the Further Ambition scenario would be 3 $MtCO_2$ (almost entirely from residual CCS emissions). The average abatement cost would be £19/tCO_2.

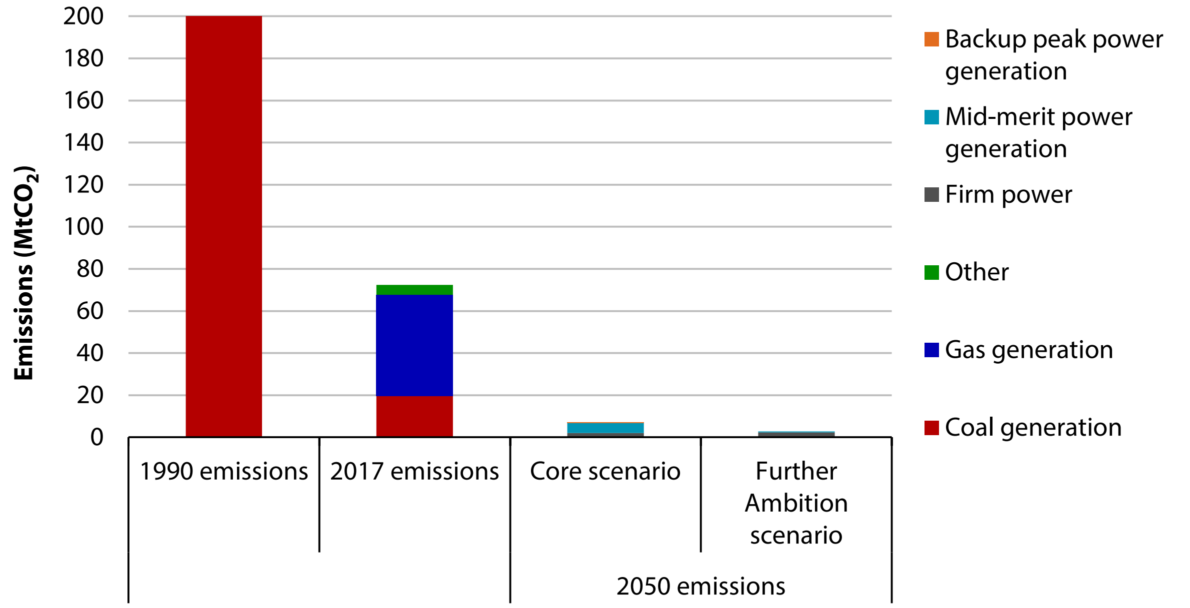
Box 2.3. Decarbonising back-up power generation

A key component of maintaining security of supply in the UK's electricity system entails ensuring that electricity supply can be provided when electricity demand is high, and renewable output is low. Backup gas-based power plants that are available at all times, but run at low levels over an average year can be used to provide electricity during these periods. If unabated, these plants could produce emissions of up to 0.3 $MtCO_2$/year on average in our scenarios, but potentially significantly higher in periods of sustained cold weather and low renewable output.

- Modelling by Imperial College suggests a need for around 40-120 GW of backup gas plant by 2050, operating in over 15% of hours but providing less than 1% of generation.[1] This capacity is built to maintain electricity supply during a period of multiple days of cold weather and low renewable output. Gas generation during this period is a small proportion (<1%) of overall generation, and if unabated (as in our Core scenario) could incur emissions of around 0.3 MtCO2. There may be occasional periods when demand for electricity is high and renewable output is low for more sustained periods, particularly if relying on electricity for heat.[2] This could increase these emissions significantly.
- Decarbonising these power plants would require the deployment of backup gas plant that can store and burn low-carbon fuels such as hydrogen (or ammonia) during periods of low wind and solar output and high electricity demand. This could reduce peak power sector emissions to zero at abatement costs of around £120/tCO_2 (emissions associated with hydrogen production would be 0.02 $MtCO_2$).
- Decarbonising backup power generation would require the development of transportation and storage for low-carbon fuels such as hydrogen or ammonia (as well as CCS infrastructure).

Source: Imperial College (2018) *Analysis of alternative heat decarbonisation pathways.*
Notes: 1) The capacity range is determined by whether heat is decarbonised using hydrogen (little impact on the electricity grid) or electricity (high impact, and corresponding capacity). Capacity could also be reduced through increased system flexibility, or electricity storage.
2) For example, gas networks are currently expected to maintain supply of gas for a '1-in-20' winter.

Figure 2.4. Scenarios for very deep emissions reductions from the power sector



Source: CCC analysis based on the capacity and generation mix in the "Hybrid 10 Mt" scenario of Imperial College (2018) *Analysis of alternative heat decarbonisation pathways.*
Notes: 'Other' includes emissions from oil generation and municipal solid waste.

Indicative generation mix

It is impossible to be precise about the generation mix that will best meet the increased demand in our scenarios at least cost while maintaining security of supply. Our scenarios make assumptions over a possible mix in order to assess feasibility and cost. They have the following features:

- **Renewables dominate.** Currently, variable renewables (e.g. onshore wind, offshore wind and solar PV) appear to be the lowest cost low-carbon generation options with the lowest barriers to deployment. Our previous analysis of intermittency demonstrated that intermittent shares of up to 50% are manageable within the constraints of managing the grid and avoiding high costs from under-utilised capacity, with shares of over 50% possible with improved system flexibility.[31] We assume that renewables contribute at least 59% of generation in 2050, though this should not be considered an upper bound for renewables deployment in the UK.[32]
- **BECCS plays a role.** Our Biomass Review concluded that where possible biomass should be used in conjunction with carbon capture and storage (CCS) to maximise the resulting carbon savings/sequestration. It is not clear now whether BECCS capacity would be most effectively used to produce electricity, hydrogen or aviation biofuels. For the purposes of our scenarios we assume it is used in the power sector. Our 2050 Further Ambition scenario therefore has 5

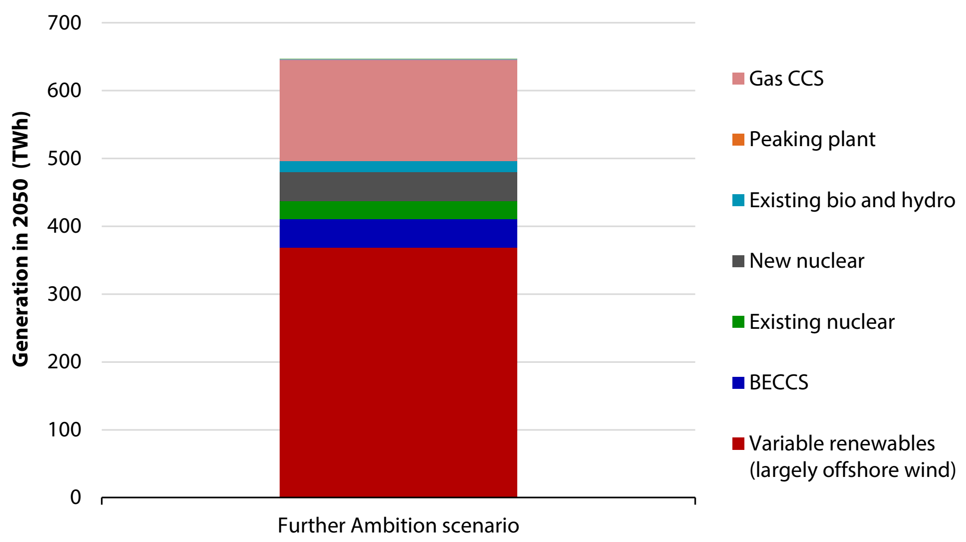
[31] See CCC (2015) *Power Sector Scenarios for the Fifth Carbon Budget*; CCC (2018) *Progress Report to Parliament* (Box 2.2).
[32] This includes generation from hydro plant and energy-from-waste plant, equivalent to 2% of generation.

GW of BECCS providing 41 TWh (6% of generation) and sequestering 35 $MtCO_2$ of emissions annually (see Chapter 10).

- **Nuclear plays a role.** A 3.2 GW nuclear plant is currently under construction at Hinkley Point C and can be expected to operate well beyond 2050, implying a minimum nuclear contribution of 26 TWh (4% of generation) in 2050.[33] New nuclear sites at Sizewell C and Bradwell could increase this to 11%.
- **Hydrogen or ammonia provide back-up.** Our scenarios involve a large amount of back-up capacity that only operates for a small proportion of the year – when variable renewable generation is low and demand is high and storage cannot close the gap. This is less than 1% of generation. We assume that most of this capacity is provided by open-cycle gas turbines or other flexible gas plant, fuelled by hydrogen and/or ammonia, which in turn we assume is produced from methane reforming with CCS.
- **We assume gas CCS meets the rest of demand.** There are multiple possibilities for the remaining 23% of generation. Some analysts have proposed scenarios where renewables provide much more than 60%.[34] A further 15 GW of nuclear plants could be built, using only around half the space for existing sites identified by the ETI. Our scenarios assume that the remaining 23% of generation comes from gas-fired plants fitted with CCS. That is a conservative assumption for our purposes, given that gas CCS has some residual emissions (which renewables and nuclear do not), and higher expected costs than renewables.

Figure 2.5 illustrates the potential mix for the Further Ambition scenario in 2050 in terms of capacity and generation.

Figure 2.5. Illustrative generation mix for a low-carbon power system in 2050



Source: CCC analysis based on the capacity and generation mix in the "Hybrid 10 Mt" scenario of Imperial College (2018) *Analysis of alternative heat decarbonisation pathways.*
Notes: The role of gas CCS in providing firm power is illustrative and could be replaced by nuclear power or alternative renewable technologies, reducing residual emissions.

[33] Additionally the 1.2 GW plant currently operating at Sizewell would run beyond 2050 if it matches the lifetimes achieved by other UK nuclear plants.
[34] Aurora Energy Research (2018) *System cost impacts of renewables*.

Alternative options for cutting power emissions

Our scenarios are focused on the emissions cuts that can be achieved. In many cases there would be alternative technical or behavioural approaches that could deliver them and it may not be necessary now to decide between them, though alternatives could well result in marginally lower emissions.

- Residual power sector emissions in our scenarios are from capturing just 95% of the emissions produced by generation from gas CCS plant. Increased electricity system flexibility, or new forms of energy storage, could allow for further variable renewables to be integrated into the system, reducing requirements for gas CCS plant on the system. Deployment of further nuclear power or alternative renewable technologies could also reduce emissions further.
  - Our scenarios are optimised around a generation mix that minimises the need to curtail renewable generation when output exceeds demand. Adding renewables above this optimum level could reduce their value, increasing costs. New forms of energy storage - such as storage with multi-day duration, or converting electricity to other energy vectors like hydrogen - could improve the economics of renewable generation. Alternatively, continued falls in the cost of renewable generation could reduce the overall cost of installing renewables, even if some generation is wasted.
  - Our scenarios include three new nuclear plants coming online by 2050. Further deployment of nuclear power could substitute for gas CCS plant.
  - Our scenarios focus on deployment of solar PV and wind power as the lowest cost technologies currently. Deployment of alternative renewable technologies such as wave and tidal power could reduce the variability of overall renewable generation, and reduce emissions further.
- Reduced energy demand (i.e. through improved energy efficiency) could reduce the amount of power generation that is required, reducing emissions.
  - Our scenarios include electrical efficiency improvements in common appliances and lighting, reducing electricity demand by 61 TWh per year by 2050. There could be potential to reduce this further.
  - Our scenarios include improvements in heat pump efficiency over time, towards an average heat pump coefficient of performance (COP) of three in 2050 (providing three units of heat per unit of electricity). Further improvements in heat pump efficiency could reduce demand from electrified heat.
  - Our transport scenarios assume a shift away from car use towards public transportation or walking and cycling, reducing energy demand. Further shifts away from car use - or potential changes through automated transportation - could reduce demand for transport, reducing overall electricity requirements.

Speculative options for cutting power emissions to 2050

'Speculative' options across the economy could further reduce power sector emissions.

- Our 'Core' and 'Further Ambition' Scenarios in the power sector assumed that where CCS technology was implemented, 95% of the combustion emissions could be captured. The International Energy Agency suggests that it may be possible to increase these capture rates to close to 98 or 99% without significantly increasing costs.[35] If 99% of emissions can be captured by CCS technologies in the power sector, this could reduce residual power emissions by 80%, to 0.6 $MtCO_2$.[36] Alternatively, a greater share for nuclear and renewable generation or production of hydrogen from electrolysis could avoid these residual emissions.

- Our scenarios assume enough electricity is produced in the UK to meet all of the UK's electricity demand. The UK could co-operate with other countries to import low-carbon electricity. Previous and current proposals have considered importing solar power from the Sahara, importing low-carbon geothermal power from Iceland or creating an offshore wind hub in the North Sea, in collaboration with Holland and Germany.
- Imports of low-carbon hydrogen are not considered in the CCC's scenarios, but could materialise over the period to 2050. This could reduce the need for domestic hydrogen production, some of which is from electrolysis and requires electricity input and some of which uses CCS and therefore involves residual emissions. Similarly, improvements in the efficiency of electrolysers could reduce electricity demands from these sources.[37]
- Our scenarios assume that 8.5% of total electricity generation is lost between the point of generation and electricity users. Opportunities may arise to reduce electricity system losses, with the potential to reduce emissions.

Some 'Speculative' options across the economy - such as Direct Air Capture and Storage (DACCs) technologies, and synthetic fuel production - could increase electricity demand. These are covered in section 2 (c).

(b) Timing for cutting emissions towards zero

The fifth carbon budget (covering 2028-2032) already requires significant progress towards these net-zero scenarios. The cost-effective path that the Committee have identified, and that can be delivered through existing policy with some strengthening, includes an increase in the share of low-carbon electricity generation from 50% today to over 75% by 2030, whilst improving system flexibility.

With a committed and well-designed policy effort it would be possible to deliver the Further Ambition options set out above in full by around 2050 (Table 2.3):

- Our power sector scenarios for 2030 include 75-85% of electricity generation being met through low-carbon sources. Continued deployment of low-carbon electricity generation will allow this share to be maintained between 2030 and 2050.
- The Government is currently committed to having the option to deploy CCUS at scale during the 2030s, and is exploring delivery models for the transport and storage infrastructure that is required to take the CO_2 from the point of capture and sequester it on a long-term basis. Any delay to having this infrastructure in place by 2030 is likely to significantly hamper the rate of decarbonisation that can be achieved in the power sector.
    - Our scenarios continue to see a role for gas generation beyond 2030. Without the opportunity to decarbonise this gas, it will continue to run unabated. It is likely that gas

[35] IEAGHG (2019) *Towards zero emissions CCS*.
[36] Alternatively, capture rates could be lower. See section 5 (b).
[37] See CCC (2018) *Hydrogen in a low-carbon economy* for more detail. Our scenarios assume electrolysers use 1.35 units of electricity per unit of hydrogen, some estimates suggest this could be reduced to around 1.1 units.

plant built between now and 2050 will need to decarbonise in order to continue operation.

- A sustained policy effort - including funding models for baseload and flexible CCS power plant, and for carbon transportation and storage infrastructure - can see mid-merit power generation be largely decarbonised by 2040-2050.

- Decarbonising backup power generation will require the production of low-carbon fuels and infrastructure to transport and store these fuels for use at times of peak demand. Successful development of this infrastructure could see the small level of emissions from peak power generation decarbonised by 2050.

This assessment allows for the various limiting factors on a realistic speed of change, without requiring significant levels of early capital scrapping:

- The majority (82%) of the UK's non-renewable capacity was built before 2005 and is expected to close by 2050. The challenge in the power sector is about building new capacity, not converting existing capacity.

- Deployment rates of power generation technologies are not expected to be a major barrier to progress (see section 2 (d)).

Achieving deep emissions reductions in the UK's power sector is contingent on CCS infrastructure and deployment support being available by 2030. This can enable both the use of gas and bioenergy with CCS for power generation, and the production of low-carbon hydrogen for use in gas plants (and potentially some mid-merit plants).

Figure 2.6 sets out the timing for when key changes would need to occur.

Figure 2.6. Timing of key decisions and changes to deliver the net-zero scenarios for the power sector

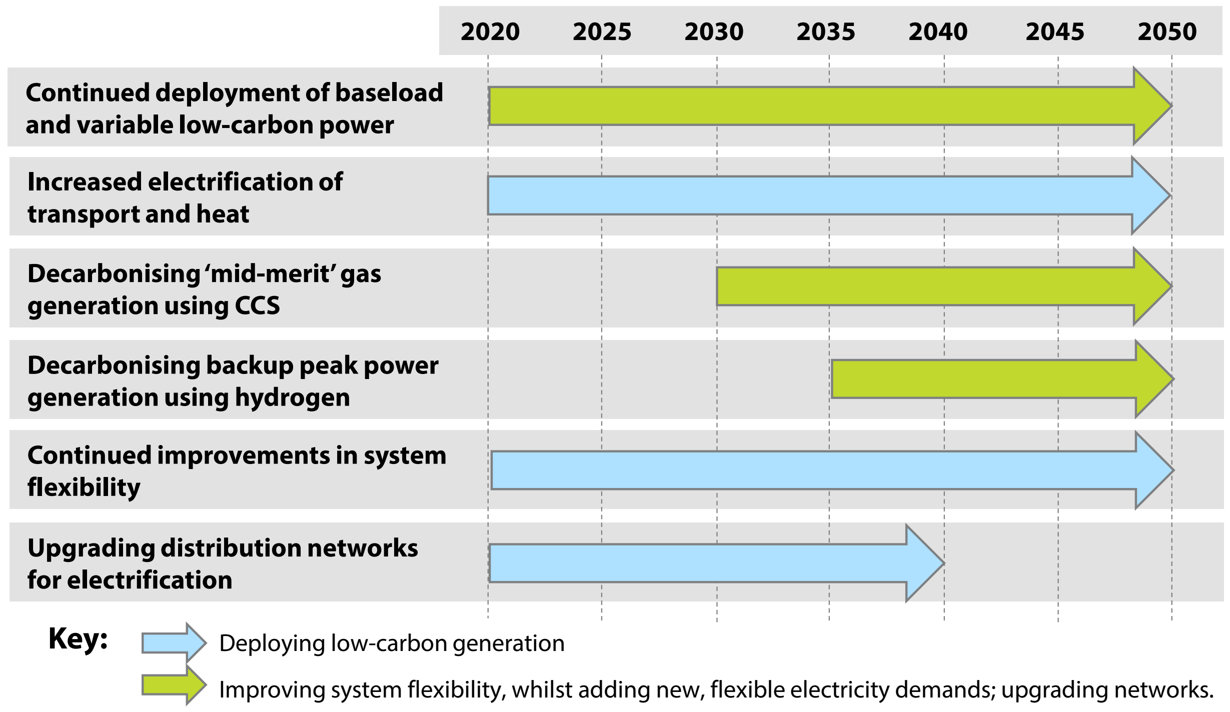


Table 2.3. Opportunities to reduce emissions from power towards zero				
Source	**2030 5CB residual emissions ($MtCO_2$)**	**Further Ambition residual emissions in 2050 ($MtCO_2$)**	**Earliest date for Further Ambition emissions**	**2050 cost £/tCO_2**
Renewables	0	0	2030-2050	-6
Firm low-carbon power	0	2.3	2030-2050	48
Mid-merit generation	16-30	0.6	2040-2050	115-120
Backup peak power generation	2-5	<0.1	2050	120

Source: CCC analysis.
Notes: £/tCO_2 cost figures represent levelised costs of abatement of the measures in place in 2050, and are averaged across multiple abatement measures applied to the same emission source.

4. Costs and benefits of deep emissions reduction in the power sector

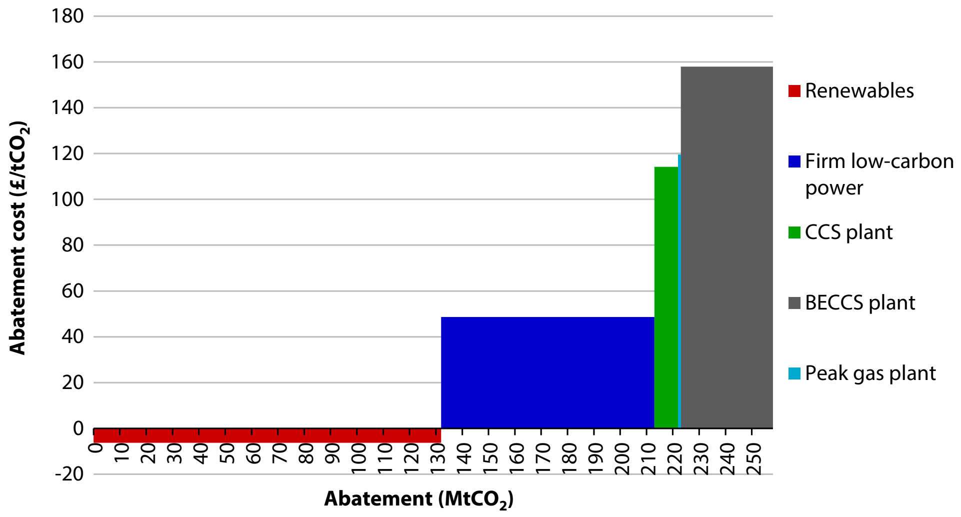
Our overall approach to assessing costs and benefits is summarised in Chapter 1 of this report and set out in full in Chapter 7 of the accompanying advice report.

Some of the low-carbon options included in our net-zero scenario for power would avoid costs compared to the high-carbon alternative (i.e. gas-fired power generation), whilst others are likely to be more expensive (Figure 2.7)

- Some renewables are cheaper than alternative forms of power generation in the UK and can be deployed at scale to meet increased electricity demand in 2050. It is already cheaper to build and run new wind and solar farms in the UK than to build and run new gas-fired capacity.[38] Between 2020 and 2050 building new renewables may become cheaper than operating existing gas plant.
- Current estimates are that nuclear costs will continue to be higher than unabated gas generation.
- CCS and hydrogen power plants, which have natural gas as an input, will be more expensive than unabated gas generation that does not face a carbon price that reflects the cost of its emissions.
- Other power generation options, such as wave and tidal technologies, and floating offshore wind technologies are currently higher cost than other power generation options, though potential has been identified for the costs of these technologies to reduce.[39] These options are not included in the Core or Further Ambition scenarios.

[38] We set out our assumptions on gas prices and costs of generation for different options in section 2.
[39] ETI (2015) *Insights into Tidal energy*; ETI (2015) *Wave Energy: Insights from the Energy Technologies Institute*.

Figure 2.7. Marginal abatement cost curve for deep emissions reductions from the power sector in the Further Ambition scenario



Sources: CCC analysis based on Wood Group (2018) *Assessing the Cost Reduction Potential and Competitiveness of Novel (Next Generation) UK Carbon Capture Technology*, CCC (2018) *Hydrogen in a low-carbon economy*, Imperial College (2018) *Analysis of alternative heat decarbonisation pathways*.
Note: Abatement from 'negative emissions' from BECCS is not counted in the power sector, nor are the costs.

Together, these costs imply a total annual cost compared to a theoretical counterfactual without any action on emissions - a power system based on unabated gas generation - of £4 billion/year (in real 2018 prices, around 0.1% of expected 2050 GDP) for cutting emissions from the power sector to close to zero in line with our Further Ambition scenario in 2050.

- A gas-based electricity system that generated 645 TWh per year of electricity demand in 2050 would cost around £46 billion/year to build and run, whilst producing 225 $MtCO_2$ of emissions. Our estimates suggest that reducing emissions to 3 $MtCO_2$ would cost an additional £4 billion/year.
- Our cost estimates assume a counterfactual where power generation is met by unabated gas at £56/MWh, based on the central values from the scenarios published by the Government for future gas prices. However, future gas prices are hard to predict. If gas prices were at the low end of the scenarios and gas generation turned out to be significantly cheaper (£38/MWh) or at the high end (£66/MWh) then the costs of the scenario would change to +£15 billion/year to -£2 billion/year respectively.[40]
- Our cost estimates also assume that deployment of electricity system flexibility reduces the cost of integrating renewables into the UK's electricity system. If system flexibility was reduced, overall system costs could increase by £3 billion/year. Conversely, further improvements in system flexibility could decrease system costs by £1 billion/year.[41]

[40] Gas prices of 41 p/therm, 69 p/therm and 85 p/therm based on BEIS (2018) *Energy and Emissions Projections 2017 - Annex M*. A 2 p/therm uplift is added to account for gas transportation costs.
[41] Scenarios with more electrified heat through (non-hybrid) heat pumps would see increased benefits from improved system flexibility.

The scenario would also bring co-benefits through improved air quality, reduced reliance on imported fuels and reduced exposure to the price fluctuations of fossil fuels and could create further economic opportunities for the UK. These are set out across the economy in Chapter 7 of the advice report.

Significant reductions in the cost of renewable generation means that the cost estimates published in this report are lower than in previous CCC reports. For example, in the Committee's 2012 report on *The 2050 Target*, the costs of power sector decarbonisation were estimated to be 0.3% of GDP in 2050. We now expect these costs to be around 0.1% of GDP. [42]

The next section considers how the scenarios can be delivered, including the need to design policy to ensure a smooth transition to a near zero-carbon power sector.

5. Delivering very deep emissions reductions in the power sector

This section has three sub-sections:

(a) Barriers that need to be overcome

(b) Uncertainties

(c) Key policy implications for driving deep emissions reductions from the power sector

(a) Barriers that need to be overcome

Delivering the level of emissions in our Further Ambition scenario will require strong and effective Government leadership at all levels, supported by actions from people and businesses.

Table 2.4 summarises our assessment of the barriers for the major opportunities to reduce emissions across a number of dimensions, in line with the approach set out in Chapter 1.

- **Cost.** Power system decarbonisation will be low cost (around 0.1% of GDP in 2050). The challenges therefore are not in finding a suitable funding source in the long-run but in making sure that delivery stays on track for the rapid scale-up that is required.
- **Investment.** Required investment levels in the UK's power sector are likely to increase as the power sector becomes more capital intensive, with increased expenditure on building low-carbon generation technologies and electricity networks. However, the cost savings of reducing fuel combustion, and replacing it with zero marginal cost low-carbon generation, will largely outweigh the capital expenditure. Government policy already supports this shift:
  - Capital investment in UK power generation and the electricity networks between 2013-2017 was £10 billion/year.[43] Our analysis suggests that the Further Ambition scenario will require investment to increase and be maintained at around £20 billion/year to 2050.
  - Combustion of fossil fuels for power generation cost around £4.5 billion in 2017. In 2050, if all electricity in our Further Ambition scenario was provided by gas generation this would rise to £28 billion/year, as both demand and forecast gas prices rise (with a range of £16-34 billion/year depending on gas price).[44]

[42] The costs of power sector decarbonisation are projected to decrease substantially as earlier, more expensive, renewable projects come off the system, from the second half of the 2020s.
[43] BEIS (2018) *UK Energy in Brief*.
[44] Gas prices of 41 p/therm, 69 p/therm and 85 p/therm based on BEIS (2018) *Energy and Emissions Projections 2017 - Annex M*. A 2 p/therm uplift is added to account for gas transportation costs.

- In delivering Electricity Market Reform the Government has recognised the increasingly capital-intensive nature of the UK's electricity system:
  - Contracts-for-Difference for low-carbon generators reduce revenue risk associated with volatile future electricity prices, and reduce the cost of capital to investors.
  - Britain's Capacity Market recognises that non-renewable generators may no longer be able to make sufficient returns in an electricity system with increasing zero marginal cost generation.[45]
  - Attracting this level of new investment will need investors to be very confident of the consistency and ambition of Government policy.

- **Supply chains.** Decarbonising the UK's power sector will require changing manufacturing practices and supply chains, presenting new challenges and opportunities:
  - Supply chains for low-carbon technologies such as offshore wind, onshore wind and solar PV have scaled up to deploy up to 5 GW/year of low-carbon generation during the 2010s. Supply chains for certain technologies - particularly offshore wind, where UK supply chains may play a greater role - may need to scale up further between now and 2050.[46]
    - Build rates for onshore wind and solar PV in the Further Ambition scenario are in line with historical deployment levels in the UK, with components for onshore wind and solar farms having largely been imported to the UK. This suggests that supply chains have and will be able to deliver onshore and solar PV in the UK.
    - Deployment of larger offshore wind turbines is more dependent on UK supply chains. Government and industry ambition is for locally supplied components to increase from almost 50% in 2017, to 60% by 2030.[47] A recent report by BVG Associates highlighted several areas where UK manufacturing facilities for offshore wind may need to scale up.[48]
  - Capturing, transporting and storing the emissions from power generation (and other sources) will create a whole new industry, albeit with similarities to existing power generation and fossil fuel industries. Development of hydrogen infrastructure could present similar challenges and opportunities.
  - The Committee's 2018 hydrogen report identified potential for low-carbon fuels such as hydrogen and/or ammonia to be combusted for power generation via gas turbines or engines. Further work is needed to understand the cost and feasibility of this, and how this may differ to the operation of fossil fuelled plant today.

- **System operation.** A transition to a low-carbon power system will involve both changes to how consumers use electricity, and power system operation.
  - Substantial costs can be saved by consumers becoming more flexible around the timing of when they consume energy, particularly for potential new electricity demands such as electric vehicles and heat pumps. The biggest benefits are from shifting demand away from peak evening periods in winter. Adoption of so-called 'smart' technology should

[45] The UK's Capacity Market is currently suspended, pending State Aid clearance from the European Commission. The UK Government has stated its intention for the Capacity Market to continue and for all capacity payments to be honoured.
[46] See Vivid Economics and Imperial College (2018) *Accelerated electrification and the GB electricity system.*
[47] Whitmarsh (2019) *The Offshore Wind Industry: Supply Chain Review.*
[48] BVG Associates (2017) *Unleashing Europe's offshore wind potential: A new resource assessment.*

enable consumers to participate in a flexible electricity system, without significant changes to their behaviour.

  - Power systems are likely to see increased variability of both electricity supply and demand. Increasing deployment of electricity storage technologies, interconnection to other countries and flexible generation capacity (alongside other system requirements) will add complexity for system operators and participants, but reduce system costs in the long-term. The System Operator is already planning to manage the grid to operate 'safely and securely at zero carbon' for parts of the year as early as 2025.[49]

- **Technologies.** Our scenarios for the UK power sector are based on technologies that are proven today. Innovation in power generation and flexibility technologies could cut costs and improve the diversity of the UK's energy mix by 2050:
  - The scenarios rely on a portfolio of low-carbon technologies including onshore and offshore wind, solar PV, nuclear, CCS, bioenergy and hydro power. Other, more novel technologies, such as wave and tidal power, or floating wind as an alternative to fixed, solid foundation wind could play a greater role in power sector decarbonisation.
  - Increased deployment of variable renewables and new electricity demands pose challenges to electricity system operation. Significant work has already been undertaken to understand the benefits of system flexibility, and deployment of enabling technologies such as battery storage, interconnections and flexible gas plant is already underway. Research, development and innovation support will be required to understand the next set of challenges facing the UK's electricity system, and develop the solutions to address these.[50]

- **Skills.** A transition to a low-carbon power sector can largely build on the skills in today's power system, however areas with new technologies, or older workforces, may require increased skills and training in the period to 2050:
  - Although our scenarios still involve a large fleet of gas-fired power stations, these could be in different locations and require different skills as they will need to run using hydrogen or CCS. Coal-fired stations are already expected to close or convert to alternative fuels.
  - There would be more jobs in renewable power generation, particularly development and construction, whereas operation of renewables is not labour-intensive. There will also be jobs in the supply chain. Although the UK is currently an importer of renewable technology, Government's recently announced Offshore Wind Sector Deal sets the ambition to increase jobs in the offshore wind industry from 7,200 today to 27,000 by 2030, much of this relating to growth in manufacturing and exports.[51]
  - The UK has a large skilled civil and military nuclear workforce, though many workers are nearing retirement age. Gaps in investment in nuclear power could present a skills gap.
  - As North Sea fuel extraction shrinks, deploying CCS transport and storage infrastructure may present opportunities for oil and gas workers, given some crossover in skills required and locations.

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[49] National Grid (2019) *Zero Carbon Operation 2025*.
[50] See the technical annex on intermittency impacts that accompanies this report.
[51] BEIS (2019) *Offshore wind: Sector Deal.*

– Improving electricity system flexibility will involve the expansion of infrastructure that exists today (e.g. interconnectors, flexible generators, storage technologies) and information technology, presenting both challenges and opportunities. The UK has a burgeoning power electronics industry and as it is likely to be at the forefront of the challenges of operating electricity systems with high levels of renewables, skills and solutions that are developed could be applicable in both UK and global markets.

These barriers indicate the need for policy to take a holistic approach and support industry in delivering the scenarios. With effective leadership from Government, particularly the setting of a clear direction and stable policy environment, the barriers can be overcome.

Table 2.4. Assessment of abatement options against various challenges for the power sector

	Abatement measure	Barriers and delivery risks	Funding mechanisms	Co-benefits and opportunities	Alternative options
Firm and variable low-carbon power	Deployment at scale of low-carbon generation to meet additional demand	High build rate required (capacity and networks). Probably need nuclear or CCS alongside renewables	Expected to cut costs	Air quality Possible negative landscape effects	Onshore wind; offshore wind; solar PV; nuclear; gas CCS; BECCS
Mid-merit (and back-up) generation	Further CCS deployment, hydrogen	CCS infrastructure and policy	Low cost in aggregate		Hydrogen or gas CCS. Possibly other forms of storage
Electricity system flexibility	Support roll-out of the above	Level of smart charging of EVs, consumer use of heat pumps	Likely to save costs for consumers	Reduced costs of system operation	

Source: CCC analysis.
Notes: The rating of measures in the table is based on the following criteria: 'barriers and delivery risks' are rated as 'red' if there is evidence that a given measure is particularly hard to implement, and 'green' or 'amber' otherwise; 'funding mechanisms' are rated as 'red' if the delivery of a given measure has high costs and these have a negative impact on businesses' competitiveness or are regressive on households, and 'green' or 'amber' otherwise; when there is evidence of positive 'co-benefits and opportunities' these are rated as 'green', otherwise no rating is given.

(b) Uncertainties

Significant uncertainties exist between now and 2050, particularly the risks of non-delivery of CCS infrastructure and power system flexibility. To some extent options exist to make up for any shortfall.

- We assume that capture rates on CCS plant are 95%, though with few existing gas CCS power plants in operation, there are high levels of uncertainty over what kind of capture rates could be achievable. Should capture rates be 85%, power sector emissions could be as high at 15 MtCO2, compared to 3 $MtCO_2$ in the Further Ambition scenario. To avoid these higher emissions, CCS would have to play a smaller role, with other technologies like nuclear and offshore wind playing a bigger part instead. This emphasises the importance for the CCS industry to achieve and demonstrate high capture rates.
- Decarbonising the remaining gas generation in the power sector without carbon capture and storage technologies will require the production of low-carbon fuels such as hydrogen without CCS. The Committee's analysis for the 2018 hydrogen report suggested that hydrogen could be produced from low-carbon electricity via electrolysis in the UK or imported from other countries. Both these options come with either increased cost or uncertainty: electrolytic hydrogen in the UK is expected to be roughly double the cost of gas-based hydrogen, and there is currently no globally traded market for low-carbon hydrogen. However, continuing rapid falls in the cost of renewables or unexpectedly high costs for CCS would change these economics.
- The uncertainties of power system flexibility are widely noted, particularly on the demand side (e.g. whether consumers support increased flexibility). Should flexibility deployment be limited, power systems can still function, albeit at additional cost.
- The overall level and carbon intensity of electricity interconnectors to other countries remains uncertain. Our analysis assumes that the UK imports no more electricity than it exports in the future, to offset the risk of importing higher carbon power. Interconnection would still be valuable as a source of flexibility - importing at times of need and exporting at times of surplus.
- Electricity system losses result from transporting power across electricity networks. There is uncertainty around whether losses could reduce in the future, due to improved networks and system operation, or indeed whether increased electrified demands at the distribution level could increase overall losses.[52]
- There are numerous other uncertainties in the analysis, such as the future costs and performance of low-carbon technologies, and the impact of high proportions of variable renewables in the UK's electricity system.[53]

A key mitigating factor for the power sector is the availability of multiple technologies for generating low-carbon power and providing flexibility. The Committee has consistently recommended a portfolio approach to power sector decarbonisation, recognising the role that alternative technologies (such as tidal range or lagoons) can play should deployment of other technologies be delayed or cancelled.

[52] We have assumed that losses remain at the 2013-17 average of 8.5%.
[53] For more information see the technical annex on intermittency that accompanies this report.

(c) Key policy implications for driving deep emissions reductions from the power sector

This report does not aim to identify a full policy package to deliver the scenarios set out above. However, there are important high-level policy implications that should be understood by Government and Parliament when considering the setting of a UK net-zero emissions target.

Paying for steady deployment of firm and variable low-carbon power

Power sector decarbonisation alongside electrification will require an expansion of low-carbon generation to up to four times today's levels - this could include a seven-fold increase in offshore wind capacity, alongside a large nuclear and/or CCS fleet. The policy instruments - such as Contracts-for-Difference, which lower risk and reduce costs - developed during Electricity Market Reform - will continue to be important

Whilst renewable projects have required significant subsidies to date, and they will continue to need market interventions in future, we do not expect them to require additional funding beyond existing commitments.

- **Current support.** Low-carbon electricity generation currently receives payments in excess of the wholesale electricity price through the Feed-in-Tariff, Renewables Obligation and Contracts-for-Difference schemes, though the first two schemes have been discontinued. In 2017, £7 billion of annual support was paid to 90 TWh of low-carbon generation. Payments to low-carbon generators are forecast to peak in the mid-2020s,[54] as the falling costs of renewables mean that they can be contracted for little or no payments above the electricity price, and as older projects come off the system.
- **Deployment of renewables.** Renewables are cheaper than alternative forms of generation in the UK and can be deployed at scale to reduce UK power emissions whilst meeting growing electricity demand. Our scenarios suggest the role of variable renewables could be four times higher than today, requiring an increased and sustained deployment of a portfolio of renewable technologies. Importantly, this can be done without increasing the overall cost of the UK's electricity system.

Costs to the Exchequer and bill payers for future nuclear projects are less clear. Investments in nuclear projects generally require more capital than individual renewable projects, and can therefore be more difficult to finance. They also have longer lead-times and may have higher pre-development costs. This may make them less suitable to CfD auction mechanisms. The Government is considering bespoke financial terms to nuclear projects to assist their deployment.

- The Government has successfully offered support through the long-term contract structure of the electricity market reform to the 3.2 GW Hinkley Point C facility being developed by EdF and CGN, which, until recently, was one of several proposed new nuclear projects in the UK.
- Recently projects at Wylfa, Moorside and Oldbury have been cancelled, raising suggestions that alternative investment mechanisms may be needed if new nuclear plants are to be developed.
- The Government is currently considering alternative support mechanisms for nuclear power, such as a Regulated Asset Base model - which allows for revenues to be earned during the

[54] HMT (2017) *Control for Low-Carbon Levies.*

construction period - direct equity shares and debt financing. This could lower the cost of financing new nuclear power.

The costs of CCS will also fall in a different way, which has not yet been decided. The Government is likely to have to take a lead in funding of early infrastructure, while capture plants could be funded with long-term contracts.

Important role for CCS and hydrogen

Full power sector decarbonisation relies on decarbonising gas generation in the power sector. CCS is key to decarbonising mid-merit power generation, and can also play a role in low-carbon baseload generation. This requires the development of CCS and hydrogen infrastructure, and policy to support their deployment.

- **Flexible mid-merit generation.** CCS technologies in the power sector are likely to provide greater value if run flexibly, rather than at baseload. CCS technology will require a bespoke investment mechanism that recognises the value it can provide to the electricity system, as well as the development of CO_2 transportation and storage infrastructure.
  - As carbon prices rise, CCS is likely to become more cost-competitive with unabated gas-fired generation, though this alone is unlikely to provide sufficient incentive to build new large-scale power CCS projects, at least to start with. Investment mechanisms and viable business cases will need to be developed that recognise that long-term contracts which insulate against carbon price or fuel price fluctuations will be valued by investors (and need to recognise the different roles that CCS can play on the system). The CfD framework would be appropriate here, with adjustments to reflect the particular characteristics of CCS (e.g. fuel price indexing). Additionally, incentive mechanisms must incentivise high capture rates.
  - Gas plant built today may still be on the system in 2050. Decisions to build gas plant during the 2020s (and beyond) should take into account the need to reduce emissions in power to close to zero by 2050, and consider opportunities for fitting CCS technology or switching to low-carbon fuels like hydrogen or ammonia during this period.
- Decarbonising **back-up power generation** will require infrastructure and incentives to promote the availability of storable low-carbon fuels such as hydrogen. This will require a mechanism that incentivises use of lower-carbon fuels in the long run. It is plausible that a carbon price could play that role, provided that a wider hydrogen industry and infrastructure has already developed. Nearer term there should be research into and demonstration of burning low-carbon fuels in gas turbines and engines to enable the later uptake of this option.
- **Negative emissions.** Bioenergy when paired with CCS, can provide negative emissions. Investment mechanisms will need to be developed that recognise and reward the value of negative emissions across a range of Greenhouse Gas Removal (GGR) technologies, whilst also incentivising energy production.

Policy to develop and deploy CCS and hydrogen for the power sector must be joined up with broader CCS and hydrogen policy.

Optionality and electrification

Renewable energy is cheaper than we thought it would be a decade ago. This could provide opportunities for low cost and more rapid electrification, and decarbonisation.

- **Deploying renewables at scale in the 2020s.** Contracts can now be signed for renewable capacity (i.e. wind and solar) in the early 2020s that is cost-competitive with high-carbon generation. As such, strong deployment of these renewables through the 2020s will not have high costs, even when including deployment of flexibility measures to accommodate high levels of inflexible generation. As costs of low-carbon generation have reduced, it has only strengthened the case for achieving a carbon intensity somewhat below 100 gCO_2/kWh by 2030.
- **Accelerated electrification.** Accelerating the rate of electrification by adding flexible loads, in the form of electric vehicles and hybrid heat pumps, to the system at scale in the 2020s would increase demand and enhance the ability of the system to accommodate inflexible generation. This would enable greater additions of renewables in parallel during the 2020s, and in doing so would reduce the average cost of electricity.[55] As well as maintaining high build rates for the power sector, this would enable the transport and buildings sectors to progress more rapidly towards zero greenhouse gas emissions and also improve air quality.
- **New networks.** The anticipated uptake of electric vehicles and full and/or hybrid heat pumps mean electricity demand will rise in most areas. Recent work for the Committee[56] shows that the cost of upgrading distribution network capacity is relatively insensitive to the size of the capacity increase, as most of the cost is in the civil works rather than the equipment (e.g. larger cables). It is essential, therefore, that when grid capacity is increased, this is to a sufficient level to avoid having to upgrade the capacity again in the following years. A relatively large expansion in capacity is likely to have low regrets, 'future-proofing' the network to enable greater electrification if necessary and/or enabling demand to respond more readily to variations in low-carbon electricity supply.
- **Additional electrification.** Keeping open the option of having a larger low-carbon electricity system than we have assumed under the Further Ambition scenario would allow for a wider range of ways to reach net-zero emissions. In order to achieve this, it will be important for build rates in the near term to be relatively high, both in order to reduce the amount that needs to be built later on and to develop supply chains.

Market design

Many of the policy instruments and market reforms required by our scenarios have already been developed by Government during the Electricity Market Reform (EMR) process, and in line with the Secretary of State's power sector principles.[57] These instruments are largely established and working well, and recognise the challenges that need to be addressed in moving to a low-carbon power system. There will undoubtedly be opportunities to improve on the design of these instruments, but the wider case for reform is limited, and must prove it is better than the arrangements currently in place.

- **Market principles.** Government clearly has a role in market design. Within a well-designed market, the market principles of competition and technology can be applied to most parts of the electricity system, helping to improve efficiency and reduce costs. This has proven successful in the auctions for offshore wind contracts and for firm capacity, where prices were far lower than most analysts predicted.

[55] Vivid Economics and Imperial College (2018) *Accelerated electrification and the GB electricity system*.
[56] Ibid.
[57] Greg Clark (2018) *After the trilemma - 4 principles for the power sector*.

- **Long-term contracts for generation.** Contracts-for-difference recognise the capital intensity of low-carbon generation technologies and provide an investment mechanism that lowers risk for developers, and lowers the costs of these contracts on consumer bills. CfDs can be used to continue and accelerate the low-carbon transition in power. Without CfDs, power decarbonisation could slow down, and emissions could rise as existing low-carbon plant retire. Though there is no case for significant reform in the near term, tweaks can be made to the current regime, and in the longer-term opportunities could arise to transfer more market risk to low-carbon generators.
- **Capacity versus generation (e.g. a capacity market).** A fleet of gas-based mid-merit and back-up generators will continue to be needed, as a complement to low-carbon generation. Though historically higher-carbon generators have been able to recoup investments through the wholesale market, as more low marginal cost generation such as renewables and nuclear comes online this revenue will reduce. Revenue streams such as the capacity market will become increasingly important, providing incentives for system security.
- **Carbon pricing** will continue to act as an important signal for dispatching lower carbon fossil generation. It will also ensure coal generation does not increase in the period preceding its closure and provide an incentive for lower carbon flexibility technologies to compete with gas generation as a complement to renewable generation.
- **System flexibility.** A low-carbon power system will require a high degree of system flexibility in order to function effectively. The Committee's 2017 Progress Report suggested a series of improvements that could be made to the UK's electricity markets in order to ensure prices reflect full system value, complexity is reduced, innovation is supported and consumer participation is incentivised. These were subsequently reflected in the Government's Smart Systems and Flexibility Plan. Successful implementations of the actions identified in the Plan by 2021 should lay the groundwork for continued improvements in system flexibility beyond then, enabling lowest cost electricity system decarbonisation.

Current Government policy

Many of the opportunities in the power sector are already included in the Government's plans, albeit with policy strengthening likely required to deliver them:

- The Government's plans to 2030 include reducing the emissions intensity of the power sector from around 250 gCO_2/kWh today to 150 gCO_2/kWh by 2030. Further deployment of low-carbon generation will be required to reduce emissions below 100 gCO_2/kWh.
  - Government policies currently support over 90 TWh/year of renewables through the Feed-in-Tariff, Renewables Obligation and Contracts-for-Difference schemes, and have contracted for an additional 70 TWh/year of renewable and nuclear generation to come online during the 2020s. This will ensure low-carbon generation reaches 46% of total generation by 2030.
  - The Government has further committed £557 million/year of funding for further contracts to come online during the 2020s. We estimate this funding could be used to contract an additional 43 TWh/year of generation, increasing the low-carbon generation share to 57%, compared to the 74-87% in our scenarios by 2030. The funding is primarily focused on offshore wind, which the Government suggests could meet around a third of electricity generation in 2030, from up to 30 GW of capacity.

- Beyond 2030, the Government's (2017) Clean Growth Strategy (CGS) recognises the challenges to decarbonising the UK's power sector by 2050, including that:[58]
  - Power sector emissions in 2050 could need to be close to zero, with power produced from a diverse range of low-carbon sources;
  - Heat and transport electrification could increase both annual and peak generation requirements on the UK's electricity system;
  - Electricity systems will need to become more smart and flexible, in order to accommodate both new forms of electricity generation and new forms of demand;
  - CCUS could play a role in the power sector, noting the potential for sustainable bioenergy to be paired with CCS. Similarly, the Government's 2018 CCUS deployment pathway states an ambition to have the option of deploying CCUS at scale in the 2030s, and sets out a detailed pathway for achieving this, including the development of CO_2 transportation and storage infrastructure.
- The Government has committed to producing an energy White Paper in 2019, based on the four principles outlined in the Secretary of State's speech in November 2018. The Committee's policy recommendations are consistent with all of these principles (Box 2.4).

The Committee's annual progress reports to Parliament include our detailed progress assessments. Our June 2018 report[59] identified a number of areas where policy strengthening was required to deliver existing ambition. These are a necessary condition to support the increased effort required to deliver a UK net-zero emissions target – we will report on progress against them in July 2019.

[58] HMG (2017) *The Clean Growth Strategy*.
[59] CCC (2018) *Progress Report to Parliament*.

Box 2.4. Future market reform

In November 2018 the Secretary of State outlined four principles for the UK's power sector, in response to a 2017 Cost of Energy review by Professor Dieter Helm, which called for widespread reform. The Government's principles are:

- **The market principle:** wherever possible, use market mechanisms that take full advantage of innovation and competition.
- **The insurance principle:** given intrinsic uncertainty about the future, government must be prepared to intervene to provide insurance and preserve optionality.
- **The agility principle:** energy regulation must be agile and responsive if it is to reap the great opportunities of the smart, digital economy.
- **The "no free-riding principle":** consumers of all types should pay a fair share of system costs.

We agree with these principles and are pleased that the Government is looking beyond the near term in considering the needs of the electricity sector.

The case for reform

The current system is working well and we do not expect its effectiveness to be materially challenged in the nearer term. Responses to the Government's Energy Cost Review Consultation suggest this is in line with a strong industry consensus. The package of instruments introduced under Electricity Market Reform (EMR) is delivering low-cost emissions reductions, whilst maintaining security of supply.

Over the longer term, wider reform should be looked at, but experience suggests this is a lengthy process which involves significant adaptation from market players so actual reform should not be entered into lightly. The high and sustained build rates required to meet a net-zero emissions target suggest that hiatuses must be avoided. Any reform should demonstrate that it is better than available alternatives, ensure arrangements are tailored to both present and future system needs and allow projects to access returns that reflect their value to the system, whilst acknowledging that some of the principles of EMR are likely to endure.

- Competitive auctions for contracts for low-carbon generation and the Capacity Market are delivering lower than expected prices, whilst the UK's carbon price support mechanism has played an important role in limiting emissions from coal power.
  - Competitive auctions for **Contracts for Difference** have procured around 45 TWh of low-carbon generation, at prices 40% below the auction price cap. Prices for contracts in these auctions are indicative of both competitive pressure and access to a lower cost of capital for developers (see Newbery 2016, Arup 2018). Renewables can now be contracted at prices below average wholesale prices. These contracts would not require any Government subsidy, and would merely offer a bankable revenue stream to financiers and developers.
  - The **Capacity Market** is delivering high security of supply at lower-than-expected prices. This has brought forward novel solutions such as batteries, demand-side response and peaking plant, and revealed high system security of supply margins, with large volumes of plant bidding in above the auction reserve margin.
  - **Carbon pricing** via the UK's Carbon Price Support mechanism - alongside other factors such as European air quality directives, fossil fuel prices and age of plant - has reduced coal generation from 32% of generation in 2008 to 7% in 2017.
- In the longer-term, for projects commissioning after 2030, there will be opportunities for market reform, though the electricity market will need to continue to incentivise both new generation and new capacity.

Box 2.4. Future market reform

- The falling costs of renewables may allow for renewables to be deployed without long-term Government contracts, but with - typically shorter-term - Power Purchase Agreements. However, as more wind or solar generation enters the system, its marginal value decreases and the volatility of revenue increases (known as 'price cannibalisation'). This could lead to a slowdown in renewable investment, and decarbonisation. It is likely that long-term contracts will continue to be needed for sustained decarbonisation.
- In the longer term (i.e. post-2030), and as low-carbon generation continues to decrease in cost, a more mature market for long-term contracts may materialise (e.g. via energy supplier or corporate Power Purchase Agreements), reducing the need for Government intervention. Long-term contracts, that reduce risk to generators, are likely to continue to be important. Government may also be able to support this development through simple regulations, such as an Emissions Performance Standard set at a very low level.
- In principle, all market participants should face the costs and benefits of their actions. For example, technologies that contribute to security of supply should be rewarded for their capacity. Similarly, projects that require or provide system flexibility should face penalties or rewards that recognise the value they provide to the system.
- It is likely that renewables already face many of the costs of the externalities they impose on the system, although steps can be taken to transfer some of the risks currently borne by consumers onto market participants. Similarly, the ongoing evolution of ancillary service markets and network pricing will likely improve the cost-reflectiveness of the current system.
- The Committee supports a move towards technology neutrality (the market principle), supplemented by innovation spending for less-mature technologies which could broaden the portfolio of low-carbon power options available to the UK (the insurance principle).
- Current Government proposals for CCS and new nuclear deployment in the UK recognise the role Government can play in reducing risk, providing insurance over future revenue streams. Government can also continue to play a role in supporting a wider portfolio of power sector technologies - such as marine renewables - that could contribute to future decarbonisation.
- Project development periods for low-carbon technologies range from 18 months to 10 years or more, requiring that industry has visibility of any reforms for the period beyond 2030, in the coming years. It is therefore welcome that the Government is considering this now, provided it does so in a way that does not undermine investments and project developments currently being considered.

Sources: Newbery (2016) *Towards a green energy economy?;* NERA (2017) *Offshore revolution?;* Gross R, Rhodes A, Staffell I (2018), *Is EMR working? Are Britain's electricity market arrangements fit for purpose or broken?*; UKERC (2018) *Response to the Cost of Energy Review*; Energy UK (2018) *Energy UK's Vision for the Five Year Review of Electricity Market Reform.*

6. Hydrogen production in a low-carbon economy

The Committee's 2018 report on Hydrogen in a Low-Carbon Economy considered potential demands for hydrogen use, and the hydrogen infrastructure required to supply these demands. The analysis in this section - and in the wider report - draws on that work, and is more limited in detail than our analysis for other sectors.

(a) Hydrogen production options

Today

The UK produces around 0.7 Mt of hydrogen annually (27 TWh)[60], the majority of which is produced via either steam methane reforming or partial oil oxidation across 15 sites. Hydrogen is largely produced for the chemical and agricultural industries (as ammonia), and not combusted for energy or heat generation. Some is used in hydrogen buses.

Hydrogen production from these sources emits carbon dioxide, but could be decarbonised using CCS.

Future

Advanced gas-reforming with CCS currently appears likely to be the lowest cost means of producing low-carbon hydrogen, although producing large volumes of hydrogen in this way could result in significant residual emissions. Other technologies are likely to play a more niche role, limited by amount of sustainable feedstock (BECCS), or costs and the impacts of the technology on the electricity system (electrolysis). International trade in low-carbon hydrogen may develop over time allowing it to be imported. However, it is not a certainty that it will and the costs may be no lower than that of domestic low-carbon hydrogen production.

- **Gas-reforming with CCS** looks likely to be the cheapest option for low-carbon hydrogen production in the UK, with costs of between £27-46/MWh, reducing emissions by 60-85%, on a lifecycle basis, compared to natural gas, and by 95% when only the residual CCS emissions are included. Although there is no real technical deployment limit to producing hydrogen via gas-reforming, in practice the deployment of this technology is likely to be limited by feasible build rates, availability of gas imports and the level of residual emissions from this technology in a decarbonised energy system.[61]
- The potential for **bio-gasification with CCS** to be deployed at scale is limited by the amount of sustainable bioenergy available, but the technology offers one way of using bioenergy with carbon capture and storage (BECCS) to maximise emissions reductions from finite sustainable bio-resources. Deployment of bio-gasification will depend on the amount of sustainable bioenergy available. The amount of BECCS assumed in our Further Ambition

[60] Energy Research Partnership (2016) *Potential Role of Hydrogen in the UK Energy System*. About half is a by-product, mainly from the chemical industry, which is either used on site or sold as chemical feedstock, with a small percentage vented. We use hydrogen to refer to energy carriers which contain large proportions of hydrogen, including ammonia.

[61] Although low-carbon hydrogen could be produced via methane reforming with emissions of around 10 gCO_2/kWh, upstream emissions from natural gas production could incur an additional 15-70 gCO_2e/kWh. Emissions from hydrogen in this chapter are CO_2 only. Other than methane leakage in natural gas production, hydrogen production and combustion doesn't produce any non-CO_2 GHGs.

scenario could be used to produce 104 TWh of hydrogen, although we have assumed that this used for other forms of BECCS to achieve very similar emissions reductions.

- **Electrolysis** is expected to be higher cost than gas reforming, but could be zero-carbon. Cost reductions in electrolysers can reduce costs, but the cost of electricity will remain the most important factor. The cost of electricity would have to be less than £10/MWh for electrolysis to be the same cost as we expect for gas reforming with CCS in the UK, or energy consumption from electrolysis would have to reduce significantly. While there is some opportunity to utilise some 'surplus' electricity (e.g. from renewables generating at times of low demand) for hydrogen production, our modelling shows that the quantity is likely to be small in comparison to the potential scale of hydrogen demand. Producing hydrogen in bulk from electrolysis would be much more expensive and would entail extremely challenging build rates for zero-carbon electricity generation capacity.
- **Imports are uncertain.** The availability of low-cost energy resources in some parts of the world - both natural gas and renewable electricity - could mean that international trade in hydrogen develops. This hydrogen could potentially be imported to the UK at similar cost to producing hydrogen directly in the UK, even when including the costs of conversion and transportation. However uncertainty around the costs and availability of these imports implies a minimum role for domestic hydrogen production across all future scenarios.

Our analysis assumes that demands for hydrogen in the UK are met through UK production, and that the majority of future hydrogen production in the UK is from advanced methane reformation with CCS (53-225 TWh), with a limited contribution from electrolysis in the Further Ambition scenario (44 TWh).[62]

(b) Hydrogen infrastructure

The UK's gas distribution networks are currently undergoing a programme of refurbishment that is replacing existing iron gas distribution pipes with plastic ones that will potentially make the networks 'hydrogen ready'. This could present an opportunity for hydrogen to be widely used in the UK, but significant new infrastructure - in the form of new hydrogen and CO_2 networks, and hydrogen storage - may be required for hydrogen production and consumption at scale in the UK. Without widespread hydrogen networks in the UK hydrogen could be transported via road or rail, albeit in limited quantities, or produced on site.

- In the **Core scenario** hydrogen use is limited to niche, localised applications, requiring limited additional hydrogen transportation or storage infrastructure.
- In the **Further Ambition scenario** hydrogen use is more widespread. Gas distribution networks are used to transport hydrogen to buildings, power generation and industrial facilities and refuelling stations. Our analysis assumes some new hydrogen transmission infrastructure is also built. Additional hydrogen storage - such as storage in salt caverns - could also be required, but is not included in our scenarios due to the limited role for hydrogen in supplying buildings heat.

[62] Methane reformation is assumed produce 0.8 units of hydrogen per unit of natural gas input (80% efficiency) and capture 95% of process CO_2. Electrolysers are assumed to produce 0.74 units of hydrogen per unit of electricity input (74% efficiency), and run at load factors of 30-90%. Estimates for CCS in power and hydrogen should be considered upper bounds. Electrolysis production is from CCC (2018) *Hydrogen in a low-carbon economy* based on Imperial College (2018) *Analysis of alternative heat decarbonisation pathways*.

(c) Hydrogen in the Committee's scenarios

Core

In the Core scenario hydrogen demand is limited to around 53 TWh, with the majority being used in shipping.

- 51.5 TWh of hydrogen is used as ammonia in domestic (25%) and international (75%) shipping (see Chapter 6).
- Hydrogen buses use around 2 TWh.

Production is largely localised, and is assumed to come from methane reformation with CCS. Producing 53 TWh of hydrogen via advanced gas reforming with CCS would result in emissions of 0.6 $MtCO_2$, assuming 95% of emissions can be captured in the process.

Further Ambition

In the Further Ambition scenario hydrogen demand is most widespread, at around 270 TWh, with expanded uses in industrial combustion, heavy goods vehicles, and buildings heat and power generation (Figure 2.8).

- 70 TWh of hydrogen is used as ammonia in domestic (25%) and international (75%) shipping (see Chapter 6).
- 120 TWh of hydrogen is used for industrial combustion, displacing coal, oil and natural gas (see Chapter 4).
- Use of hydrogen in surface transport is more widespread, with HGVs using 22 TWh, hydrogen buses around 3 TWh and hydrogen trains using 0.3 TWh (see Chapter 5).
- Hydrogen is also used for peak heat in buildings, requiring 53TWh (see Chapter 3).
- Hydrogen and/or ammonia acts as a storable low-carbon fuel for peak power generation, using 2 TWh of hydrogen (see above).
- 2 TWh in agriculture from use in vehicles (see Chapter 7).

In our Further Ambition scenario hydrogen production is more centralised, based on advanced methane reformation with CCS, with hydrogen being distributed via gas networks, as well as a limited role for electrolysis.

- Producing 225 TWh of hydrogen via advanced gas-reforming could require up to 30 GW of hydrogen production capacity, equivalent to 30-60 hydrogen production plants.
- Producing 44 TWh of hydrogen via electrolysis could require between 2-7 GW of electrolysers, depending on the load factors of the plant. Electrolysers are much smaller, modular technologies that are currently up to around 10 MW in scale. This implies 200-700 electrolyser units, though groups of units could be co-located.

Residual emissions from hydrogen production in our scenario are 3.1 $MtCO_2$ in 2050, assuming 95% of the emissions in the process can be captured. If capture rates could only reach 85% emissions could be as high as 9.3 $MtCO_2$.

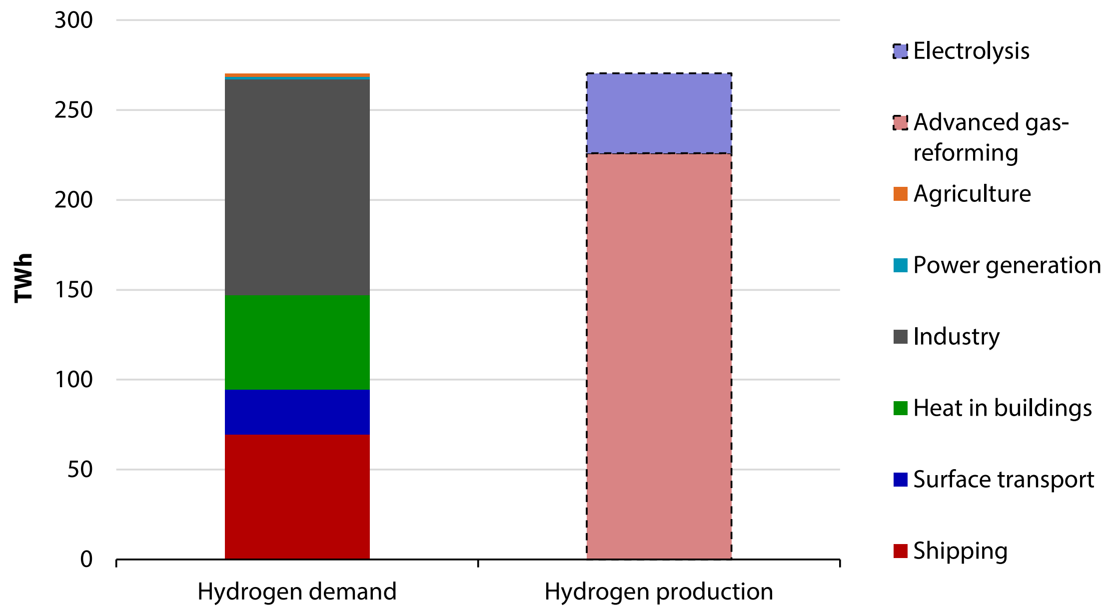
Our hydrogen review identified the possibility of greater end-use demand for hydrogen. For example, our Further Ambition scenario only includes hybrid heat pumps in a quarter of homes whereas take-up of hybrids could be higher and some communities on the gas grid may prefer to switch to hydrogen than to heat pumps. That would not dramatically change costs or emissions (e.g. even with four times the demand we have assumed from buildings under 2 $MtCO_2$ would be added). However, it could make an already challenging industry development and scale-up become insurmountable and would further increase reliance on natural gas imports and carbon capture and storage (CCS).

Alternative and speculative options for cutting hydrogen emissions to 2050

Our scenarios draw on the Committee's 2018 hydrogen report to present plausible estimates for producing low-carbon hydrogen in the UK. Other production opportunities may arise that could lower the carbon footprint - both of production and supply chain emissions - of hydrogen production in the UK:

- Higher CO_2 capture rates or imported renewable hydrogen could reduce emissions by at least 2.5 Mt, to 0.6 $MtCO_2$ or below.
- Our scenarios assume electrolysers use 1.35 units of electricity per unit of hydrogen (74% efficient), some estimates suggest this could be reduced to around 1.1 units (90% efficient).
- Our scenarios assume that sustainable biomass is used in power generation with CCS, resulting in low-carbon power generation and negative emissions. Biogasification with CCS could be a plausible, yet less developed, low-carbon means of producing hydrogen at scale in the UK.
- Novel hydrogen production methods could materialise, with potentially lower carbon footprints than methane reformation.[63]

Figure 2.8. Use and production of hydrogen in the Further Ambition scenario (2050)



Source: CCC analysis.
Notes: Our analysis assumes the majority of future hydrogen production in the UK is from advanced methane reformation with CCS (225 TWh), with a limited contribution from electrolysis (44 TWh).

[63] See The Royal Society (2018) *Options for producing low-carbon hydrogen at scale.*

(d) Developing a new industry to provide low-carbon hydrogen

Building a low-carbon hydrogen economy in the UK will involve investment in hydrogen production facilities, networks and appliances. The costs of these investments and the fuel used to produce the hydrogen are included in the costs of hydrogen use in individual sectors.

Widespread use of hydrogen is a key enabler for economy-wide decarbonisation in 2050, but is reliant on near term actions. The Committee recommend the following range of actions on strategy, deployment, public engagement, demonstration, technology development and research:

- **Hydrogen deployment.** We now recommend that significant volumes of low-carbon hydrogen should be produced at one or more industrial clusters by 2030, and be used in industry and in applications that would not require major infrastructure changes (e.g. power generation, injection into the gas network and depot-based transport).
- **Identification of low-regret hydrogen deployment opportunities.** The Government should assess the range of near-term opportunities for hydrogen use across the energy system and set a strategic direction for low-regret use of hydrogen in the 2020s.
- **Public engagement.** Currently the general public has a low awareness of the need to move away from natural gas heating, and what the alternatives might be. There is a limited window to engage with people over future heating choices, understand their preferences and factor these into strategic decisions on energy infrastructure. This is especially important if solutions to heat decarbonisation could differ in different parts of the UK.
- **Demonstration.** In order to establish the practicality of switching to hydrogen, trials and pilot projects will be required for buildings, industry and transport uses. It is also necessary to demonstrate that hydrogen production from CCS can be sufficiently low-carbon to play a significant role:
  - Before any decision to repurpose gas grids to hydrogen for buildings' heat, pilot schemes will be necessary to demonstrate the practical reality of such a switchover. These must be of sufficient scale and diversity to allow us to understand whether hydrogen can be a genuine option at large scale.
  - Hydrogen use should be demonstrated in industrial 'direct firing' applications (e.g. furnaces and kilns).[64]
  - Depending on international progress in demonstrating hydrogen HGVs, the Department for Transport should consider running trials in the early 2020s, in order to feed into a decision in the second half of the 2020s on the best route to achieving a zero-emission freight sector.
  - A substantial role for hydrogen produced from natural gas with CCS depends on delivering emissions savings towards the higher end of our estimated range of 60-85% on a lifecycle basis. This means demonstrating that it is feasible to achieve very high CO_2 capture rates (e.g. at least 90%) at reasonable cost from gas reforming.
- **Technology development.** There are technologies that are not yet deployable at scale but could play important roles within hydrogen use in the energy system by 2050. These include hydrogen-ready technologies, such as boilers and turbines, as well as hydrogen HGVs and

[64] Direct firing refers to combustion-based heating processes (such as furnaces and kilns) where the combustion gases come into direct contact with the product that is being heated.

biomass gasification. It is important that these are a focus for government support, in order to create a sufficiently wide range of pathways to achieve long-term emissions targets.

- **Further research** is required in a number of areas to establish the feasibility and desirability of using hydrogen in a range of applications:
  - Alongside a major role in industry and shipping, there is a key opportunity for hydrogen to provide low-carbon energy at peak times, performing a role currently played by natural gas. Key to this will be the ability to deliver large quantities of hydrogen in a short space of time. It is therefore important to establish how the various options to store hydrogen perform under different patterns of operation that may be required.
  - Research and development is required on hydrogen technologies for industrial heating applications, especially where there may be technical barriers to use of hydrogen.
  - The implications of hydrogen combustion for NOx emissions must be established – compared to fossil fuels and to any low-carbon alternatives – across applications in buildings, industry and power. This includes identifying potential technologies that can mitigate these NOx emissions.
  - The feasibility of hydrogen use in gas turbines for power generation should be established, with consideration given to making new gas-fired capacity 'hydrogen ready'.
  - The most cost-effective way to produce and distribute hydrogen in order to supply a nationwide refuelling network for heavy-duty vehicles should be assessed, in consideration of hydrogen purity requirements and how these can be met.
  - It will be important to complete the work currently underway to establish the safety of hydrogen use, and to understand the implications of this for hydrogen deployment. Ongoing work on quality standards and billing, both for hydrogen blended with natural gas and for 100% hydrogen supplies should also be brought to timely conclusions.
  - Further work is required to establish whether and to what degree hydrogen acts as an indirect greenhouse gas if emitted to the atmosphere.

The difference in the role for hydrogen in our Core scenario (that would broadly deliver the UK's existing emissions targets) and our Further Ambition scenario (required for a net-zero emission target) is striking. Low-carbon hydrogen moves from being a useful option to a key enabler. Updates to policy alongside adoption of our recommended target should reflect that.

Any use of hydrogen must be low-carbon, so development of CCS is a top priority, with a role for hydrogen production from the start. At least one of the clusters to be developed by 2030 should include large-scale production of low-carbon hydrogen.

Supply and demand must be joined up, with strong coordination and integration of supporting policy and regulatory networks and a strong Government direction and leadership in infrastructure development.

The scale-up implied in our scenarios is undoubtedly challenging (a ten-fold increase from the hydrogen industry today and a complete switch to low-carbon methods). However, it also presents an important opportunity to develop another key low-carbon industry in the UK and to demonstrate progress in an area that could also play a big part in reducing global emissions.

Chapter 3: Buildings

Introduction and key messages

This chapter sets out the scenarios for the buildings sector that inform the Committee's advice on reviewing long-term emissions targets for the UK, Scotland and Wales. It draws on new research we have commissioned to understand in greater detail the range of characteristics which make homes hard to decarbonise, and how this influences the solutions and the associated costs.

Near-full decarbonisation of heat for buildings is one of the biggest challenges in reducing emissions from the energy system to net zero by 2050. The policies put in place to drive the required changes will determine how the costs of this decarbonisation are allocated between consumers and taxpayers. Government must review the plan for the distribution of these costs as an early priority to ensure that the wider transition - for workers and energy bill payers - is perceived to be fair.

It is critical that measures to reduce emissions are not viewed in isolation. A holistic approach is required to deliver buildings which are low-carbon, thermally-efficient, better adapted to a changing climate, with safe moisture levels and excellent indoor air quality.

The key messages from this chapter are:

- **Background.** Direct emissions from buildings result primarily from the use of fossil fuels for heating. Electricity consumption mainly stems from the use of lighting and equipment in homes and non-residential buildings, but emissions associated with this are included in our assessment of the electricity sector.[65] Direct greenhouse gas (GHG) emissions from buildings were 85 $MtCO_2e$ in 2017, accounting for 17% of UK GHG emissions. The majority of these emissions are CO_2. Direct CO_2 emissions from buildings have fallen by 11% from 1990.[66] This largely reflects energy efficiency improvements in buildings and growth in bioenergy use.[67]
- **'Core' measures**
  - In residential buildings, the parts of the stock which are generally easier and/or less costly to decarbonise include new homes, homes off the gas grid, homes suitable for district heating, and homes on the gas grid with relatively low barriers (i.e. with no space or heritage constraints). These homes are decarbonised in our Core scenario using a mixture of energy efficiency and low-carbon heating measures. This reduces direct emissions by 66 $MtCO_2e$, leaving around 20 $MtCO_2e$ in 2050. This scenario also includes lighting and appliance efficiency improvements.
  - Government aspirations and commitments, whilst in need of strengthening, currently target the decarbonisation of homes across these groups. They include the Future Homes standard, the commitment to phase out high-carbon fossil fuel heating installations off the gas grid, and broader aspirations and initiatives around home retrofits (EPC band C by 2035) and low-carbon heating.

[65] Direct emissions are from sources that are owned or controlled by the reporting entity. Indirect emissions are a consequence of the activities of the reporting entity, but occur at sources owned or controlled by another. Indirect emissions are currently most commonly associated with electricity use.
[66] Temperature-adjusted emissions, to show underlying trend.
[67] Most bioenergy in buildings is used in stoves or on open fires, rather than in efficient boilers linked to central heating.

- For non-residential buildings, a combination of energy efficiency, heat networks and heat pumps lead to near complete decarbonisation, with residual emissions of 3 $MtCO_2e$ from peaking gas used in heat networks and N_2O used as an anaesthetic in hospitals.

- **'Further Ambition' scenario**
  - In residential buildings, our Further Ambition scenario additionally deploys low-carbon heating and energy efficiency measures for homes which are considered more costly and/or difficult to decarbonise. This includes homes on the gas grid with space constraints, and homes with heritage value (listed buildings and buildings in conservation areas). This scenario also includes the conversion of residual gas demands to hydrogen and biomethane injection into the gas grid. Altogether, this delivers 83 $MtCO_2e$ of abatement in total, leaving residual emissions of up to 4 $MtCO_2e$ in 2050.
  - In non-residential buildings, our Further Ambition scenario abates all residual CO_2 emissions. Gas used for peak heating demand in heat networks is decarbonised by shifting to hydrogen. The use of N_2O as an anaesthetic in hospitals leaves residual emissions of 0.6 $MtCO_2e$.

- **Speculative options**
  - The remaining emissions in our Further Ambition scenario in 2050 mainly occur in homes. They can be characterised in various ways and could be associated with continued fossil fuel use in heating from around 10% of the housing stock which is most costly to decarbonise (with the combined cost of measures exceeding around £420/tCO_2e). Alternatively, this level of remaining emissions is equivalent to around half of the remaining gas demand from hybrid heat pumps and district heating not being converted to hydrogen. In both of these cases, decarbonisation is feasible, but due to uncertainty, costs and/or difficulty may require until 2060 to approach zero emissions.
  - In non-residential buildings, alternative forms of anaesthesia could replace N_2O.

- **Costs and benefits.** Our analysis has confirmed that reaching net-zero emissions in buildings is achievable but that it remains costly, with a total annual cost compared to a theoretical counterfactual without any action on emissions estimated to be in the region of £15 billion in 2050. A key question for Government will be how to allocate these costs across society: distributional considerations will be central to determining the policy mechanisms to deliver low-carbon heat. Alongside these costs there are expected to be a range of co-benefits. These include alleviating fuel poverty; improving the comfort, health and wellbeing of occupants; and unlocking the significant industrial opportunities associated with low-carbon and resilient buildings.

- **Delivery.** The priorities now must be to:
  - **Develop a fully-fledged strategy for decarbonised heat in 2020.** The strategy must be designed to fully decarbonise buildings across the UK in line with the net-zero goal. It is essential HM Treasury commits to working with BEIS on this and allocates sufficient funding.
  - **Set a clear trajectory of standards.** This includes delivering commitments announced under the Future Homes Standard, alongside ambitious standards for new non-residential buildings, delivering commitments on energy efficiency standards across the stock, and a long-term regulatory approach for delivering low-carbon heat.

– **Tackle performance and compliance issues to ensure that new buildings and measures retrofitted in existing buildings perform as they should.** This includes overhauling compliance and enforcement; refocussing on high-quality 'as-built' performance.

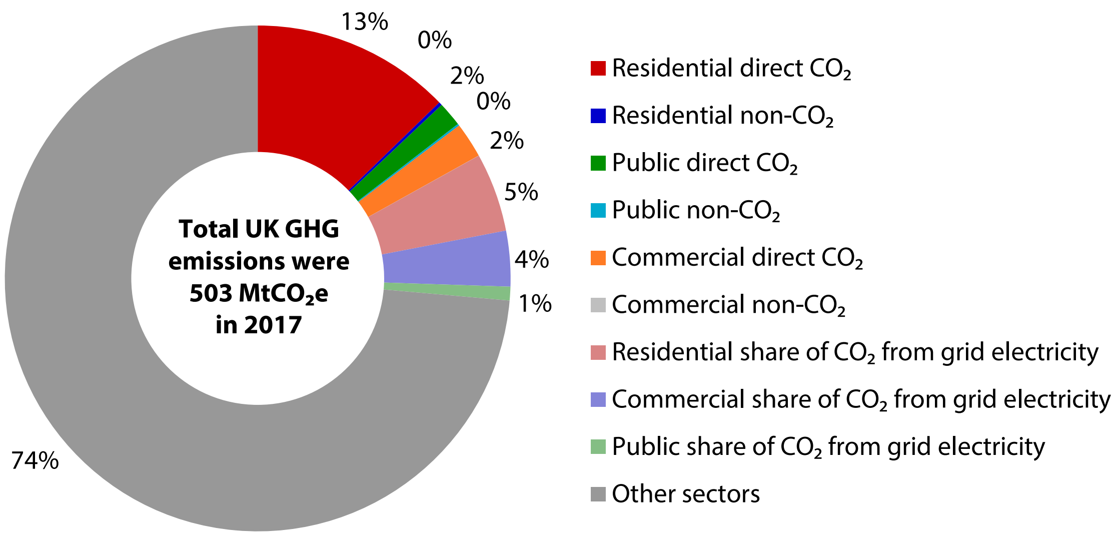
We set out our analysis in the following sections:

1. Current and historical emissions in buildings
2. Reducing emissions in buildings
3. Scenarios for minimising buildings emissions
4. Costs and benefits of achieving very deep emissions reductions in buildings
5. Delivering very deep emissions reductions in buildings

1. Current and historical emissions in buildings

Direct greenhouse gas emissions from buildings were 85 MtCO2e in 2017, 17% of the UK total (Figure 3.1). When including indirect emissions, buildings account for 26% of the UK total.

Figure 3.1. Breakdown of buildings sector emissions into sources (2017)



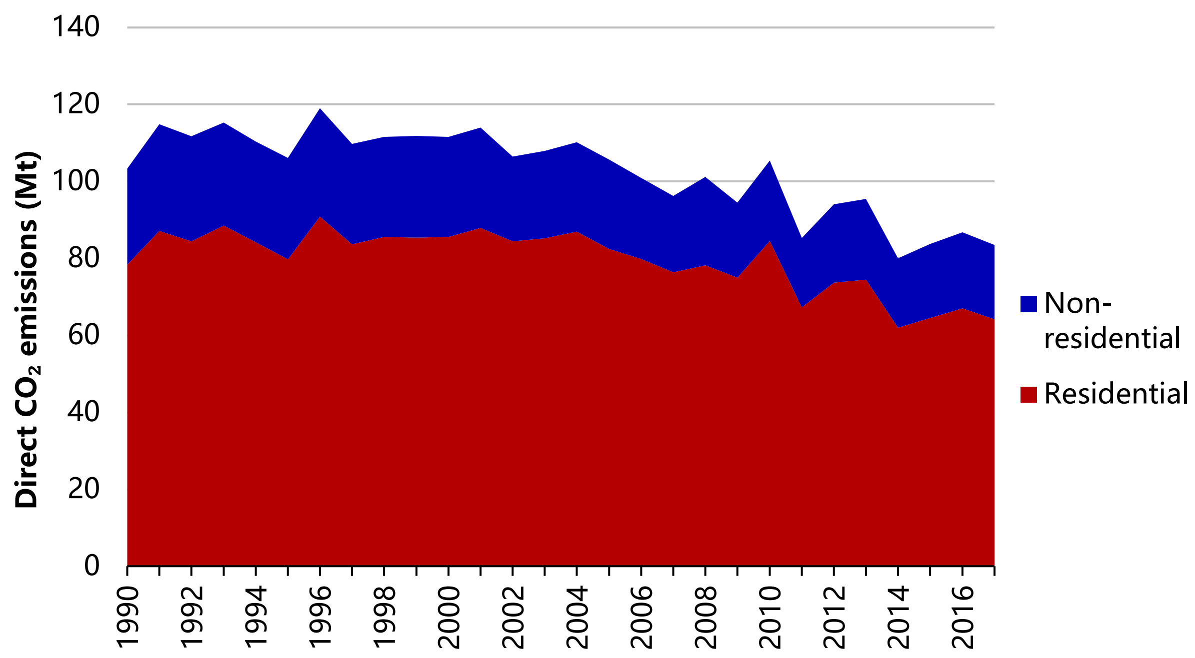
Source: BEIS (2018) *Final UK greenhouse gas emissions national statistics 1990-2016*; BEIS (2018) Provisional UK greenhouse gas emissions national statistics 2017; BEIS (2018) *Energy Trends, March 2018*.
Notes: 2017 emissions are based on provisional emissions data. Residential, public and commercial non-CO_2 emissions round to 0% of total UK emissions, but are non-zero.

Direct emissions in buildings result primarily from the use of fossil fuels for heating. Around 75% of the UK's heating demand in buildings is met by natural gas, 8% by oil, with most of the remainder from electricity. Electricity consumption mainly stems from the use of appliances and lighting in homes, and cooling, catering and ICT equipment in non-residential buildings:[68]

- Direct building CO_2 emissions were 83 $MtCO_2$ in 2017, split between homes (77%), commercial buildings (14%) and public buildings (10%).
- Buildings are responsible for 66% of UK electricity consumption, equivalent to a further 48 $MtCO_2e$ of indirect emissions. Indirect emissions have been falling at an average rate of 8% per year since 2009, due to both reductions in demand and the decarbonisation of electricity generation.
- Around 2 $MtCO_2e$ of non-CO_2 emissions (methane and nitrous oxide) were associated with buildings in 2017.

Direct emissions from buildings have fallen by 11%[69] from 1990. Falls in emissions largely reflect energy efficiency improvements in buildings and growth in bioenergy use (Figure 3.2).

Figure 3.2. Direct CO_2 emissions from the buildings sector since 1990



Sources: BEIS (2018) *Final UK greenhouse gas emissions national statistics 1990-2016*; BEIS (2018) *Provisional UK greenhouse gas emissions national statistics 2017*.
Notes: 2017 emissions are provisional. Emissions data are not temperature-adjusted.

[68] In existing homes, lighting and appliance demand is responsible for around 16% of annual energy consumption. In new homes it is estimated to be responsible for around a third of total demand. CCC (2018) *UK housing: Fit for the future?*
[69] Temperature-adjusted emissions, to show underlying trend.

2. Reducing emissions in buildings

(a) The current role of low-carbon sources

In 2017, 4.5% of total buildings heat demand was supplied from low-carbon sources. However, around 82% of that was bioenergy,[70] which is not the long-term best use of finite bioenergy resources.

- Biomass is currently mainly used in domestic stoves (around 1 million homes) with low numbers of biomass boilers. In addition to being poorly aligned with longer-term best use, burning biomass can lead to air quality issues.
- Deployment of heat pumps has remained stagnant, accounting for under 1% of annual heating system sales.
- In non-residential buildings, there are poor data around current electric heating demands and uncertainty around the level of reversible air conditioning units, but growing levels of bioenergy use supported by the Renewable Heat Incentive.
- Only 7% of heat in heat networks comes from low-carbon primary fuel sources. Around 2 TWh of biomethane is currently injected in to the gas grid every year.

(b) Options for reducing emissions further

In the buildings sector, opportunities for further emission reductions are in three main areas: switching away from fossil-fuel based heating; increasing the energy efficiency of the building stock, and improving the energy efficiency of lighting and electrical appliances.

- **Low-carbon heat.** In the Committee's scenarios for the fifth carbon budget the low-carbon share of heat in buildings increases to at least a quarter by 2030. Our central scenario included a little under 50 TWh of low-carbon heat in the non-residential sector, alongside heat pumps in 2.3 million homes and low-carbon heat networks in 1.5 million homes.
- **Residential energy efficiency.** Our central scenario for the fifth carbon budget in 2030 factored in a 6 $MtCO_2e$ reduction in direct emissions from energy efficiency measures in homes. This included insulating solid walls in 2 million homes, cavity walls in 6 million homes and topping up loft insulation in 9 million homes. In addition, we estimate that take-up of energy efficiency measures could reduce electricity use by 30 TWh by 2030, largely driven by uptake of the most efficient white appliances, electric ovens and televisions, with 7 TWh associated with the switch to more efficient lighting.
- **Non-residential energy efficiency.** Our central scenario for the fifth carbon budget includes a 5 $MtCO_2e$ reduction in direct emissions to 2030 from energy efficiency. This involves energy management and energy efficiency in heat, cooling and ventilation. The scenario also includes a 20.5 TWh reduction in electricity demand from efficient lighting; heating, cooling and ventilation, and other equipment.

Reducing emissions further towards net-zero will require more ambitious action on low-carbon heat, with energy efficiency playing a critical role to enable this. The decarbonisation of cooking

[70] Including biomass use in agricultural buildings, domestic wood use in biomass boilers, animal biomass and anaerobic digestion, plant biomass, sewage gas, and landfill gas. Excludes wood burnt on open fires.

will also be necessary. A range of supporting technologies can help facilitate the transition at a household and system-wide level:

- Energy efficiency remains an important facilitator of low-carbon heat, alongside reducing emissions and energy bills, improving competitiveness and asset values for business, improving health and wellbeing, and helping tackle fuel poverty.
- In addition to the role for heat pumps, district heat networks and storage heating examined in the Committee's advice on the fifth carbon budget, our latest work examines a wider range of technologies in greater detail, including hybrid heat pumps on and off the gas grid,[71] communal heating systems, solar thermal and heat batteries.[72]
- There are a number of facilitating technologies that can play an important role, including storage and flexibility measures. These have potential to offer bill savings to businesses and householders alongside wider system benefits (e.g. supporting management of peak demand).
- Emissions from cooking can be reduced by switching from gas appliances to electric or hydrogen appliances.[73]

It is important that deployment of low-carbon measures is not considered in isolation. The way homes are designed and lived in affects both the level of greenhouse gas emissions, and how exposed people are to the impacts of a changing climate such as hot weather and flooding. In particular, measures to address thermal efficiency, overheating, indoor air quality and moisture must be considered together when retrofitting or building new homes.

(c) Challenges in avoiding emissions from different parts of the buildings sector

There are some sources of emissions from the building stock that are relatively easier to decarbonise – with lower costs and/or fewer barriers:

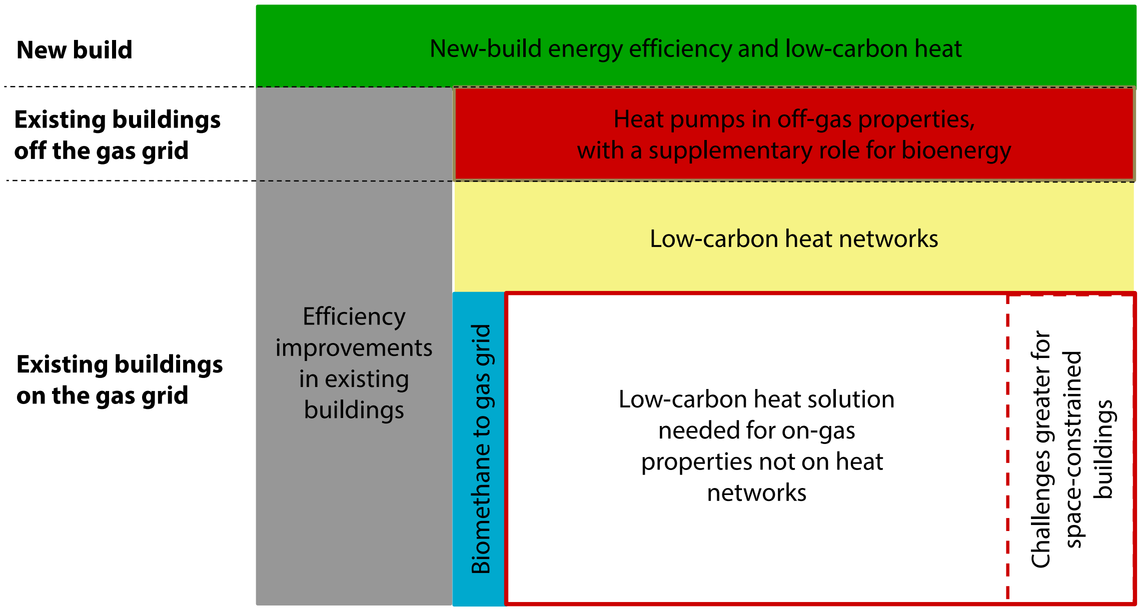
- **New buildings** are one of the most straightforward sectors of the stock to decarbonise. Our 2019 report on UK housing recommended that by 2025 at the latest, no new homes be connected to the gas grid. Instead these homes should be fitted with low-carbon heating systems (for both space and water heating) and ultra-high levels of energy efficiency. Research by Currie and Brown and Aecom also identified potential to cost-effectively tighten standards for new non-domestic buildings.[74] These steps, alongside the decarbonisation of cooking, would eradicate direct emissions from new buildings.

[71] Hybrid heat pumps can be installed alongside existing heating systems, with these secondary fuels later transitioning to low-carbon sources. For hybrid heat pumps on the gas grid, peaking gas use can be transitioned to hydrogen, whilst off the gas grid, biofuels can be used (assumed to be bio LPG for the purposes of our modelling).
[72] Heat batteries work through the use of phase change materials, which can be melted and frozen to store energy. A heat battery, equivalent in size to a slimline dishwasher, is expected to be be sufficient to service hot water demands in a typical home. Evidence from trials shows that heat batteries have been successfully used alongside heat pumps in homes, including smaller homes comparable in size to those considered in our modelling. See: Sunamp (2018) *Eastheat Interim Report*.
[73] Cooking can be decarbonised through a range of routes including electric ovens and hobs, induction hobs or hydrogen cookers and hobs where an area is converted to hydrogen.
[74] For the limited archetypes studied, a 15% reduction in carbon emissions compared to part L was found to be cost-effective against central carbon values in 2020 with savings of 20-25% cost effective by 2020 or 2025 depending on the heating system and archetype. Currie and Brown and Aecom for the CCC (2019) *The costs and benefits of tighter standards for new buildings*.

- Buildings **off the gas grid** have previously been identified as a low-regrets opportunity for deploying low-carbon heat, and heat pumps in particular. This finding has been reinforced by our latest modelling which illustrates net cost savings associated with retrofit measures in off-gas homes. In the residential sector, the latest statistics estimate that 13.9% of households in Great Britain are not connected to the gas grid.[75] Northern Ireland has a significantly lower proportion of homes that are connected to the gas grid compared to the rest of the UK, with just 24% of all households using gas for central heating in 2016. Most public and commercial buildings have either gas or electric heating, with only around 3 $MtCO_2e$ of emissions from oil-heated buildings.
- Our analysis for the fifth carbon budget found cost-effective potential for **low-carbon heat networks** with uptake in 1.5m homes to 2030 and uptake of 27.5 TWh in non-residential buildings. District heating can offer a reduced level of disruption at a building level relative to some other low-carbon heating technologies. It is widely applicable to different types of home, due to the ease of integration with existing wet-based heating systems, the direct replacement of the existing boiler with a heat exchange unit (avoiding the need for any additional space requirements) and a reduced need for radiator upgrades where heat networks are operating at higher temperatures relative to technologies such as heat pumps. Non-residential buildings can provide an anchor load for heat networks, given their greater demand.
- Buildings currently connected to the gas grid and which are not in areas suitable for heat networks face a higher cost barrier (i.e. relative to gas heating). However, our analysis has suggested that the barriers and costs of decarbonising vary significantly across homes on the gas grid and that there is a subset of on-gas homes that will generally be easier to decarbonise. These include **homes on the gas grid which do not have any constraints** on the measures they are able to take up - the key influencing factors being that they are not space constrained or of heritage value (Figure 3.3). There is a large uncertainty range on the number of homes that fall into this category, but for the purposes of this analysis we have assumed that approximately 80% of homes are not subject to space constraints.

[75] BEIS (2018) *Sub-national electricity and gas consumption statistics, Regional and Local Authority*.

Figure 3.3. Low-regrets measures and the remaining challenge for existing buildings on the gas grid



Notes: The sizes of the blocks broadly reflect the scale of emissions reduction, but do not do so precisely. Some potential for heat networks will be in new-build and off the gas grid, rather than all on-grid as presented. Biomass for heat may also play a role in hard-to-insulate rural properties. Heritage buildings have not been illustrated but will be present on and off the gas grid, as well as in areas suitable for low-carbon heat networks.

There are several constraints which can make it more difficult and/or more costly to retrofit energy efficiency measures and low-carbon heating in some segments of the stock. This includes buildings which are space-constrained, and those with heritage value:

- Where buildings are subject to **space constraints**, this can restrict the range of low-carbon heating technologies that can be installed and/or increase the costs associated with the installation of those technologies.[76] Heat pumps and electric heating for instance require hot water storage to service hot water demand. Some homes may not have rooms or cupboard space big enough to accommodate a traditional hot water tank. There are solutions which avoid the need for large hot water tanks, such as 'point of use' hot water systems and heat batteries which use phase change materials. However they can be associated with higher costs and there is a greater degree of uncertainty around the willingness of householders to accept any additional space requirements in smaller homes. The size of the home may also restrict the energy efficiency measures that can be applied, requiring the use of thin internal wall insulation (aerogels) for instance.
- A small proportion of buildings may face additional challenges as a result of having some form of **heritage status**, including buildings that are listed or in conservation areas. These buildings will be subject to more onerous planning restrictions, and may require more costly and bespoke solutions which enable the character of the property to be retained.

[76] For the purposes of our latest analysis, space constrained homes have been defined by the average room size, derived from the total floor area of the building divided by the number of habitable rooms. The threshold for a building to be considered space constrained was set at 16 m^2 which captures the smallest 20% of the stock.

Modifications to the planning framework, sensitive to heritage concerns, along with specialist training for planning officers and installers are likely to be necessary.

(d) The strengthened evidence base used in this report

We have drawn in this report on the evidence published in recent Committee reports – our advice on the fifth carbon budget and our recent reviews of hydrogen, biomass, and heat, alongside our latest report on UK housing:[77]

- Our 2016 heat report identified low-regret routes to reducing emissions from heating buildings. This has informed the approach to stock segmentation that is reflected in our scenarios.
- Our recent report on hydrogen concluded that hydrogen is best used selectively where it adds most value, alongside widespread electrification and improvements to energy and resource efficiency. This is reflected in our scenarios, which are developed on the basis of electrification, combined with the longer-term use of hydrogen to service peak heat demand, both in hybrid heat pumps and in district heating.
- Our previous analysis has emphasised the importance of limiting bioenergy use in buildings to biomethane produced from anaerobic digestion and other niche uses (as part of hybrid heat pumps systems in off gas homes and local heat networks). Our scenarios restrict the use of bioenergy to biomethane and serving peak demand in off-gas buildings with hybrid heat pumps.
- Our recent report on UK housing set out the range of policy steps that are urgently required to abate emissions from homes. We reflect these in the policy priorities we set out at the end of this chapter.

We have also commissioned and undertaken new analysis for this report. This has been focused on understanding the challenges and solutions associated with removing emissions from those homes which are expected to be amongst the hardest in the residential stock to decarbonise (Box 3.1). We reflect the new evidence along with our existing evidence base in our scenarios in section 3.

Our analysis for non-residential buildings follows a similar approach to that used for the fifth carbon budget, but has been developed using an updated baseline, new assumptions on energy efficiency based on the Building Energy Efficiency Survey (BEES) and new information on costs and system efficiencies. Evidence from the BEES and our approach to energy efficiency in non-residential buildings is summarised in Box 3.2.

Box 3.1. New research on 'hard to decarbonise' homes

We commissioned Element Energy and UCL to undertake analysis on how to abate greenhouse gas emissions from 'hard-to-decarbonise' homes, which we define as the homes for which the decarbonisation costs will be higher, the barriers harder to overcome, or the solutions more complex.

The new analysis has been developed using a spatial housing stock model of the UK. This incorporates a representation of the prevalence and coincidence of different characteristics which influence difficulty in decarbonising, including how the stock varies by country. Characteristics which have been

[77] CCC (2016) *Next steps for UK heat policy*; CCC (2018) *Hydrogen in a low-carbon economy*; CCC (2018) *Biomass in a low-carbon economy*; CCC (2019) *UK housing: Fit for the future?*

Box 3.1. New research on 'hard to decarbonise' homes

mapped include physical building attributes (such as wall type, size and heritage characteristics), location attributes (such as local heat density and availability of the gas grid) and consumer attributes (such as fuel poverty and tenure).

The analysis incorporates the latest evidence on the costs and energy savings associated with measures. For energy efficiency packages, costs and savings are based on data from real-life case studies as well as modelling to provide realistic estimates of the savings associated with measures in different archetypes. We have assumed a 16% uplift in savings to represent closure of the performance gap - in line with the recommendations made in our 2019 report, *UK housing: Fit for the future?*[78]

The analysis considers the cost optimal mix of energy efficiency and low carbon heating technology for each type of home, selecting those packages of measures which have the lowest costs in £/tCO_2e emissions saved:

- Three energy efficiency packages were modelled: low intervention (targeting a 25% reduction in heat demand), medium intervention (targeting a 40% reduction) and high (representing the highest achievable improvement).
- A wide range of low-carbon heating technologies were modelled, including heat pumps (air source, ground source and communal), hybrid heat pumps (on and off the gas grid), electric heating, storage heating, district heating, and configurations which include solar thermal and additional thermal storage. Hydrogen and biomass boilers were included but uptake was restricted in our main scenarios to reflect the findings of past research on the merits of a niche role for hydrogen and minimal use of bioenergy in buildings.
- Wider associated household costs were also modelled including radiator and piping upgrades, hot water storage, conversion costs associated with a switch away from natural gas to hydrogen, ventilation measures (focused on purge and extract ventilation), and overheating measures (focused on shading for archetypes deemed to be most at risk from overheating).

Analysis and scenario development was based around segmentation of the stock into key groups, differentiated by the ease and cost of decarbonisation. Particular analytical focus was put into those groups found to be hardest to decarbonise, namely homes with space constraints and heritage homes.

The analysis represents an advancement on our past modelling in a number of areas, including further spatial mapping of multiple characteristics, integration of real life data, and a broader range of technologies included. Nevertheless, there are key dynamics it has not been possible to incorporate which will remain important for future work. These include a spatial representation of network interactions and system level dynamics (e.g. tipping points for decisions around hydrogen grid conversion).

Source: Element Energy and UCL for the CCC (2019) *Analysis on abating direct emissions from 'hard-to-decarbonise' homes, with a view to informing the UK's long term targets.*

[78] See Element Energy and UCL for the CCC (2019), *Analysis on abating direct emissions from 'hard-to-decarbonise' homes, with a view to informing the UK's long term targets.* Whilst there is a lack of robust data, a number of studies have suggested the performance gap in best practice construction is on average 16% from 'predicted/deliverable' savings. This is distinct from the gap between actual and modelled savings (e.g. in SAP) which would be expected to be larger.

Box 3.2. Building Energy Efficiency Survey (BEES)

The Building Energy Efficiency Survey (BEES) was commissioned by the Department for Energy and Climate Change (now BEIS) in 2013 to improve the evidence-base on non-residential buildings. It reports on the energy use and potential for reduction in energy use in non-residential buildings in England and Wales in 2014-15.

The survey was based on a large sample of telephone interview with follow ups. It covers ten sectors: community, arts and leisure; education; emergency services; health; hospitality; industrial; military; offices; retail and storage:

- The largest sectors in terms of energy consumption were offices (17%), retail (17%), industrial (16%), health (11%) and hospitality (11%). Together these make up 71% of non-residential energy demand.
- The four largest energy end uses were space heating, internal lighting, catering and cooled storage (for storage of food and drink), which accounted for 70% of total consumption.

Abatement potential for a 39% reduction from current energy consumption was identified. Almost half of this came from measures with a private investment payback of three years or less. The greatest contributors to energy savings were carbon and energy management, building instrumentation and control, lighting, space heating and building fabric measures.

Use of the BEES in our analysis

We have excluded industrial buildings in the BEES data from the analysis in this chapter since these are covered in our industry analysis. We have also excluded abatement potential from space heating to avoid any potential double counting, as we consider heat pumps and heat networks separately.

BEES data on energy consumption and abatement costs are scaled to cover the UK building stock. We use the non-electric fuel savings from the BEES to inform our heat savings (adjusting for system efficiency when we apply this to electric heating). We use the remaining electricity abatement potential (after deducting electric heat savings) to reduce electricity demand from non-residential buildings, reducing indirect emissions.

The energy savings potential resulting from this analysis is lower than the headline result suggested in the BEES, with 25% savings for non-electric heating fuels, 20% for electric heating and 21% of non-heat electricity consumption. This is a result of a combination of excluding savings from industry (which has 46% savings potential) and space heating and our adoption of a conservative approach so as not to assume that the savings from the BEES would necessarily be representative of all non-residential buildings.

Since data are not available on the split of total abatement costs between electricity savings and non-electric fuel savings, we have apportioned costs. We have assigned the full costs for building fabric measures and hot water measures and a small share of costs of some other abatement types to heat savings. We assign the remaining costs to non-heat electrical savings.

Source: BEIS (2016) *Building Energy Efficiency Survey 2014-15: Overarching Report* and *BEES Overarching Tables*.

Other evidence we have reviewed for the purposes of this report includes the range of submissions made to the Committee's call for evidence on a Zero Carbon Economy, and recent reports relating to buildings and net-zero ambitions released by the Energy Technologies

Institute, the Energy Systems Catapult, the European Commission and the International Energy Agency amongst others.[79]

3. Scenarios for minimising buildings emissions

(a) Opportunities for cutting emissions towards zero

As set out in Chapter 1, we have classed the options for cutting emissions towards zero in three categories:

- **Core options** are those low-cost low-regret options that make sense under most strategies to meet the current 80% 2050 target. For most the Government has already made commitments or begun to develop policies (although in many cases these need to be strengthened).
- **Further Ambition options** are more challenging and/or more expensive than the Core options, but are all likely to be needed to meet a net-zero target.
- **Speculative options** currently have very low levels of technology readiness, very high costs, or significant barriers to public acceptability. It is very unlikely they would all become available. Some of these options would be required to reach net-zero GHG emissions domestically.

We have created our Core and Further Ambition scenarios for residential buildings on the basis of the difficulty of decarbonising different segments of the stock (defined predominantly by building or locational characteristics), and the costs of decarbonising these segments. We have not directly allocated homes to different scenarios according to tenure or fuel poverty, although these are important characteristics which influence the difficulty of decarbonisation and will need to be addressed through appropriate policy measures.[80]

For non-residential buildings, our scenarios reflect the difference in difficulty and cost of decarbonising different segments. Since we assume that near-complete decarbonisation of non-residential buildings is possible, the difference between our scenarios is largely around the timing of transition.

We set out the scenarios for residential buildings and non-residential buildings in the following sections, before bringing the two together in the final section.

Residential buildings

Our residential scenarios represent one illustration of how different levels of abatement might be achieved. Whilst a number of significant uncertainties remain, the new analysis reinforces findings to date on the critical role of energy efficiency in the near term and on the role that can be played by hydrogen as a complement to electrification. It also acts as a first step in analysing

[79] Energy Technologies Institute (2018) *Clockwork and Patchwork - UK Energy System Scenarios, Options, Choices Actions (Updated*); Energy Systems Catapult (2019) *Smart Energy Services for Low Carbon Heat;* European Commission (2018) *A Clean Planet for all;* International Energy Agency (2019) *Perspectives for the Clean Energy Transition - the critical role of buildings.*

[80] An assessment of our stock segmentation indicates that tenure is fairly evenly spread across stock segments overall, albeit with a slightly higher proportion of local authority and private rented properties with space constraints.

those characteristics which distinguish some of the hardest to decarbonise sectors of the building stock.

Core options in homes

Our Core scenario for residential buildings includes deployment of energy efficiency and low-carbon heating measures in low-cost and/or 'easier-to-decarbonise' segments of the stock, namely new homes; homes off the gas grid; homes suitable for low-carbon heat networks (both heritage and non-heritage); and homes on the gas grid with relatively low barriers (i.e. no space or heritage constraints). Where hybrid heat pump solutions are deployed on the gas grid, they are assumed to consume natural gas, such that peak heat demand is not decarbonised.

The weighted average cost of decarbonisation for each group of homes in the Core scenario is under £250/tCO_2e (Table 3.1). However, by definition some of the homes in this scenario have costs above the average, and up to around £420/tCO_2e.[81] The most costly homes tend to be the smaller, more energy efficient properties that receive higher cost low-carbon heating systems without potential for significant improvement in energy efficiency. Nevertheless where energy efficiency improvements are made, there are expected to be additional co-benefits that have not been costed (e.g. comfort and health).

We have made a simplifying assumption to allocate these homes to the Core scenario, but in practice they may be expected to decarbonise in the latter part of the trajectory to 2050.

Together, the homes decarbonised in our Core scenario make up around 85% of the total stock, and deliver 66 MtCO_2e of direct abatement, leaving residual emissions of up to 20 MtCO_2e.

- Our Core scenario is associated with a mix of insulation measures providing a 21% reduction in energy demand in homes. This compares to a 17% reduction assumed in our fifth carbon budget 'max' scenario to 2050.[82] The higher levels of energy efficiency are associated with more optimistic assumptions on loft insulation potential,[83] as well as incorporation of the latest evidence on the costs and savings associated with energy efficiency measures and an approach to determining cost-effectiveness linked to our new research (Box 3.1). Early deployment of these measures maximises energy bill and carbon savings (including delivering benefits for fuel poor households), and prepares the stock for low carbon heating.
- In terms of low-carbon heat, alongside the 5m homes in our Core scenario connected to low-carbon heat networks, our Core scenario includes use of heat pumps in 17 million homes (including Air Source Heat Pumps (ASHPs), Ground Source Heat Pumps (GSHPs), communal ASHPs and hybrid heat pumps both on and off the gas grid). For homes with hybrid heat pumps off the gas grid, we include a switch to biofuels to meet peak heat demand. Hybrid heat pumps on the gas grid, and low-carbon heat networks, continue to use gas to meet peak demand. The technology mix also includes a small number of homes reliant on electric storage heating (around 260,000).
- We assume levels of lighting and appliance efficiency consistent with those developed for the fifth carbon budget max scenario (equivalent to a 27 TWh reduction in electricity

[81] Where the costs of decarbonisation exceed around £420/t for homes in archetypes assigned to the Core scenario, these homes instead receive energy efficiency measures in our Further Ambition scenario and remain on their counterfactual heating systems, only getting fully decarbonised in the Speculative scenario.
[82] Representing savings in homes relative to 2015, excluding boiler efficiency.
[83] These include the insulation of lofts with less than 50 mm of insulation currently, and further top-ups for those lofts that already have 200 mm of insulation. We intend to consider levels of energy efficiency further for the sixth carbon budget.

demand in 2050), and we have also assumed that from 2030 all cooker replacements are electric.[84]

Government aspirations and commitments, whilst in need of strengthening and extending, target the decarbonisation of homes across these groups. Current Government commitments include:

- The Clean Growth Strategy aspirations around home retrofits (EPC band C by 2035 where practical, cost-effective and affordable), which should lead to widespread energy efficiency improvements both on and off the gas grid, preparing these homes for low-carbon heat.[85] Achieving this will require a reversal of recent slow-downs in energy efficiency installations (with installation rates in 2017 just 5% of peak market delivery in 2012).
- The Future Homes Standard announced in the 2019 Spring Statement, which should ensure new build homes have low-carbon heating and world-leading levels of energy efficiency by 2025.
- Phasing out the installation of high-carbon fossil fuel heating in homes off the gas grid in the 2020s, with a planned consultation on the regulatory framework.
- The commitment in the Clean Growth Strategy to build and extend heat networks across the country, and the recent consultation on developing a market framework for heat networks.
- Current funding for low-carbon heating which is sufficient to 2020/21. Funding beyond this has yet to be announced.

Further Ambition options in homes

In our Further Ambition scenario for residential buildings, harder and/or more costly segments of the stock are decarbonised, namely homes on the gas grid with space constraints, and homes with some form of heritage value. As in the Core scenario, the most costly 10% of homes remain using fossil fuel heating in 2050 (but benefit from energy efficiency improvements).

Homes in the Further Ambition scenario are associated with 83 $MtCO_2e$ of abatement in total, leaving residual emissions of up to 4 $MtCO_2e$ in 2050. This includes 0.2 $MtCO_2e$ of savings resulting from biomethane injected into the gas grid.

The segments of abatement additionally included in the Further Ambition scenario are practicable, but more difficult and/or more costly to achieve than the segments allocated to the Core scenario:

- **Converting residual gas demand to hydrogen**. The future role of hydrogen rests on strategic decisions about how the decarbonisation of heat will be delivered in the UK. It also relies on the implementation of Carbon Capture and Storage (CCS), given its importance for low-carbon hydrogen production at scale. When technical feasibility is demonstrated and decisions made, production (primarily from natural gas) will require a significant

[84] This is a simplifying assumption. Alternative technologies include induction hobs and hydrogen cookers where hydrogen is available. Induction hobs are more energy efficient, but can also interfere with pacemakers so are not suitable for all households.

[85] We have not undertaken analysis on the equivalence of levels of energy efficiency in our scenarios and EPC ratings. Since EPC ratings are cost-based, they are more suited to issues around fuel poverty rather than energy efficiency improvements or emission savings. The ratings are subject to fuel price variations over time which can lead to perverse incentives where emission saving measures involve a switch in fuels. For further discussion see CCC (2019), *UK housing: Fit for the future?*

infrastructure programme to build dedicated new hydrogen transmission pipelines, hydrogen storage capacity (e.g. salt caverns), large volumes of CCS and hydrogen production capacity. On this basis we have allocated the conversion of the gas grid to hydrogen to the Further Ambition scenario. Estimated costs associated with switching residual demand to hydrogen are based on the assumption that hybrid homes have hydrogen-ready boilers.[86]

- **Homes on the gas grid with space constraints**. Compared to those homes on the gas grid included in our Core scenario, homes with space constraints (such as smaller rooms) are generally expected to be more expensive to decarbonise. This reflects the restricted number of technologies suitable for these homes and increased costs associated with some space-saving technologies (Box 3.3).
- **Heritage homes**. Whilst there is uncertainty over the number of homes with heritage characteristics, our analysis estimates there to be around 1.3m heritage homes in total (including Grade I/II*/II listed buildings and buildings in conservation areas), with around 825,000 occurring outside of heat dense areas.[87] There is a large degree of uncertainty over the costs and suitability of different measures in these homes, but decarbonisation is expected to be more challenging than for other segments of the stock (Box 3.4).

Box 3.3. Decarbonising space-constrained homes

For the purposes of our latest analysis, we define space-constrained homes using a room-size metric, designed to capture the 20% of homes with the smallest rooms.[88]

Homes with space constraints are generally expected to be more expensive to decarbonise, as a result of the restricted number of technologies suitable for these homes and increased costs associated with some space saving technologies:

- Heat pumps and electric heating typically require hot water storage, conventionally in the form of a large hot water tank, to service hot water demand. There are innovative solutions which remove the need for a conventional hot water tank, reducing space requirements in the home.
  - Heat batteries have potential to offer improved heat storage (including greater storage capacity and lower losses) in a smaller space.
  - Point-of-use water heating delivers localised hot water to sinks, baths or showers using a resistive heating module which can be located under the water outlet.
  - Where these technologies are viable they are currently more expensive than conventional technologies when purchased at household level. With increased uptake and innovation there is scope for cost reductions and technological improvements, and there are also expected to be savings in installation and maintenance costs. We assume that heat batteries become cost competitive with hot water cylinders by 2030.

[86] Where this is not possible, it is expected that boiler replacements would need to take place before the end of the natural lifetime of existing boilers, driving up costs.
[87] Element Energy and UCL for the CCC (2019) *Analysis on abating direct emissions from 'hard-to-decarbonise' homes, with a view to informing the UK's long term targets.* Based on data taken from English heritage GIS layers on the number and location of listed buildings, and from Bottrill, C. (2005) *Homes in Historic Conservation Areas in Great Britain: Calculating the Proportion of Residential Dwellings in Conservation Areas.* The total number remains uncertain however. In addition to uncertainty around the number of homes in conservation areas, there is uncertainty over the degree of overlap between heritage and conservation area homes.
[88] Defined as those with an average total dwelling floor area per habitable room of 16 m^2 or less - based on EPC data.

Box 3.3. Decarbonising space-constrained homes

- We have made a conservative assumption that even with space-saving technologies, heat pumps remain suitable in only 50% of space-constrained homes, due to uncertainties over consumer acceptability of remaining space demands. We have assumed that hybrid heat pumps with thermal storage are not viable in space constrained homes (due to the need to accommodate a heat pump and a boiler, alongside thermal storage), but that hybrid heat pumps without thermal storage are suitable in 50% of space constrained homes.
- The size of the home may also restrict the energy efficiency measures that can be applied, necessitating the use of thin internal wall insulation (typically 10-18 mm thick) in place of conventional internal wall insulation (typically 60 mm thick). In the absence of detailed evidence on the costs and savings potential associated with thin internal wall insulation, we have made a simplifying assumption that space-constrained homes can be fitted with conventional solid wall insulation. However, thin internal wall insualtion is likely to be necessary. It is expected to be available at lower cost and with lower associated energy savings relative to conventional insulation, which can in turn be expected to impact the cost-effectiveness of deployment of decarbonisation packages. This remains an area for future analysis.

Sources: Element Energy and UCL for the CCC (2019) *Analysis on abating direct emissions from 'hard-to-decarbonise' homes, with a view to informing the UK's long term targets;* Sunamp (2018) *Eastheat Interim Report.*
Notes: Heat batteries have been assumed to be necessary in space constrained homes with heat pumps, whilst homes with resistive or storage heating have been assumed to require point-of-use water heating. In each case the alternative technology may also be viable. Where hybrid heat pumps are installed without thermal storage, they will be capable of decarbonising space heat demand in the home but not hot water demand.

Box 3.4. Decarbonising heritage homes

The UK has some of the oldest housing stock in Europe, with nearly 38% of its homes dating before 1946 according to data from BRE. Many of these homes will have some form of heritage status.

In general, homes with heritage status are likely to be subject to more onerous planning restrictions, and may require more costly and bespoke decarbonisation solutions which enable the character of the property to be retained.

Of the 1.3m heritage homes in our scenarios, around 450,000 are assumed to be in areas suitable for low-carbon heat networks. We have made a simplifying assumption that these homes are likely to remain easier to decarbonise as a result of the relative ease of retrofitting heat exchangers in homes, and the reduced need for energy efficiency where low-carbon heat networks provide heat at high temperatures.

825,000 heritage homes remain which we have assumed to be subject to restrictions on the suitability of measures they are able to take up, and higher costs in retrofitting measures:

- A stricter planning regime is assumed to exist in some areas. On this basis, we assume that heat pumps and solar thermal are only suitable in 50% of heritage homes. We have also allowed for limited suitability of a range of insulation measures, including assuming double glazing is unsuitable in listed properties. We have included cautious assumptions in this area, which are judged to align broadly with current perspectives on acceptability.
- Cost uplifts are predominantly assumed to be associated with listed homes, rather than unlisted homes in conservation areas. In listed homes, our central assumptions include a 50% uplift in heat emitter and resistive and storage heating costs to allow for additional costs associated with piping and wiring, and for the installation of systems which retain the character of the property. For

Box 3.4. Decarbonising heritage homes

energy efficiency measures, we have assumed cost uplifts of 80% for timber framed windows in conservation area homes, and increased costs for secondary glazing, wall, floor and loft insulation measures in listed homes to account for the need to apply them in such a way that historic detailing can be retained (with assumed uplifts of 100%, 150%, 100% and 15% respectively).

In our Further Ambition scenario and based on our central assumptions, we find the weighted average costs of measures in heritage homes to be around £200/tCO_2e.[89] That this appears low relative to other segments of the stock is likely to reflect that suitability constraints are only assumed to apply to roughly 50% of heritage homes, and due to the high proportion of homes in conservation areas that are not listed (given that these face very only limited cost uplifts). The heritage homes which are decarbonised in the Further Ambition scenario include those with access to lower cost forms of heating such as heat pumps and hybrid heat pumps.

The heritage homes which fall into our Speculative scenario are predominantly those where relatively costly electric storage heating systems are the cheapest suitable technology. The homes in the speculative stock tend also to be smaller, where the cost of the renewable heating system per unit of heat delivered is higher.

The total weighted average cost for all heritage homes outside of heat dense areas is around £275/tCO_2e in 2060. The costs are highly uncertain however. We modelled the impact of using upper bound cost assumptions, finding that this leads to a 12% increase in the weighted average costs.[90]

These costs exclude the additional costs associated with obtaining planning permission.

In addition to the need for further research on the costs and difficulty of decarbonising heritage homes, a policy focus in two key areas has potential to support reductions in decarbonisation costs for this segment of the stock:

- The potential for cost-effective decarbonisation will grow in the context of an ambitious and forward-looking planning framework. Modifications to the planning framework, sensitive to heritage concerns, will need to be considered.
- The cost of installing measures will also be a function of the level of skill and experience amongst installers. This should be considered as part of initiatives under the Construction Sector Deal to tackle the low-carbon skills gap.

Sources: Element Energy and UCL for the CCC (2019) *Analysis on abating direct emissions from 'hard-to-decarbonise' homes, with a view to informing the UK's long term targets;* BRE (2016) *The cost of poor housing in the European Union*; Sustainable Traditional Buildings Alliance *Responsible retrofit guidance wheel*; engagement with Historic England, Historic Environment Scotland, Welsh Government, PDP London, Gannochy Trust, and the Passivhaus trust.
Notes: No heritage flats are deemed suitable for heat pumps or solar thermal. The heritage assumptions have been informed by UCL's research and experience, the STBA's 'Responsible Retrofit Wheel, case study data on retrofit costs for older and heritage homes and consultation with heritage bodies alongside a small number of professionals working in retrofit of heritage buildings.

[89] Also including the costs associated with hydrogen and biofuel conversion for peak demand associated with hybrid heat pumps in these homes.
[90] In listed homes, upper bounds include a 75% increase in the cost of heat emitters and in resisitve and storage heating costs, and increases of 300%, 200% and 80% in insulation of walls, floors and lofts respectively. The impact on total costs is moderate due to the relatively low incidence of efficiency measures subject to these cost increases in the scenario.

As for the Core scenario, our analysis has reinforced the value of energy efficiency and electrification, alongside illustrating the complementary role that can be played by hydrogen for low-carbon heat:

- In total the energy efficiency measures in our Further Ambition scenario represent a 25% reduction in energy demands as a result of fabric efficiency measures. This includes around 6 million cavity walls and 6 million solid walls (of which 3.25 million are for wider benefits).[91] It also includes more optimistic assumptions on loft insulation potential relative to our fifth carbon budget.
- Alongside 5 million homes connected to low-carbon heat networks, our Further Ambition scenario includes around 19 million heat pumps in homes. Around three quarters of these are full heat pump installations,[92] whilst a quarter are heat pumps installed as part of a hybrid system, relying on alternative fuels to meet heat demand at peak - hydrogen for homes on the gas grid and bio-based fuels (modelled as bio LPG) for homes off the gas grid. Deploying heat pumps at this scale will require a very substantial increase in the rate of uptake in homes. In addition to requiring growth in the number of heat pumps installed at the point of heating system replacement, there is scope for hybrid heat pumps to be retrofitted at the same time as energy efficiency improvements are made. The scale of deployment should be such that hybrids are widely used by 2035 (e.g. in 10 million homes), reducing the later challenge of tackling residual gas use. The technology mix in our Further Ambition scenario also includes around 460,000 homes with electric storage heating.
- For the Further Ambition scenario we assume levels of lighting and appliance efficiency consistent with those developed for the fifth carbon budget (equivalent to a 27 TWh reduction in electricity demand in 2050), and we have assumed that from 2030, no new gas cooking appliances are installed.

Alternative options to deliver the Further Ambition scenario in homes

In many cases there are alternative technical or behavioural approaches that could deliver emission savings. For residential buildings, the Further Ambition scenario could be delivered with a range of different heating technology mixes.

Our new analysis and the findings of our recent Hydrogen review suggest that there are three approaches to decarbonising residential buildings with roughly similar costs:

- **Hybrid heat pumps.** The new analysis finds that conventional heat pumps and hybrid heat pumps are finely balanced in terms of cost effectiveness with the cost-optimal mix heavily influenced by small changes in the capital and operational costs (Box 3.5). The level of energy efficiency deployed is also expected to be a determinant. The role of hybrid heat pumps on

[91] In our fifth carbon budget central scenario, we included 2 million additional solid wall insulation measures for wider benefits, including greater energy affordability, particularly for the fuel poor, and the associated health benefits from living in better insulated homes. We increased this to 4.5 million measures in the fifth carbon budget max scenario. For our current assessment we have assumed a mid-point between these values, and have included an additional 3.25 million solid wall insulation measures for wider benefits.

[92] Approximately 1 million have a communal configuration (either a communal air source heat pump, or a ground source heat pump with a shared ground loop), and around 1.7 million are installed alongside heat batteries in homes with space constraints. There is potential for heat batteries to play a larger role across the stock, to the extent they offer an affordable and more acceptable solution for householders as a result of reduced space requirements, or increased heat storage capacity. Where at cost parity with hot water tanks, the two technologies can be considered as interchangable in our scenarios.

the gas grid in 2050 is also fundamentally dependent on the feasibility of hydrogen conversion in relevant areas of the grid, where seeking to get to towards net-zero emissions.

- **Full electrification.** We have also examined the implications of removing hydrogen and gas to deliver full electrification. This leads to uptake of 19 million heat pumps in homes for the Further Ambition scenario. As implied by the fine balance of cost effectiveness between hybrid and full heat pumps, in this alternative scenario costs are broadly similar. Emissions are still reduced to around 4 $MtCO_2e$ before accounting for biomethane.
- **Hydrogen boilers.** In line with our recent Hydrogen report, our scenarios are based on the assumption that hydrogen is best used selectively, where it adds most value alongside widespread electrification and improvements to energy and resource efficiency. However it is also possible that hydrogen could play a more dominant role. Uptake of 16 million hydrogen boilers could deliver similar emissions savings as our Further Ambition scenario, which predominantly uses heat pumps. At a building level this could be cheaper (with hydrogen boiler costs assumed comparable to conventional boilers), but our previous work has shown that when modelled at a system level (incorporating detailed representation of national infrastructure costs), the costs of a range of pathways for heat decarbonisation are similar.[93]

In addition to variations in the dominance of core technologies in the mix of measures, there are also other technologies such as solar thermal heating that could play a niche or supporting role (Box 3.6).

Box 3.5. Heat pumps and hybrid heat pumps in homes

The new analysis confirms the view that conventional heat pumps and hybrid heat pumps are finely balanced in terms of cost-effectiveness.

Sensitivities run on our scenarios show that small changes in the input assumptions lead to large changes in uptake. For instance, where hybrid heat pump maintenance costs ('opex') are reduced by around £50,[94] the cost optimised technology mix results in a swing from a quarter of heat pumps being hybrids, to 61% of all heat pumps being hybrids. Where capex for hybrids is also reduced by around £500 (for instance where the need to replace gas pipework in homes is avoided), the hybrid proportion increases to 77%. A sensitivity which assumes an increased cost of capital (7.5% relative to the 3.5% assumed in our main scenarios), also leads towards a hybrid dominated mix.[95]

We set out below the input assumptions that have been used to develop our scenarios. Input assumptions have been drawn from the latest available research and evidence, including Element Energy's Hybrid Heat Pump analysis for BEIS (2017).

[93] CCC (2018) *Hydrogen in a low-carbon economy*; and Imperial College London for the CCC (2018) *Analysis of Alternative UK Heat Decarbonisation Pathways*.
[94] This would be equivalent to assuming no increase in opex associated with adding an additional heating technology (i.e. the opex for a heat pump is equivalent to a boiler plus a heat pump), but retaining the additional opex associated with the catalyst to reduce NO_x emissions from the hydrogen boiler.
[95] This reflects the lower capital cost of hybrids relative to heat pumps on average, once the household conversion costs are included (such as emitter upgrades and hot water cylinders, which are more commonly required in the case of heat pumps than hybrids).

Box 3.5. Heat pumps and hybrid heat pumps in homes

Heating technology costs

Assumptions on heat pump costs remain broadly comparable to those assumed in the fifth carbon budget. In line with the fifth carbon budget we have also assumed a 20% reduction in the cost of heat pump units and installation by 2030.

Opex costs are generally assumed to be around £100/yr across technologies. However for the hybrid heat pump system we have assumed that the opex is equivalent to the sum of the two components of the hybrid system, with a £50 saving reflecting economies of scale. For on-gas hybrids a 50% uplift in the hydrogen boiler opex component is applied, due to the need to replace the catalyst for reducing NO_x emissions. Off-gas hybrids are associated with higher opex to cover the cost of LPG delivery and storage.

Table B3.5. Cost assumptions for heat pumps and hybrid heat pumps

Heating technology	Fixed capex		Marginal capex		Opex
	2025	2050	2025	2050	
Air source heat pump	4404	3914	264	235	102
Ground source heat pump - shared ground loop	8478	7988	264	235	102
Hybrid heat pump - on gas, with hydrogen	5677	5187	264	235	191
Hybrid heat pump - off gas, with biofuels	5963	5480	264	235	219

Sources: Element Energy (2018) *Hydrogen supply chain evidence base, Report for BEIS*; Element Energy (2017) *Hybrid Heat Pump analysis for BEIS* https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/700572/Hybrid_heat_pumps_Final_report-.pdf.

Notes: All costs in 2018 prices. Costs for heat pumps include heat pump unit and installation, excluding the costs of low-temperature radiators and hot water storage. For ground source heat pumps, it has been assumed that the ground loop costs are shared between properties, with each property having an individual heat pump. Hybrid heat pump costs include the cost of a heat pump unit, hydrogen-ready boiler, controller unit, and installation costs. Total capex costs for a unit are the sum of the fixed capex component, and the marginal capex multiplied by the size of the unit in kW.

Box 3.5. Heat pumps and hybrid heat pumps in homes

In addition to heating technology costs, a range of associated measures have been costed according to need. This includes the installation of a hot water tank or heat battery to enable hot water provision in homes,[96] the upgrade of piping and radiators in homes where needed to facilitate low-temperature heating, replacement of cooking appliances in switching from gas to non-gas heating systems, and hydrogen pipework and conversion (including around £50 of labour costs for the switchover of the Hyready boiler at the point of hydrogen conversion).

Efficiencies

Heat pump and boiler efficiencies have been broadly aligned with assumptions for the fifth carbon budget. Heat pump efficiencies have been modified to vary with the the flow temperature assumed in the home, as facilitated by any radiator upgrades. An increase of 0.5 in seasonal performance factors (SPFs) is assumed by 2030 (e.g. from an SPF of 2.5 to 3). Where a hybrid heat pump is installed with thermal storage (in the form of a hot water cylinder or hot water tank), the heat pump is assumed to be able to meet 80% of both space heat and hot water demand. Where installed without thermal storage, it is assumed to be able to service 80% of space heat demand only, with all hot water demand being met by the boiler.

Lifetimes

In line with our assumptions for the fifth carbon budget we have assumed that air source heat pumps have a lifetime of 18 years, ground source heat pumps have a lifetime of 20 years and that boilers and hybrid heat pumps have a lifetime of 15 years.

Sources: CCC; Element Energy and UCL for the CCC (2019) *Analysis on abating direct emissions from 'hard-to-decarbonise' homes, with a view to informing the UK's long term targets.*

Box 3.6. Other technologies considered in our scenarios

We modelled a range of heating system configurations in the scenarios. This included solar thermal heating being installed alongside an air source heat pump, storage heater, or a resisitive heating system. It also included allowing for uptake of additional thermal storage in homes with heat pumps to allow for peak shifting.

- Solar thermal uses the energy of the sun to heat hot water through panels, typically installed on rooftops. It is not a standalone heating technology, but can be integrated into a system to supply hot water during months with high solar radiation. If used with a large thermal store, it can also supplement space heating. This approach combines well with heat pumps, as the thermal store simultaneously improves the efficiency of the heat pump by reducing cycling, and allows consumers to make use of off-peak electricity tariffs.
- Additional thermal storage can come in the form of a larger hot water tank, or alternatively a heat battery. There is also potential for the building fabric of homes to act as a thermal store, enabling home owners to preheat the home during off-peak hours, although this latter capability was not modelled.

[96] For a medium-sized building in 2020, a hot water cylinder is assumed to cost in the region of £1060, and a heat battery is assumed to cost in the region of £1720, reaching cost parity with hot water cylinders by 2030. For hybrid heat pumps, an option was provided in the model to include or exclude thermal storage. Where included, thermal storage can enable decarbonisation of both space heat and hot water demand. Where excluded, hybrid heat pumps are able to decarbonise space heat demand only. This latter configuration has been the focus on the majority of research to date.

Box 3.6. Other technologies considered in our scenarios

There is limited take up of these technologies in our scenarios on the basis of the input assumptions used in this modelling. However there remains scope for them to play a role in the heating mix.

- For solar thermal, developing a full picture of cost-effectiveness across the building stock requires detailed consideration of a range of issues such as variation between summer and winter efficiencies of the back-up heater, and interactions with the rest of the heating system (e.g. electric showers) which it has not been possible to assess in this work. There may also be also scope for bigger systems to offer better economic potential, particularly incorporated in to low-carbon heat networks.
- Recent modelling by Imperial College London confirms that using thermal storage in domestic premises to shift demand for electric heating can be a viable alternative to other methods of providing electricity system flexibility such as battery storage or electrolysis.

Sources: CCC; Element Energy and UCL for the CCC (2019) *Analysis on abating direct emissions from 'hard-to-decarbonise' homes, with a view to informing the UK's long term targets*; Imperial College London for the CCC (2018) *Analysis of Alternative UK Heat Decarbonisation Pathways.*

Speculative options in homes

Achieving emissions reductions consistent with the Further Ambition scenario by 2050 is ambitious, but achievable with a concerted and robust policy framework from Government. Nevertheless, there remain a number of significant uncertainties which make it likely that a small tranche of abatement will remain particularly difficult to decarbonise by 2050.

Our Further Ambition scenario has up to around 4 $MtCO_2e$ of emissions unabated in 2050:

- Such a level of remaining emissions in 2050 could be associated with leaving around 10% of the residential housing stock which is most costly to decarbonise, using fossil fuel heating.
  - These homes are generally small- or medium-sized properties which are relatively energy efficient (i.e. have insulated walls and roofs) but require higher cost low-carbon heating systems (e.g. electric storage heating). Half of these homes are space-constrained.
  - For this group of homes there is a greater level of uncertainty over appropriate low-carbon heating solutions. Where these homes are on the gas grid in areas which are converted to hydrogen, hydrogen boilers are likely to prove a straightforward and cost-effective solution. However, where off the gas grid, or in areas not converted to hydrogen, these homes can be expected to remain the most expensive to decarbonise, therefore remaining on fossil fuel heating for the longest.
- Alternatively if installing low carbon heating in all homes, a 4 $MtCO_2e$ residual would be equivalent to around half of the remaining gas demand from hybrid heat pumps and district heat networks not being converted to hydrogen.
  - As set out in our 2018 report, *Hydrogen in a low-carbon economy*, we do not face a simple choice between conversion to hydrogen of every gas network or complete electrification of heat everywhere. Different solutions might be appropriate to different areas, either because of public preferences or local circumstances (e.g. clusters of industrial activity, proximity to carbon storage or grid status).
  - It may be that in some areas, conversion of the gas grid to hydrogen is uneconomic, requiring hybrid homes or district heating systems in those areas to remain using

peaking gas for the longest, likely accompanied by eventual full conversion to electrification.

- Heritage homes outside of heat dense areas are associated with 3.3 $MtCO_2e$ of baseline emissions. The residual emissions left from the Further Ambition scenario could therefore be associated with a high proportion of these homes failing to be decarbonised by 2050. Emissions from heritage homes are most likely to remain where installations of heat pumps are not deemed suitable due to planning restrictions, and where electric heating is not viable due to the heat demand of the building exceeding fuse limits. In reality, decarbonisation solutions are expected to be viable even for these homes (e.g. with improved acceptability of heat pumps, or with the installation of a hydrogen or biomass boiler).

There are a range of circumstances which are consistent with residual emissions in residential buildings after 2050. Across these cases, decarbonisation is expected to be technically feasible, but costly or difficult. We assume therefore that the speculative scenario is likely to require until 2060 to approach zero emissions.

Non-residential buildings

Core options for non-residential buildings

Our Core scenario for non-residential buildings relies on a combination of energy efficiency, low-carbon heat networks and heat pumps to reach near decarbonisation of heating and hot water:

- **Energy efficiency** plays an important role in reducing heat demand in our Core scenario. We include direct abatement from a 25% reduction in heat demand for non-electric fuels due to energy efficiency savings. There is a 28 TWh reduction in heat demand from non-residential buildings in 2050 due to energy efficiency. Our updated analysis is based on the Building Energy Efficiency Survey (BEES) commissioned by BEIS (Box 3.2).
- **Low-carbon heat networks** are deployed in heat dense areas. The assumptions underlying this are consistent with our central scenario for the fifth carbon budget and have been adjusted to reflect our new baseline. This accounts for 46% of the remaining heat demand in 2050 from non-residential buildings (41 TWh). In line with our central scenario for the fifth carbon budget, we assume that gas boilers are used in heat networks to meet peak demand. This leaves 2.3 $MtCO_2e$ residual emissions from heat networks in our Core scenario in 2050.
- **Heat pumps** are assumed to be taken up in non-residential buildings in less heat dense areas. These account for the remaining 54% (49 TWh) of heat demand after efficiency improvements. In the Core scenario, we assume that gas, oil and conventional electric heating systems are replaced by heat pumps by 2045 and biomass boilers are replaced by heat pumps by 2050. This is in-line with heat pumps being installed as part of stock turnover once they are cost-effective and is consistent with the commitment in the Clean Growth Strategy to phase out the installation of high-carbon fossil fuel heating by 2030.

Aside from heating and hot water demand, our Core scenario for non-residential buildings also includes:

- 4$MtCO_2e$ of emissions abatement from electrification of catering and other non-heat uses of gas and oil.[97]

[97] Catering makes up around 53% of this energy demand, based on ECUK 2018. Due to a lack of information on the composition of the 'other' demand, the total demand has been treated as though it was for catering in our analysis.

- Significant reductions in electricity demand for non-heat uses, due to energy efficiency improvements. A 21% reduction in electricity demand has been assumed based on BEES data (Box 3.2). This is equivalent to a 35 TWh reduction in electricity demand in 2050.
- Residual emissions of 0.6 $MtCO_2e$ in 2050 from N_2O as an anaesthetic in hospitals.

Further Ambition options for non-residential buildings

As in the Core scenario, half of heat demand is assumed to convert to low-carbon heat networks and the other half to heat pumps, both combined with improved energy efficiency. The key differences to our Core scenario are in the timing of these changes and the removal of the 2.3 $MtCO_2e$ of CO_2residual emissions from our Core scenario to reach zero direct CO_2emissions from non-residential buildings by 2050:

- In the Further Ambition scenario, we assume that natural gas used to meet peak heat demands on heat networks serviced by large heat pumps is displaced, either through a combination of larger heat pumps and large water stores or hydrogen should this be available through the gas grid.
- This leaves residual emissions of 0.6 $MtCO_2e$ in 2050 from N_2O as an anaesthetic in hospitals.

The more ambitious timing of changes in heating non-residential buildings is considered in section 3b.

Alternative options to deliver the Further Ambition scenario in non-residential buildings

An alternative option to deliver the further ambition scenario would be to rebalance our abatement to use a greater share of hydrogen and less electrification. Our Further Ambition scenario only uses hydrogen for a share of low-carbon heat networks. Our recent hydrogen report[98] showed that hydrogen could play a valuable role as part of a heating solution for UK buildings, in combination with heat pumps as part of a hybrid system. Heat pumps would offer the potential to provide heat efficiently for most of the time, with hydrogen boilers contributing mainly to meet peak demands on the coldest winter days. This option is particularly useful in homes (where demands correspond to morning and evening peaks) and in buildings with large hot water demands (homes, hospitality). In buildings such as offices with low-levels of hot water demand and cooling loads, reversible air-to-air heat pumps are typically better suited and provide a greater overall level of efficiency.

Speculative options for non-residential buildings

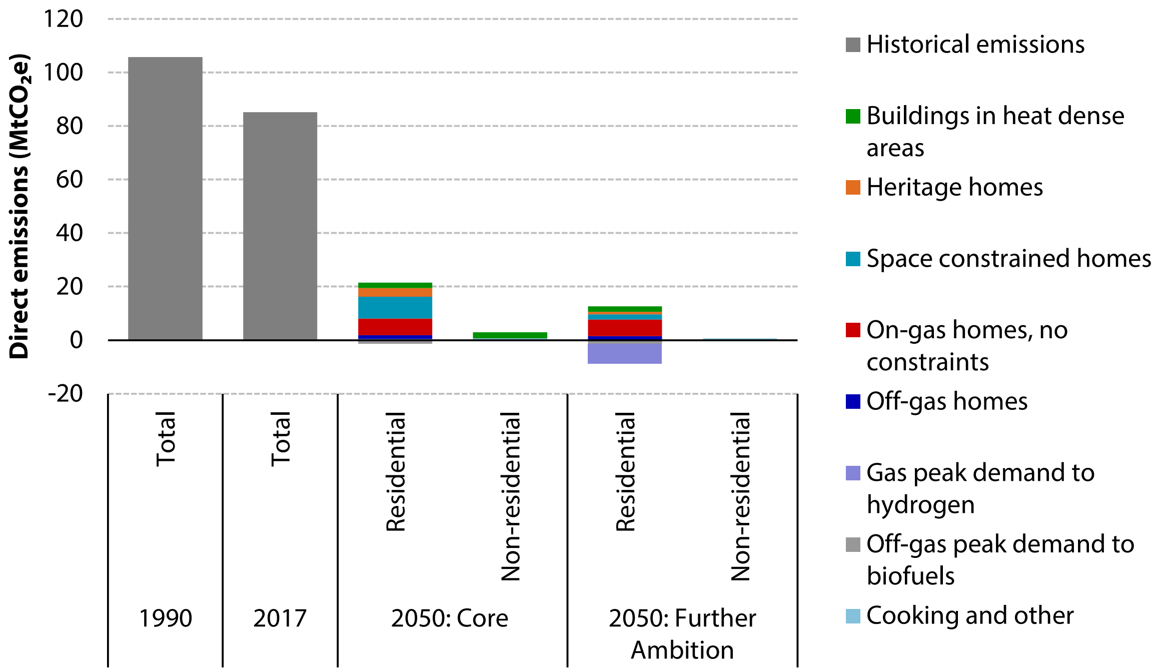
The only residual emissions remaining in our Further Ambition scenario come from the use of N_2O as an anaesthetic in hospitals. It could be feasible to switch to other forms of anaesthesia. Xenon is a gas which has similar properties, although it is currently high cost (over 1000 times the cost of N_2O).

Scenario summary for all buildings

Across buildings our Further Ambition scenario leaves around 4 $MtCO_2e$ of emissions unabated in 2050 (Figure 3.4). These remaining emissions are associated with residual fossil fuel use in residential buildings and use of N_2O as an anaesthetic in hospitals.

[98] CCC (2018) *Hydrogen in a low-carbon economy.*

Figure 3.4. Scenarios for very deep emissions reductions from the buildings sector



Sources: CCC; Element Energy and UCL for the CCC (2019) *Analysis on abating direct emissions from 'hard-to-decarbonise' homes, with a view to informing the UK's long term targets;* BEIS (2018) *Final UK greenhouse gas emissions national statistics 1990-2016*; BEIS (2018) *Provisional UK greenhouse gas emissions national statistics 2017.*
Notes: 1990 and 2017 emissions based on BEIS emissions data. Scenario emissions based on CCC analysis and work undertaken by Element Energy and UCL. Emissions are presented excluding biomethane use in the gas grid, which is responsible for 0.2 $MtCO_2e$ of further abatement. In residential buildings, emissions associated with hybrid heat pumps and district heating are presented on the basis of peak demand being serviced by fossil fuel heating systems. The decarbonisation of this fossil fuel residual (through conversion to hydrogen or biofuels) is presented separately, and appears as negative emissions. The total remaining emissions are therefore net of these savings. 'Cooking and other' category includes cooking and catering, other non-heat use of fossil fuels in non-residential buildings, N_2O use as an anaesthetic, appliance and lighting efficiency in homes (expected to be associated with some direct emissions as a result of the heat replacement effect), use of non-aerosol consumer products and accidental fires.

(b) Timing for cutting emissions towards zero

Residential buildings

The fifth carbon budget (covering 2028-2032) already requires significant progress towards these net-zero scenarios. The cost-effective path that the Committee have identified includes:

- A reduction in direct CO_2 from buildings by 32% by 2030, from 1990 levels, incorporating a 24% reduction in direct CO_2 from homes, and a 58% reduction in direct CO_2 from non-residential buildings.
- At least a quarter of heat for buildings from low-carbon sources by 2030, around 40 TWh of heat supplied through low-carbon heat networks by 2030 and around 20 TWh of biomethane injection into the grid.
- All practicable lofts insulated by 2022, all practicable cavity walls insulated by 2030 and 2 million sold walls insulated by 2030.

As set out in our 2018 Progress Report to Parliament, there remain significant policy gaps that pose delivery risks for the fifth carbon budget. Current Government policy is failing to drive uptake of energy efficiency measures, and further action is urgently needed to deliver cost-effective uptake of low-carbon heat. With a committed and well-designed policy effort, it should be possible to go beyond this to deliver the Further Ambition options set out above, without requiring early scrapping of significant levels of capital investment:

- Implementation of the proposed Future Homes standard will enable all new homes from 2025 or earlier to be fully decarbonised.
- For energy efficiency in existing homes, deployment is expected to be feasible over the course of the next two decades (with some deeper retrofits taking longer). Research undertaken by Element Energy for the Committee indicates that feasible rates of retrofit are likely to vary crucially on the type of tenure residents have:
  - The social rented sector faces the fewest restrictions on timings with regard to retrofits, as they are not contingent on the end of tenancies or other trigger points. The Government's former CESP programme targeted social housing, with the majority of measures delivered in the final six months of the scheme at a rate equivalent to 340,000 homes per year, or 9% of the social rented stock. This implies that the social rented stock could plausibly be retrofitted within a timeframe of 10-11 years.[99] This sector is also well suited to early action, given regulatory levers, large housing portfolios, and wider benefits for low-income tenants.[100] The Clean Growth Strategy included an ambition to upgrade as many socially-rented homes as possible to EPC band C by 2030, although policy has yet to be announced in this area, whilst the Scottish Government has made commitments to maximise the number of social-rented homes achieving EPC band B by 2032.
  - 25% of private renters move each year, compared to 3% of owner occupiers and 5% of social renters.[101] Shorter tenancies in this segment of the stock imply that the timeframe for implementation could be faster than for owner-occupiers. There are also clear regulatory levers in the form of Minimum Energy Efficiency Standards which can be used to drive up standards in privately rented homes. The Clean Growth Strategy included an ambition to upgrade as many privately-rented homes as possible to EPC band C by 2030, with the Scottish Government committing to the same aspiration. Major delivery risks around Private Rented Sector regulations still remain, with recent Government regulations requiring just 48% of EPC F- and G-rented properties to be improved to EPC E by 2020.[102]
  - For owner-occupied homes, just over half have carried out renovations over the past ten years, with 11% planning renovation in the next year.[103] At current rates, this implies

[99] Element Energy and UCL for the CCC (2019) *Analysis on abating direct emissions from 'hard-to-decarbonise' homes, with a view to informing the UK's long term targets.*
[100] The retrofit of social housing in Nottingham to Energiesprong standards also demonstrates how carbon reductions can be delivered whilst reducing total social housing spend over a 30-year period. For further discussion see: https://www.theccc.org.uk/wp-content/uploads/2019/02/UK-housing-Fit-for-the-future-CCC-2019.pdf
[101] Element Energy and UCL for the CCC (2019) *Analysis on abating direct emissions from 'hard-to-decarbonise' homes, with a view to informing the UK's long term targets.*
[102] BEIS (2018) *Domestic rented sector minimum level of energy efficiency - Government response*; BEIS (2018) *Final stage impact assessment: Amending the private rented sector energy efficiency regulations.*
[103] Element Energy and UCL for the CCC (2019) *Analysis on abating direct emissions from 'hard-to-decarbonise' homes, with a view to informing the UK's long term targets.*

energy efficiency measures could be installed as part of house renovations over the next two decades, provided strong policy is put in place with incentives to drive uptake and green finance.[104] However, evidence also suggests that owner occupiers are more likely to renovate in stages, implying that deeper retrofits may take longer. The feasibility of these timeframes will also relate to the ease and convenience of retrofit, which will in part be a function of technology advancements. The Clean Growth Strategy included a commitment to upgrade as many homes as possible to EPC band C by 2035, with the Scottish Parliament giving majority backing for proposals to ensure all Scottish homes achieve EPC band C by 2030. Backstop mandatory requirements, as proposed in the Energy Efficient Scotland Route Map, would create policy certainty and drive innovation and growth. We have previously advised that in the owner occupied sector, minimum standards are phased in across all buildings, e.g. at point of sale.

- For heat in existing homes, 2050 is a realistic timeframe by which heating systems can be fully decarbonised in the Further Ambition scenario. It implies regulation by 2035 at the latest to ensure all heating system replacements are low-carbon (assuming additional policy to ensure scrappage of any remaining fossil fuel heating). It will also require timely decisions on the future of the gas grid, with rollout for on-gas buildings of hydrogen and/or full heat pumps from 2030 or 2035:
  - The minimum deployment period for maximum uptake of low carbon heating is 15 years (assuming an average lifetime of 15 years for fossil fuel-based heating systems).[105]
  - As part of the Government's commitment to phase out the installation of high-carbon fossil fuel heating systems off the gas grid in the 2020s, regulation should ensure that these homes are fitted with low-carbon heating systems. Where regulation is in place by 2030 at the latest, this should enable heating in off-gas grid homes to be decarbonised by 2045.
  - For the wider stock, a deployment period of 15 years implies that regulation must be in place by 2035 at the latest to ensure all heating system replacements are low-carbon, and to ensure scrappage for any remainder.
  - Whilst 15 years represents the minimum deployment period, uptake of low-carbon heat must be accelerated now in order to ramp up supply chains and drive down carbon emissions. There is scope for hybrid heat pumps to be retrofitted at the same time as energy efficiency improvements are made, to minimise disruption and improve outcomes.[106] The scale of deployment should be such that hybrids are widely used by 2035 (e.g. in ten million homes), reducing the later challenge of tackling residual gas use.

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[104] In the 2016 Heat report, we set out the need for an attractive package of measures targetting the able-to-pay market and aligned to trigger points such as moving home or renovating. This must go alongside a major increase in green finance, as considered in our 2019 Housing report.

[105] Analysis by Element Energy suggests an average stock turnover of closer to 16 years based on reported sales of gas boilers. Some degree of scrappage is likely to be necessary to remove any remaining fossil fuel heating within a 15-year timeframe. Element Energy and UCL for the CCC (2019), *Analysis on abating direct emissions from 'hard-to-decarbonise' homes, with a view to informing the UK's long term targets.*

[106] There are benefits in installing low carbon heating measures alongside energy efficiency retrofits as part of a 'whole house' approach.

Non-residential buildings

There are anticipated to be fewer barriers to the uptake of low-carbon heating and energy efficiency measures in non-residential buildings. With well-designed and timely policy, direct CO_2 emissions in non-residential buildings could be fully abated by 2050 and well ahead of this in some segments:

- We assume that low-carbon heat networks can be deployed fully by 2050, assuming a smooth rollout profile over time and strategy of phased network development.[107]
- The rate of uptake of heat pumps is likely to vary across segments of non-residential buildings depending upon existing heating systems and the relative cost-effectiveness of heat pumps. We base our scenarios on a stock turnover of 15 years for fossil-fuelled heating systems.
  – In the Core scenario we assume that heat pumps fully replace gas, oil and electric heating systems by 2045. We expect heat pumps to be cost-effective in gas heated non-residential buildings by around 2030, so anticipate the stock could be fully replaced without significant scrappage by 2045. Heat pumps are already cost-effective in off-gas buildings, so could progress ahead of this timescale. The government has indicated in its Clean Growth Strategy that it is committed to phasing out the installation of high-carbon fossil fuel heating (e.g. oil) by 2030 and our assumption of 2045 is consistent with stock turnover from that point. Our Core scenario allows longer for conversion from biomass boilers, until 2050, to allow use of biomass to reduce emissions in the interim.
  – In the Further Ambition scenario we maintain our core assumption on replacing biomass boilers by 2050. We assume that buildings using electric and oil heating systems can be fully converted to heat pumps by 2035, based on stock turnover if a policy was swiftly put in place to take advantage of existing cost effectiveness for these segments. This assumption represents a stretch in terms of policy delivery and supply chain development. We also make a more ambitious assumption than the Core scenario on replacing gas boilers by 2040. This implies heat pumps becoming cost-effective by 2025 (as we find with optimistic assumptions), or some uptake ahead of this point and/or a small amount of scrappage.

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

(c) Summary table of the opportunities to reduce emissions from buildings towards zero

Table 3.1. Opportunities to reduce emissions from buildings towards zero

Source	2030 5CB residual emissions ($MtCO_2$)	Further Ambition residual emissions in 2050 ($MtCO_2e$)	Earliest date for Further Ambition emissions	2050 cost £/tCO_2e
Residential buildings				
New homes	62	0.0	2050	69
Cooking		0.0	2045	240
Heating in homes off the gas grid		1.4	2045	-18
Heat in homes in heat dense areas		2.0	2050	195
Heat in homes on the gas grid without constraints		6.2	2050	223
Heat in homes with space constraints		2.0	2050	311
Heat in heritage homes		0.9	2050	196
Conversion of gas peak demand to hydrogen for heat in existing homes		-7.4	2050	215
Conversion of off gas peak demand to biofuels for heat in existing homes		-1.4	2045	47
Non-residential buildings				
Heat in heat dense areas - core demand	11	0.0	2050	195
Heat in heat dense areas - peak demand		0.0	2050	144
Heat in less heat dense areas - displacing gas		0.0	2040	59
Heat in less heat dense areas - displacing oil		0.0	2035	-41
Catering and other non-heat uses		0.0	2050	189
N_2O as an anaesthetic		0.6	2050	

Sources: CCC analysis; Element Energy and UCL for the CCC (2019) *Analysis on abating direct emissions from 'hard-to-decarbonise' homes, with a view to informing the UK's long term targets.*

Notes: Fifth carbon budget emissions are CO_2 only. Further Ambition emissions are all GHGs. £/tCO_2e cost figures represent levelised costs of abatement of the measures in place in 2050, and are averaged across multiple abatement measures applied to the same emission source. In residential buildings, emissions associated with hybrid heat pumps and district heating are presented on the basis of use of fossil fuels for servicing peak heat demand for each of the segments of the stock. The decarbonisation of this fossil fuel residual (through conversion to hydrogen or biofuels) is presented in a separate step as negative emissions. Not all segments of emissions and abatement are listed. Exclusions include lighting and appliances, use of non-aerosol consumer products and accidental fires. Emissions are presented excluding biomethane use in the gas grid, which is responsible for 0.2 $MtCO_2e$ of further abatement.

4. Costs and benefits of achieving very deep emissions reductions in the buildings sector

Our overall approach to assessing costs and benefits is summarised in Chapter 1 of this report and set out in full in Chapter 7 of the accompanying Net Zero advice report.

Some of the low-carbon options included in our net-zero scenarios for buildings would avoid costs compared to the high-carbon alternative, whilst others are likely to be more expensive.

Our Further Ambition scenario implies a total annual cost compared to a theoretical counterfactual without any action on emissions of £15 billion in 2050 (in real 2018 prices, 0.4% of expected 2050 GDP) for cutting emissions from buildings to around 4 $MtCO_2e$.

We have not undertaken detailed analysis of the pathway to 2050 for this work, but costs on the pathway to 2050 can be expected to increase over time as more of the stock is decarbonised.

That the costs for decarbonising buildings are a significant proportion of the total economy-wide costs, reflects the importance and the challenge in achieving the necessary emissions reduction overall from buildings by mid-century. A key question for Government will be how to allocate these costs across society - distributional considerations will be central to determining the policy mechanisms to deliver low-carbon heat.

In addition to emissions savings, the scenarios can also be expected to deliver a range of significant co-benefits which are not reflected in the costs we have presented. These include alleviating fuel poverty; improving comfort, health and well-being for occupants; and unlocking the significant industrial opportunities associated with low-carbon and resilient buildings:

- We expect the scenarios to deliver material co-benefits in alleviating fuel poverty. In addition to immediately cost-effective energy efficiency measures, we have included an additional 3.25m solid wall insulation measures for wider fuel poverty benefits.
- Where properly planned and used, buildings can be low-carbon, more affordable to run, more comfortable to live in, and better for our health. It is important that measures to address poor thermal efficiency, overheating, indoor air quality and moisture are considered together when retrofitting existing buildings, and when building new ones. Doing so should deliver comfort and health benefits for occupants. The health cost to the NHS of conditions exacerbated by poor housing is currently estimated to be £1.4-2.0 billion per year in England alone.[108]
- Developing expertise in low-carbon, resilient buildings represents an industrial opportunity, both to generate high quality jobs in the UK and for the UK to export innovation and skills. The construction sector, encompassing contracting, product manufacturing and professional services, exported over £8bn of products and services in 2016.[109] European requirements on net-zero energy buildings, and growing interest in markets such as Canada and China could represent export opportunities for UK innovation and expertise.[110]

[108] Nicol S. et al. (2015) *The cost of poor housing to the NHS*.
[109] Published in HM Government (2018) Industrial Strategy: Construction Sector Deal, based on Office for National Statistics - *UK Balance of Payments Pink Book* (2017). Table 9.11 and Table 3.8 for data construction contracting and services exports. BEIS, *Monthly Statistics of Building Materials and Components*, 2017 for data on construction products exports.
[110] British Columbia has a goal for all new buildings to be net-zero energy ready by 2030. In 2017 it introduced the British Columbia Energy Step Code, which is a voluntary provincial standard that paves the way for this progress; British Columbia (2017) *BC Energy Step Code: A Best Practice Guide for Local Governments*. China aims to increase the

The wider benefits associated with our scenarios are set out across the economy in Chapter 7 of our advice report.

The next section considers how the scenarios can be delivered, including the need to design policy to ensure the wider benefits associated with low-carbon buildings are realised.

5. Delivering very deep emissions reductions in buildings

(a) What is needed to deliver the scenarios

Delivering the level of emissions in our Further Ambition scenario can only be achieved with strong and effective Government leadership at all levels, supported by a clear rollout plan which engages people and creates local supply chains.

Table 3.2 summarises our assessment of the degree of challenge for the major opportunities to reduce emissions across a number of dimensions, in line with the approach set out in Chapter 1.

Table 3.2. Assessment of abatement options against dimensions of challenge for buildings

Source	Abatement measure	Barriers and delivery risks*	Funding mechanisms	Co-benefits and opportunities	Alternative options
Residential buildings					
New homes	Ultra high energy efficiency with low carbon heat by 2025	Compliance, skills and the performance gap	Costs may be borne by developers, land owners or consumers	Comfort and health benefits, industrial opportun-ities	Tighten sooner
Cooking	Electric cookers	Associated behaviour change	Costs passed onto end users	Indoor air quality	Hydrogen cookers
Heating off gas homes	Energy efficency and low-carbon heat	Compliance, skills and the performance gap; supply chains; behaviour change	Risk funding is regressive and perceived to be unfair. Government review of distributional impacts and costs allocation needed	Fuel poverty, comfort and health benefits, industrial opportun-ities	Vary proportion of heat pumps and hybrid heat pumps, full electrifi-cation, or deployment of hydrogen boilers
Heating homes in heat dense areas					
Heating homes with no constraints					

share of new green buildings in urban areas to 50% by 2020, and China Green Building Council has recently partnered with the World Green Building Council (World GBC) and committed to introducing a 'nearly net zero' standard for its Three Star rating system in 2018 as part of World GBC's Advancing Net Zero project. See: https://www.worldgbc.org/news-media/world-green-building-council-and-china-green-building-councilannounce-partnership-0

Table 3.2. Assessment of abatement options against dimensions of challenge for buildings

Source	Abatement measure	Barriers and delivery risks*	Funding mechanisms	Co-benefits and opportunities	Alternative options
Heating space-constrained homes		Compliance, skills and the performance gap; supply chains; behaviour change and consumer acceptability			
Heating heritage homes					
Gas peak demand	Conversion to hydrogen	Techincal feasibility to be demonstrated/ significant infrastructure programme required			
Off gas peak demand	Conversion to biofuels	Competing resource demands			
Non-residential buildings					
Heat in heat dense areas - baseload	Low-carbon heat networks and energy efficiency	Compliance, skills and the performance gap; supply chains; behaviour change	Commercial sector: upfront cost borne by business; Public sector: taxation. Rebalancing of tax and regulatory costs across fuels.	Energy efficiency can improve comfort and health for occupants; industrial opportun-ities.	Range of technology mixes capable of delivering similar outcomes, including scenarios with hydrogen boilers or hybrid heat pumps.
Heat in heat dense areas - peak					
Heat in less heat dense areas - displacing gas	Heat pumps and energy efficiency				
Heat in less heat dense areas - displacing oil					

Table 3.2. Assessment of abatement options against dimensions of challenge for buildings

Source	Abatement measure	Barriers and delivery risks*	Funding mechanisms	Co-benefits and opportunities	Alternative options
Catering and other non-heat uses	Electrification	Behaviour change (amber)	Upfront costs equivalent. Fuel costs should be subject to rebalancing (green)	Indoor air quality (green)	Hydrogen

Notes: *Barriers and delivery risks include supply chains. The rating of measures in the table is based on the following criteria: 'barriers and delivery risks' are rated as 'red' if there is evidence that a given measure is particularly hard to implement, and 'green' or 'amber' otherwise; 'funding mechanisms' are rated as 'red' if the delivery of a given measure has high costs and these have a negative impact on businesses' competitiveness or are regressive on households, and 'green' or 'amber' otherwise; when there is evidence of positive 'co-benefits and opportunities' these are rated as 'green', otherwise no rating is given.

Whilst we have set out above a range of characteristics which influence the difficulty of decarbonisation for the segments of the stock we have examined, there are some cross-cutting themes which illustrate where action will be needed to realise ambitious emissions reductions:

- **Investment levels and financing.** The costs associated with heat decarbonisation are expected to remain a significant proportion of the total costs of decarbonising the UK economy. By 2050 costs are expected to reach up to around £20 billion per year of capital investment relative to a no-policy scenario (with capital investment varying depending on the technology mix deployed). However, as costs of decarbonisation in other sectors decline, there is scope for redeployment of funding to meet costs in buildings. Payments under the Levy Control framework are due to peak at around £9 billion per year in the mid-2020s.[111] Payments to legacy projects will then fall to below £1 billion by 2050 - this funding could be redirected to pay a portion of low-carbon heat investments (e.g. the upfront cost of installing a heat pump).
- **Skills and supply chains.** Rapid changes in UK Government policy have inhibited supply chain and skills development in building design, construction and in the installation of new measures.
  - Our scenarios include substantial deployment of measures such as heat pumps and wall insulation. However, in both of these critical areas deployment has stalled.
  - Alongside increasing uptake, the low-carbon skills gap must be tackled if we are to deliver homes which maintain comfort levels for occupants, and do so affordably, whilst reducing emissions. Whilst skills will need to be developed across the new build and retrofit sectors, particular challenges exist for some segments of the stock, such as heritage buildings where different approaches may be needed.
- **Research and innovation.** Further research is required in a range of areas to inform decisions on how decarbonisation of heat will be delivered in the UK, and to drive down costs for key technologies. This includes further research on hybrid heat pumps and their potential to decarbonise both heat and hot water demand in different types of home,

[111] HMT (2017) *Control for Low-Carbon Levies.*

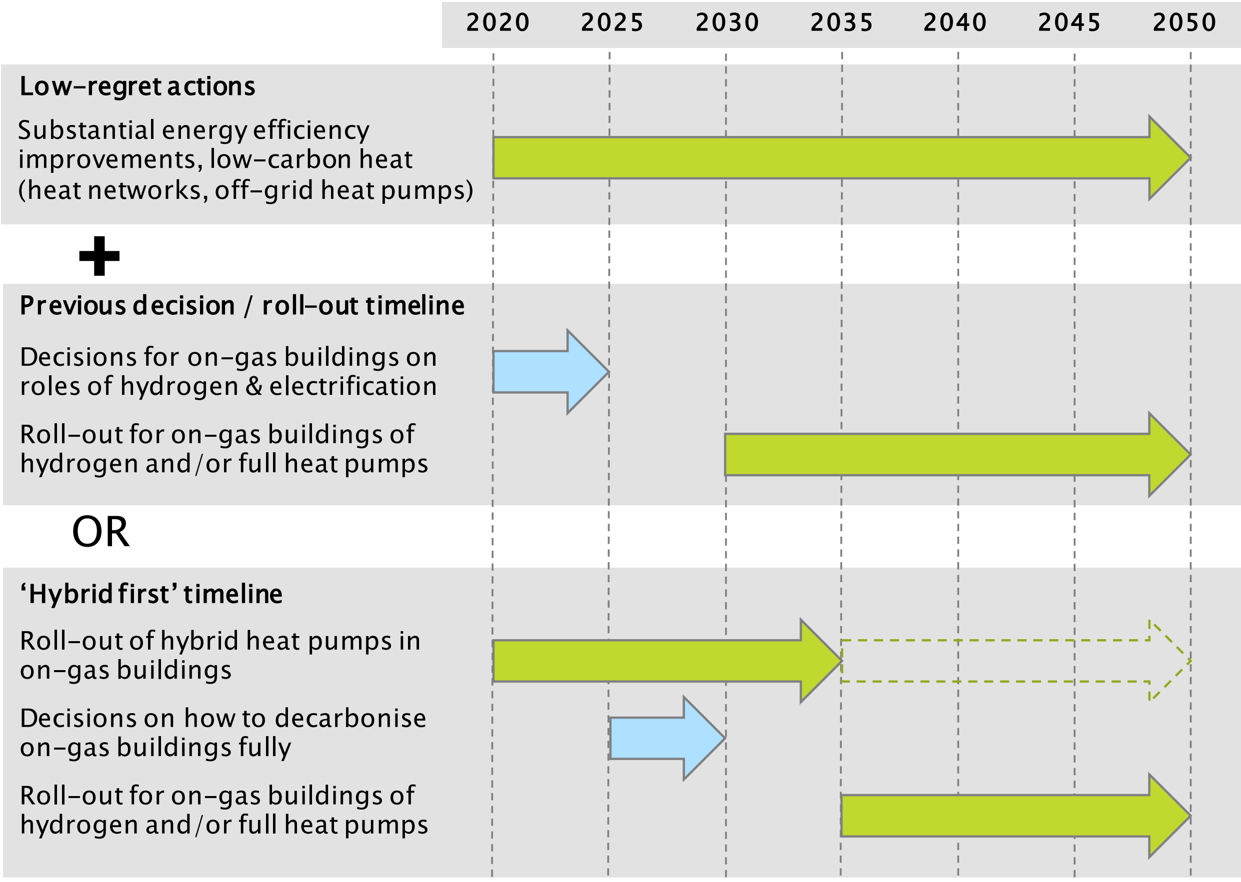
research and trials to support decisions on the future of the gas grid and the practicalities of converting to hydrogen,[112] and research and innovation to address challenges in decarbonising the most difficult segments of the stock, including space constrained homes and homes with heritage characteristics.

- **Public awareness, engagement and behaviour change.** Public acceptance will be required in order to enable the deployment of measures to realise deep emissions reductions in buildings. However, awareness of the changes needed is currently very low,[113] and barriers exist which can prevent uptake even where there is occupant appetite. Furthermore, it is important that once measures are installed, they perform as they should - in some cases this will require behaviour change.
  - Even where building occupants are aware of the need for low-carbon measures, there can be barriers which prevent them from being installed. One example is the challenge posed by freehold/leasehold distinctions in property ownership, which can create significant barriers for renovation of these buildings.
  - Once measures are installed, they must be used effectively. Our scenarios assume a move towards more 'informed' average use for occupants such as adequate window opening for ventilation and avoidance of moisture build-up, appropriate temperature set points, and maintaining integrity and avoiding damage of insulation layers. Behaviour changes will be needed here but effective design can also play an important role. In some cases it could remove the need for occupant intervention altogether.[114]
  - New business models, alongside smarter technology, also have potential to support occupants in adopting and using low-carbon heating effectively, including 'heat as a service' propositions.[115]

We set out below the timings for key decisions to deliver the net-zero scenarios for buildings (Figure 3.5).

[112] Including hydrogen-ready boilers and the ability for large quantities of hydrogen to be delivered in a short space of time to service peak demand.
[113] Madano for the CCC (2018) *Public acceptability of the use of hydrogen for heating and cooking in the home*.
[114] The concept of 'design for sustainable behaviour' works on the basis that if appropriate strategies are applied to the design of a product, the designer can positively influence the sustainable use of the product. For further discussion see: Delzendeh, E. et al. (2017) The impact of occupants' behaviour on building energy analysis: A research view. *Renewable and Sustainable Energy Reviews, 80*, 1061-1071.
[115] Energy Systems Catapult (2019) *Smart Energy Services for Low Carbon Heat.*

Figure 3.5. Timing of key decisions and changes to deliver the net-zero scenarios for buildings



Source: CCC.
Notes: 'Low-regret' actions are those that the Committee recommended in 2016 should be pursued immediately, with subsequent decisions to be made by the mid-2020s on the respective roles of hydrogen and electrification in on-gas buildings outside heat network areas, for roll-out between 2030 and 2050 (shown in the middle sections of the diagram). The 'hybrid first' timeline would entail pursuing the low-regret actions now alonside deployment of hybrid heat pumps in on-gas properties, with decisions on achieving full decarbonisation able to come slightly later.

There remain a number of significant uncertainties which will impact the costs and optimal path to decarbonisation:

- The most **appropriate mix of electrification and hydrogen use in buildings** is uncertain. In addition to being informed by the costs of different alternatives, both at a buildings and a systems level, there are important questions to be resolved around the public acceptability of different approaches to heat decarbonisation, and around the feasibility of wide scale hydrogen rollout.[116]

[116] Work we commissioned from Madano on public acceptability of hydrogen and heat pumps showed that when faced with a choice between hydrogen and heat pumps, preferences were not fixed. Respondents were influenced by how the information was presented, preferring options with the least disruption and with little change compared to their existing system. See CCC (2018) *Hydrogen in a low-carbon economy*; Madano for the CCC (2018) *Public acceptability of the use of hydrogen for heating and cooking in the home.*

- There are likely to be additional costs associated with retrofitting those sectors of the building stock which are **space-constrained**. In addition to uncertainties over the space availability in homes, there is also uncertainty over consumer acceptance of additional space requirements, which could either increase or reduce the number of buildings subject to this cost premium.
- There are uncertainties around the costs of retrofitting measures in buildings with **heritage value**. Costs and suitability constraints are highly case specific and uncertain. The number of buildings which have heritage value is also uncertain - in addition to poor data quality over the exact number of heritage homes, there are likely to be many more older homes in the housing stock where householders will wish to retain historic features and detailing, in turn driving up the costs of retrofit.
- **Data quality** is an issue for non-residential buildings, particularly regarding the impact on suitability of the stock for heat pumps for small buildings which are space-constrained. We have not modelled the higher costs of decarbonising public and commercial heritage buildings, but if there are higher barriers then this could add up to around 0.5 $MtCO_2e$ of emissions in 2050.

(b) Key policy implications for driving deep emissions reductions from the buildings sector

This report does not aim to identify a full policy package to deliver the scenarios set out above. However, there are important high-level policy implications that should be understood by Government and Parliament when considering the setting of a UK net-zero emissions target.[117]

In particular for buildings, the retrofit of the 29 million existing homes across the UK must be treated as a national infrastructure priority. **A fully-fledged UK strategy for decarbonised heat must be developed in 2020.** In our 2019 Housing report we said that Government should develop a strategy within the next 18 months to three years. Net-zero targets and the pressing need for clarity imply that earlier in the period would be better. The Government's planned 2050 heat roadmap must establish a new approach that will lead to full decarbonisation of buildings by 2050. It is essential that HM Treasury commits to working with BEIS on this and to allocating sufficient funding. The strategy must include:

- **A clear trajectory of standards covering owner-occupied, social- and private-rented homes and non-residential buildings, announced well in advance.** This includes standards for energy efficiency, detailed plans on phasing out the installation of high-carbon fossil fuel heating and improvements in the efficiency of existing heating systems. Energy efficiency is the key precursor to low-carbon heat and delivers most benefits where deployed early.
- **A regulatory and support framework for low-carbon heating** (heat pumps, biomethane, and networked low-carbon heat) to address the multi-billion pound funding gap. Decarbonising homes by 2050 implies ensuring that by 2035 at the latest, all new heating system installations are low-carbon. In order to develop supply chains, this will require signalling well in advance, alongside deployment of heat pumps at scale in the 2020s.

[117] Further detail is available across a range of our recent reports: CCC (2016) *Next steps for UK heat policy*; CCC (2018) Progress Report to Parliament; CCC (2018) *Hydrogen in a low-carbon economy*; CCC (2018) *Biomass in a low-carbon economy*; CCC (2019) *UK housing: Fit for the future?*

- **A review of the balance of tax and regulatory costs across fuels** in order to improve alignment with implicit carbon prices and reflect the progressive decarbonisation of electricity: costs are significantly larger for electricity than gas or oil heating, and the full carbon costs are not reflected in the pricing of heating fuels. These factors currently weaken the private economic case for electrification.
- **An attractive package for householders aligned to trigger points** (such as when a home is sold or renovated). Regulatory and support frameworks for energy efficiency and low-carbon heat should facilitate this. It is critical that this also includes removal of barriers which prevent occupants from bringing about the necessary action to improve the quality of the buildings they live and work in. This could require legislative reform to address issues such as the misalignment of freeholder and leaseholder incentives.
- **A nationwide training programme to upskill the existing workforce**. A properly skilled workforce is critical to enabling effective deployment of energy efficiency and low-carbon heating measures which perform as they should. The UK Government should use initiatives under the Construction Sector Deal to tackle this low-carbon skills gap. New support to train designers, builders and installers is urgently needed for low-carbon heating (especially heat pumps), energy and water efficiency, ventilation and thermal comfort, and property-level flood resilience.
- **A governance framework to drive decisions on heat infrastructure** through the 2020s. Making strategic decisions on the future of heat provision and the gas grid will be difficult for any government. It requires the acceptance of higher short-term costs and a long-term outlook, beyond the standard Parliamentary timetable. Nevertheless, as an infrastructure issue with long lead-times, it must be addressed with strategic decisions in the 2020s if we are to meet 2050 targets.

The allocation of costs to consumers and the Exchequer will depend on policies put in place to drive the required changes. HM Treasury should undertake a review of where the costs of the transition fall and develop a strategy to ensure this is perceived as fair. In relation to buildings, it should include consideration of the use of fiscal levers and Exchequer revenue, costs from carbon trading schemes, the costs to industries, and the impact on energy bill-payers (including the fuel poor). It should cover the costs over the full period from now to 2050.

The Government must implement policies to deliver the commitments announced under the Future Homes standard - namely to **ensure new build homes have low-carbon heating and world-leading levels of energy efficiency by 2025,** alongside ambitious standards for new non-residential buildings. In addition to being low-carbon, these new buildings must be energy and water efficient and climate resilient.

New build standards and a strategy for decarbonised heat must be accompanied by ambitious product standards for lighting and appliances, which drive uptake of the most efficient products.

Realising deep emissions reductions in buildings, will require co-ordination and co-operation across all levels of Government, industry, businesses and householders. Policy development by central Government and Devolved Administrations must be implemented effectively at local level, with evolution in the planning system to keep pace with Government ambitions. Cooperation from industry is central, driving down costs through innovation and delivering solutions in homes and businesses.

Finally, the absence of public engagement on these critical issues must be addressed, to prepare for and inform the changes to come and to enable individuals to take action now to drive down emissions associated with their homes and businesses.

Chapter 4: Industry

Introduction and key messages

This chapter sets out the scenarios for industry that inform the Committee's advice on reviewing long-term emissions targets for the UK, Scotland and Wales. The key messages from this chapter are:

- **Background**. Industrial emissions of 105MtCO_2e made up 21% of UK greenhouse gas (GHG) emissions in 2017. Manufacturing represents 60% of these emissions while the remaining 40% come from fossil fuel production,[118] refining and fugitive emissions. [119] 93% of industry emissions were CO_2, 7% were from CH_4 and N_2O.
- **'Core' measures**. A range of emission reduction options can be implemented at relatively low cost and some of these are already included in the Government's ambitions, albeit with significant policy strengthening required to deliver them. These include energy and resource efficiency, reductions in methane venting and leakage, some Carbon Capture and Storage (CCS) in the ammonia, cement, iron and steel sectors and small amounts of electrification using heat pumps. These could reduce industry emissions to 56 MtCO_2e in 2050.
- **'Further Ambition' Scenario**. Our 'Further Ambition' Scenario reduces emissions to 10 MtCO_2e by 2050 through a range of options including use of hydrogen, electrification, CCS (including BECCS), low-carbon off-road mobile machinery, reductions in methane venting and leakage, as well as energy and resource efficiency. This is a challenging scenario that requires a fast pace of deployment of low-carbon technology in comparison to the natural turnover rate of industrial assets.
- **Speculative options**. We consider two main additional options for going further.
  - Further abatement of 2 MtCO_2e might be achieved, by increasing the carbon capture rates on sites that are fitted with carbon capture, and also by capturing from smaller, more challenging sources. These technologies have not been demonstrated yet.
  - Faster deployment of low-carbon-fuelled technologies could reduce 2050 emission by a further 2 MtCO_2e. This may require earlier scrapping of assets.
- **Costs and benefits**. Some of the low-carbon options included in our net-zero scenario for the industrial sector, such as energy and resource efficiency, would avoid costs compared to the high-carbon alternative, whilst fuel-switching and CCS are more expensive. We estimate a total annual cost of £8 billion (0.2% of expected 2050 GDP) for cutting emissions from industry to 10 MtCO_2e in line with our Further Ambition Scenario in 2050, compared to a theoretical scenario with no climate change policy action at all. There would also be important co-benefits for improved air quality, strong regional job markets as well as the potential to attract increased investment in productive new and existing industries, and the development of new businesses and products.
- **Delivery**. The Government must urgently establish an overall framework to support long-term industrial decarbonisation, as committed to in the Government's Clean Growth Strategy, if it is to enable decarbonisation towards the Committee's recommended net-zero

[118] Mainly oil and gas extraction.
[119] Within 'fugitive emissions' we include methane leakage from the gas distribution and transmission networks, methane and CO_2 from flaring and venting during oil and gas production and methane leaks from closed (and existing) coal mines.

target. Delay will mean less decarbonisation of industry is possible or a greater role for scrapping assets.

- The design of the policy framework to reduce UK industry emissions must ensure it does not drive industry overseas, which would not help to reduce global emissions, and be damaging to the UK economy. This will require either consumers or taxpayers to bear much of the cost of decarbonisation of industrial subsectors or sites so long as they are at risk of carbon leakage.
- Policies should include a funding mechanism for industry decarbonisation, to support near-zero emission technologies, including use of hydrogen, electrification and CCS (including BECCS), a mechanism to support CO_2 transport and storage infrastructure by the end of 2019, and support for energy and resource efficiency.
- CO_2 transport and storage infrastructure should be operational in at least one industrial cluster by 2026 and available to all major industrial clusters soon afterwards, alongside hydrogen for all clusters where it is the best fuel-switching option for some sites. A network to provide hydrogen to industry outside the main industrial clusters should be established by 2035, or potentially slightly later if 'hydrogen-ready' appliances can be deployed in industry prior to this.
- By providing an attractive investment environment, including stable policy, the UK can become a leader in production of low-carbon goods, attract increased investment in new and existing industries, and develop new businesses and products. This should involve encouraging subsectors and technologies where the UK may have a competitive advantage.

We set out our analysis in five sections:

1. Current and historical emissions from industry
2. Reducing emissions from industry
3. Scenarios for minimising emissions from industry
4. Costs and benefits of achieving very deep emissions reductions in industry
5. Delivering very deep emissions reductions in industry

1. Current and historical emissions from industry

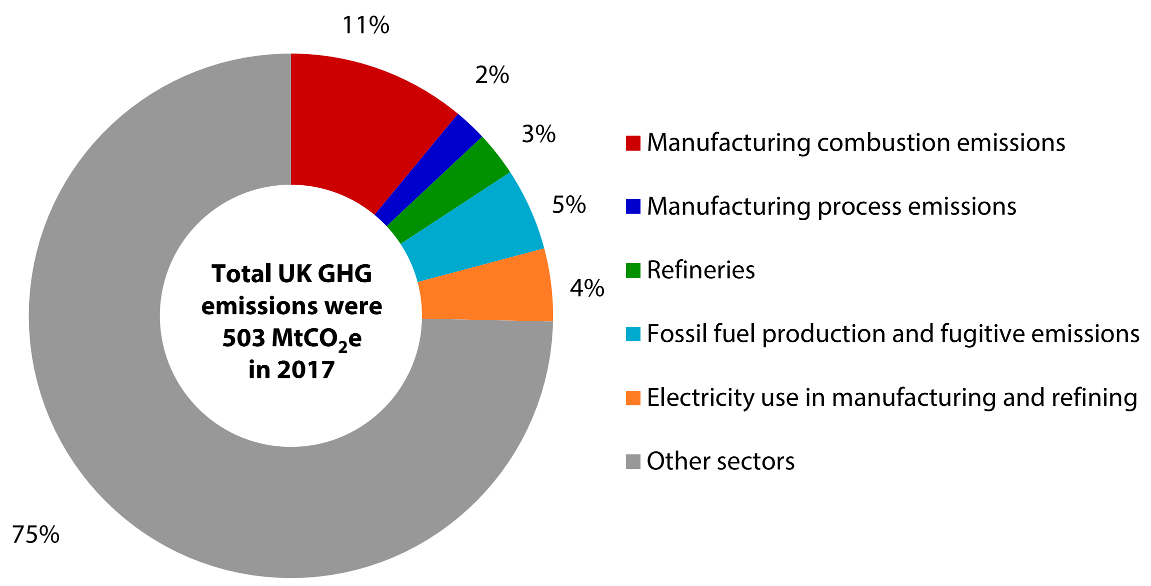
Greenhouse gas emissions from industry were 105 $MtCO_2e$ in 2017, 21% of the UK total (Figure 4.1). They were produced from a combination of manufacturing and energy supply:

- Manufacturing represents 60% of emissions. Of these, 85% were from fuel combustion (for high and low grade heat, drying/separation, space heating and off-grid electricity generation) and 15% were process emissions (which arise from a range of chemical reactions e.g. from the calcination of limestone for cement). Manufacturing emissions are spread across a wide variety of subsectors (Figure 4.2).
- The remaining 40% of emissions were from fossil fuel production (mainly extraction of oil and gas), refining and fugitive emissions.
- Most (93% of) emissions were of CO_2, 5% were of CH_4 and 1% of N_2O. Half of CH_4 emissions were from leakage from the gas grid.

Industry emissions have fallen by 52% since 1990 (Figure 4.3). This largely reflects energy efficiency improvements and fuel-switching, structural changes in the economy and falls in non-CO_2 emissions:

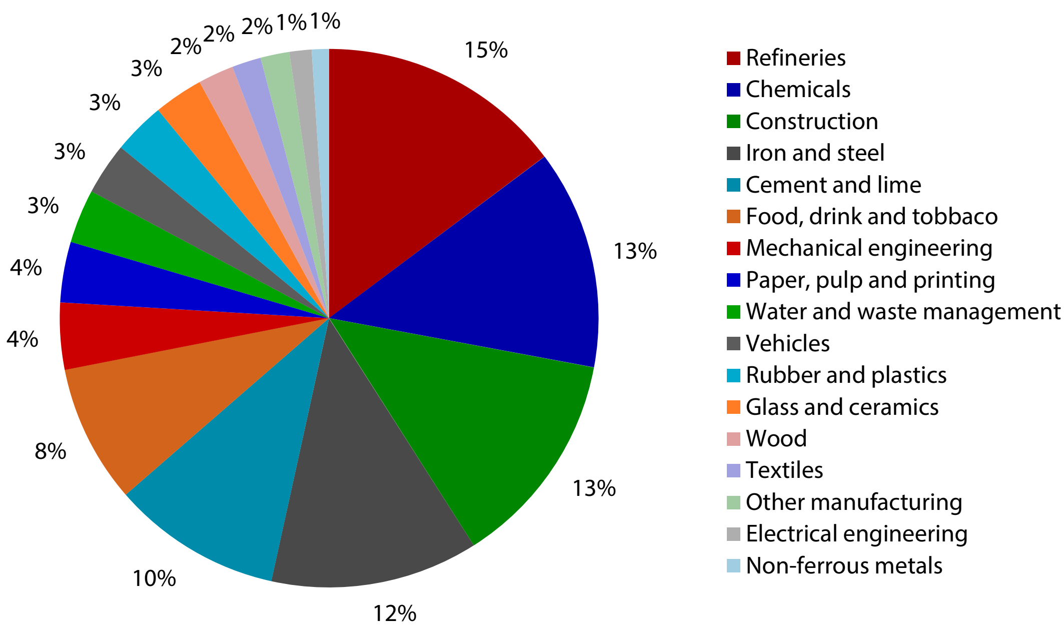
- Between 1990 and 2017 industry emissions fell by 52% while output grew 8%. This largely reflects a combination of improved energy intensity and a shift to less carbon-intensive energy sources.
- There has been a shift of industrial production from more to less energy-intensive sectors. Since 1990, emissions-intensive sectors of the economy have contracted (GVA from refineries, for example, has fallen by 25%).
- Non-CO_2 emissions have fallen since 1990 as a result of reduced methane leakage from coal mines and the gas distribution network along with abatement technologies for N_2O emissions from industrial processes.

Figure 4.1. Current emissions from industry (2017)



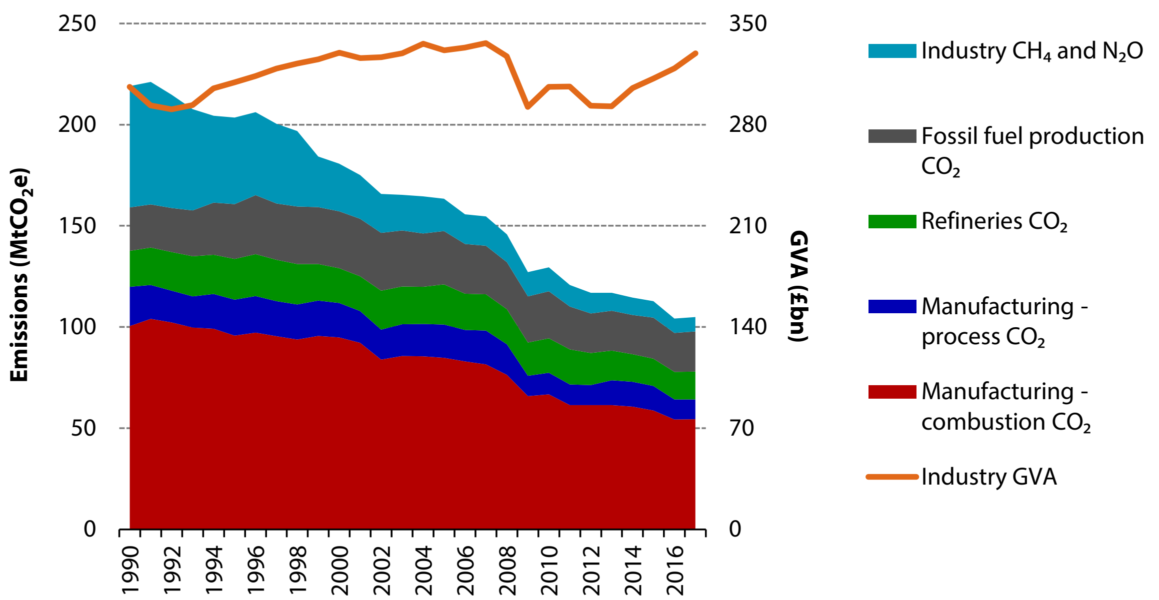
Sources: BEIS (2018) *Provisional UK GHG statistics*, BEIS (2017) *Digest of UK Energy Statistics (DUKES)*, BEIS (2018) *Energy Trends*, CCC analysis.
Notes: The 2017 provisional estimates for non-CO_2 emissions assume no change from final 2016 emissions.

Figure 4.2. Direct manufacturing and refining GHG emissions by industrial sector (2016)



Source: ONS (2018) *ONS Environmental Accounts.*
Notes: Percentage figures may not sum to 100% due to rounding. Based on the latest data from ONS environmental accounts, which are published each July with an 18-month lag.

Figure 4.3. GHG emissions from industry (1990-2017)



Sources: BEIS (2018) *Provisional UK GHG national statistics*, BEIS (2018) *Final UK GHG national statistics*, National Atmospheric Emissions Inventory, ONS (2018) GDP low level aggregates, CCC analysis.
Notes: 2017 emission estimates are provisional. The 2017 provisional estimate for non-CO_2 emissions assumes no change from final 2016 emissions.

2. Reducing emissions from industry

This section sets out options for reducing industry emissions, current Government ambitions, and challenges for avoiding emissions from industry.

(a) Options for reducing industry emissions

Figure 4.4 summarises the options for reducing industry emissions. Our understanding of abatement options has drawn on a range of new evidence, as listed in Box 4.1, alongside our existing evidence base:

- **Hydrogen, electricity and bioenergy** can all be used to meet industrial heat (and motion) demands, thus replacing the use of fossil fuels and reducing GHG emissions.[120]
  - There are a range of hydrogen, electrical and bioenergy heating technologies, which are designed to provide different types of industrial heat demand (Table 4.1).
  - Some fuels or heating technologies have wider potential than others. For example, biomass is not always suited to replacing natural gas for direct high temperature heating because the resulting combustion gases have a less desirable composition than those from natural gas. Analysis by Element Energy and Jacobs for BEIS suggests that hydrogen is most widely applicable and likely cheaper than most electrical heating technologies, apart from heat pumps (which have limited applicability for industrial processes). More of

[120] When the hydrogen and electricity are low-carbon and biomass is sustainable.

the analysis from this study and an extension commissioned for this report is presented in Box 4.2.

- Biomass should only be used in industrial applications with CCS in the long-term, based on analysis from our Biomass Review.[121] This combination is referred to as Bioenergy Carbon Capture and Storage (BECCS) and has the net effect of removing CO_2 emissions from the atmosphere. The review also concluded that some biomethane could be injected into the gas grid.
- Each of these energy sources are already used in industry to some extent, although mostly not due to climate policy and sometimes they are not low-carbon or used for energy. In 2017, 34% of industrial energy demand was met through electricity, with a further 5% from biomass and waste.
  - Electricity is currently used to meet a variety of industrial energy demands, including driving motors (35%) and to produce process heat (27%). The largest electricity-using sectors are chemicals, and rubber and plastic production.
  - Biomass and waste are currently used to produce electricity and heat in the cement and paper industries.
  - Hydrogen is used in refineries, predominantly as a feedstock to 'crack' heavier hydrocarbons into lighter hydrocarbons, and in ammonia production, for the Haber-Bosch process. This hydrogen is not produced using CCS or electrolysis, so it is not low-carbon.
- Low-carbon fuels could be used to replace 'internal fuels' - fuels produced by industry feedstock (blast furnace gas and coke oven gas in the iron-making sector, and some less valuable hydrocarbons in the refining and petrochemicals sectors). However, the economics may be more challenging, because these internal fuels may be relatively low cost to the industrial consumer, since they are residuals of the industrial process. We have not considered this option in the analysis for this report (see Figure 4.4).
- These could also be used to fuel the engines of off-road mobile machinery, such as forklifts and mobile power generators, which typically use gas oil as a fuel. Hydrogen in particular could provide the autonomy and flexibility that this machinery requires to operate across different settings.

• **Carbon Capture and Storage (CCS)** can be used to capture CO_2 produced by larger industrial point sources, and transport it to a storage site, thus reducing emissions to the atmosphere. The captured CO_2 may alternatively be used in Carbon Capture and Use (CCU), although the potential amount that could be used is expected to be substantially smaller than that which could be stored.
  - CCS can capture non-combustion process CO_2 emissions (from chemical reactions such as the calcination of limestone in cement production) and combustion emissions, including those arising from the combustion of internal fuels.
  - When capturing emissions from biomass combustion, reduction or fermentation, this results in BECCS.

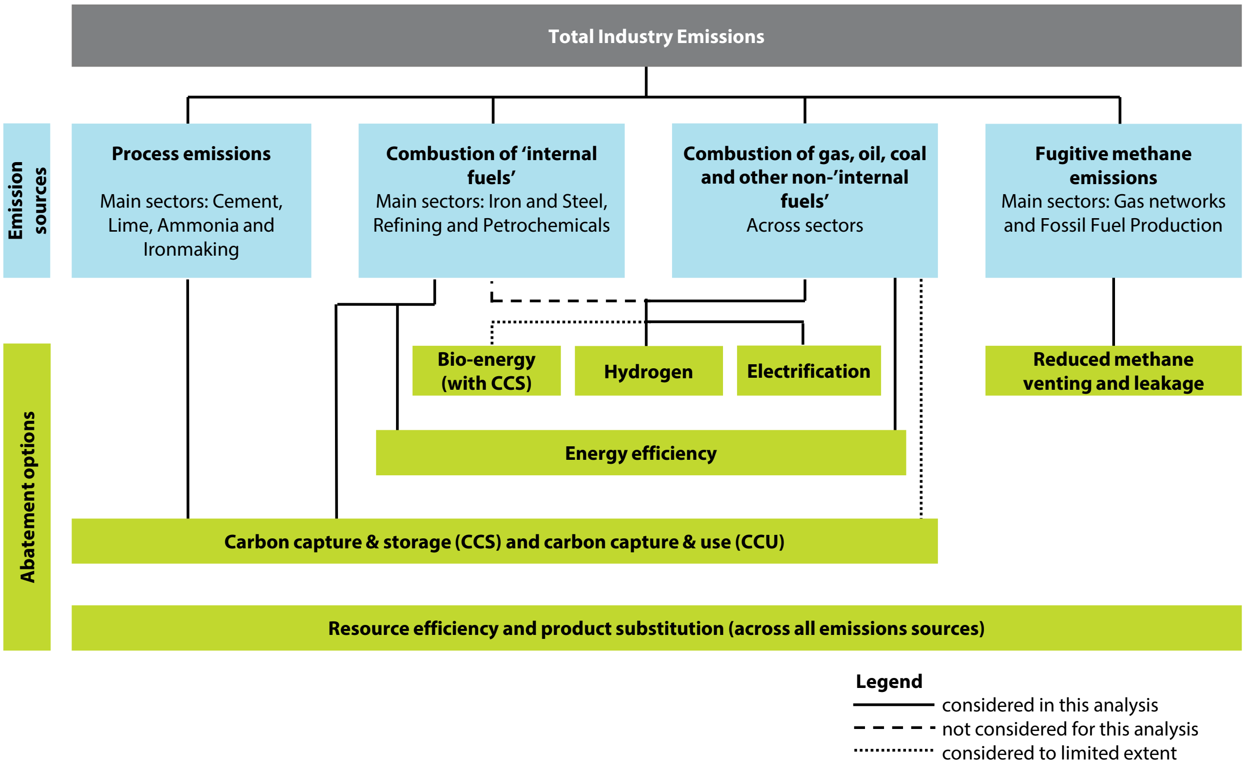
• **Energy efficiency and resource efficiency**. Using energy more efficiently reduces costs whilst cutting emissions. Reducing the flow of materials through the economy and using

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

products more efficiently (and for longer) can also reduce industrial emissions, as part of a shift towards a more circular economy.[122,123,124] Box 4.3 summarises new evidence on resource efficiency and material substitution that we used within our analysis for this report.

- **Reduced methane venting or leakage.** The amount of methane that is vented from oil and gas production and exploration and from the gas pipe network can be reduced through a series of measures. Venting from oil and gas production can be reduced either through improved gas recovery or, where necessary,[125] by flaring. Venting from exploration wells can be reduced through reduced emissions completions. Leakage of methane from the gas network can be reduced through periodic 'leakage detection and repair' or more expensive 'continuous monitoring'. Box 4.4 summarises new evidence commissioned for this report covering these measures and others to reduce emissions from fossil fuel production.

Figure 4.4. Schematic of abatement options for industry emissions and scope of CCC report analysis



Notes: Combustion of gas, oil and coal includes off-road mobile machinery which can be abated with the fuel switching options. Fugitive CO_2 emissions are considered within process emissions above. The lines for CCS and CCU indicate the consideration of CCS; CCU has not been considered in this analysis. 'Internal fuels' are fuels. produced by industry feedstock (blast furnace gas and coke oven gas in the iron-making sector, and some less valuable hydrocarbons in the refining and petrochemicals sectors).

[122] Example measures include the light-weighting of cars, as well as using consumer goods such as clothes and computers for longer before replacing them.
[123] Energy Transitions Commission (2018) *Mission Possible*, http://www.energy-transitions.org/mission-possible
[124] European Commission (2018) *Final Report of the High-Level Panel of the European Decarbonisation Pathways Initiative*, https://ec.europa.eu/clima/policies/strategies/2050_en#tab-0-1
[125] In case of health and safety emergencies.

Box 4.1. The strengthened evidence base used in this report

We have drawn together a range of new evidence to underpin the analysis of long-term industrial decarbonisation that is presented in sections 2-5 of this chapter. This predominantly updates and adds to the evidence base collated for our advice on the fifth carbon budget, which considered decarbonisation to 2050, although with a focus on the fifth carbon budget period 2028-2032.

Firstly, we have drawn on the evidence published in and alongside recent Committee reviews of Hydrogen and Biomass:

- The Hydrogen review drew on new evidence about fuel-switching in industry, produced by Element Energy and Jacobs, which suggests that hydrogen has the technical potential to reduce emissions from most forms of industrial combustion. It also showed that low-carbon hydrogen has a unique role to play in reducing emissions from direct firing - where the flame (and subsequent combustion gases) need to come into direct contact with the material or product being produced. For instance, in furnaces and kilns. The only other option for most direct firing applications is biomethane; however, there is a limited supply of biomethane and biomass.
- The Biomass review considered the role of bioenergy in industrial applications, in particular in combination with CCS (BECCS). Evidence from the 2018 Element Energy and Jacobs fuel-switching study along with energy system modelling undertaken for the review suggests that biomass can contribute to near-term emissions reductions in industry. However, in the longer term it should only be used in industrial applications with CCS, unless there are any applications where coal combustion could not otherwise be displaced. The review suggested that there could be around 10 $MtCO_2e$ of cost-effective industrial BECCS abatement,[126] although further work is required to confirm this potential as the results are highly sensitive to assumptions.

We have also commissioned and have undertaken new analysis for this report:

- We commissioned an extension of the 2018 Element Energy and Jacobs fuel-switching study to consider the potential of low-carbon fuels to abate some industrial combustion emissions that the previous study had not considered. The results of the study extension are outlined in Box 4.2.
- We commissioned Element Energy and the Sustainable Gas Institute to undertake new research on the costs and abatement of fossil fuel production and fugitive emissions, which currently produce annual emissions of around 25 $MtCO_2e$ (Box 4.4).
- We undertook a review of evidence on the abatement potential of resource efficiency (Box 4.3), along with the potential to reduce emissions from off-road mobile machinery and some of the smaller non-combustion process emissions sources.

Sources: CCC (2018) *Hydrogen in a low-carbon economy* and CCC (2018) *Biomass in a low-carbon economy*, Element Energy and Jacobs (2018) *Industrial Fuel Switching Market Engagement Study.*

[126] Including both stored and avoided CO_2.

Table 4.1. Industrial heat processes and suited fuel switching technologies

Processes driven by	Process type	Suitable fuel switching technologies	Key sectors relying on these processes
Direct Heating	Low temperature	Electric heaters, hydrogen heaters	Vehicles, other smaller manufacturing sectors
	High temperature	Solid biomass combustion, hydrogen heaters, electric kilns / furnaces, radio frequency heating, electric plasma gas heaters	Glass, Ceramics, Cement, other non-metallic minerals
Indirect Heating	Low temperature (including space heating)	Solid biomass boilers, hydrogen boilers, electric boilers, electric heaters, heat pumps, microwave heaters	Vehicles, other smaller manufacturing sectors
	High temperature	Electric heaters, hydrogen heaters (hydrogen replacing gas in burners)	Refining, Petrochemicals and Ammonia
	Steam	Solid biomass boilers, hydrogen boilers, electric boilers, heat pumps in limited applications	Food and drink, Paper, Chemicals

Source: Element Energy and Jacobs (2018) *Industrial Fuel Switching Market Engagement Study*.
Note: Direct heating refers to whenever the flame and subsequent combustion gases need to come into direct contact with the material or product being produced/heated. The other smaller manufacturing sectors are not sufficiently disaggregated in our data to identify them.

Box 4.2. Summary of new research on industrial fuel-switching

The 2018 Hydrogen report drew on new evidence on industrial fuel-switching in cross-sectoral combustion processes commissioned by BEIS. This work was undertaken by Element Energy and Jacobs. The study covered just over half of fossil fuel use in manufacturing (120 TWh out of a total of 215 TWh) and identified 90 TWh of industrial energy use which could be switched to hydrogen by 2040. This included 15 TWh of demands for firing applications, for which biomass and electrification are rarely technically suited.

We commissioned an extension to develop the evidence further including consideration of previous gaps such as options to reduce emissions from: coking and blast furnaces (12 $MtCO_2e$), combustion of 'internal' fuels produced as part of industrial processes such as blast furnace and coke oven gases (14 $MtCO_2e$), waste heat produced from other sites' combustion and sources that needed a combination of technologies to be fully abated cost-effectively (e.g. the use of hydrogen and heat pumps). It covers the abatement potential and costs from fuel-switching to hydrogen, biomass and electricity, alongside CCS.

Fuel-switching potential is considered in the main energy-intensive sectors including Chemicals, Food and Drink, Paper, Vehicles, Refining, Ethylene, Ammonia (electrolysis for hydrogen production), Non-metallic minerals, Non-ferrous metals and Secondary steel production and processing. The work also covers less energy-intensive sectors which had previously been an area where our evidence base was weaker.

CCS is considered in the following sectors: Primary iron production, Refining, Ethylene, Cement (including with some biomass for BECCS) and Ammonia. The study also considered abatement process emissions in the sectors.

Just over 40 $MtCO_2e$ of industrial emissions of 105 $MtCO_2e$ were out of scope of the study.

The results indicate that full decarbonisation of stationary combustion in manufacturing is possible using hydrogen, CCS, BECCS and electrification. Cost estimates range from £30-120/tCO_2e for CCS with most mature technologies (with lowest cost opportunities in ammonia), £30-190/tCO_2e for CCS with best available technologies; £65-240/tCO_2e for hydrogen and £-90-400/tCO_2e for electrification, including heat pumps for space heating.

Linking to hydrogen and CO_2 pipelines will be harder for some industry, which may require trucking, for example for off-gas-grid industry and industry outside of early 'decarbonisation clusters'. Additional costs were taken into account for inshore cement plants.

Source: Element Energy and Jacobs (2018) *Industrial Fuel Switching Market Engagement Study*,
Element Energy (2019) *Extension to Fuel Switching Engagement Study, for Committee on Climate Change.*
Notes: CCS costs above are based on 90% capture rates, where capture is applied. The lower end of the electrification cost range represents heat pumps.

Box 4.3. Summary of latest evidence on resource efficiency and material substitution

We have considered the potential for improvements in resource efficiency to reduce UK greenhouse gas emissions, largely based on the results of a recent University of Leeds and University of Manchester study. The measures we considered are summarised below (Table 4.2).

The study produced three scenarios: low, medium and high material productivity, reflecting different levels of ambition in changing production and consumption practises. The medium and high scenarios lead to a 6% and 12% reduction in UK industrial emissions respectively. They also reduce non-UK emissions as these measures will affect imported products - see Net Zero advice report chapter 5.

These are ambitious scenarios, which we assume are accompanied by action on resource efficiency by other countries. However, there is evidence that even larger emissions savings are possible, with the Energy Transition Commission estimating that 40% of emissions from heavy industry can be avoided through circular economy strategies.

Table 4.2. Summary of resource efficiency and material substitution strategies

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

Source: Scott, K., Giesekam, J., Barrett, J. and Owen, A. (2018) Bridging the climate mitigation gap with economy-wide material productivity, *Journal of Industrial Ecology*, https://doi.org/10.1111/jiec.1283, Energy Transitions Commission (2018) *Mission Possible*, http://www.energy-transitions.org/mission-possible
Notes: Scott et. al. scenarios have been adjusted to include CCC analysis on clinker substitution in cement, wood in construction, increase in use of recycled glass, and analysis from the Government's Industrial Decarbonisation and Energy Efficiency Roadmaps to 2050 for yield improvements in steel production. We assume that the measures from the Scott et. al. are rolled out by 2050 rather than 2032, which was the year used in the study.

Box 4.4. Summary of new research on fossil fuel production and fugitive emissions

We commissioned Element Energy and the Sustainable Gas Institute at Imperial to undertake research on the costs and abatement potential for reducing emissions from UK fossil fuel production and fugitive emissions - currently 24 $MtCO_2e$ in total.

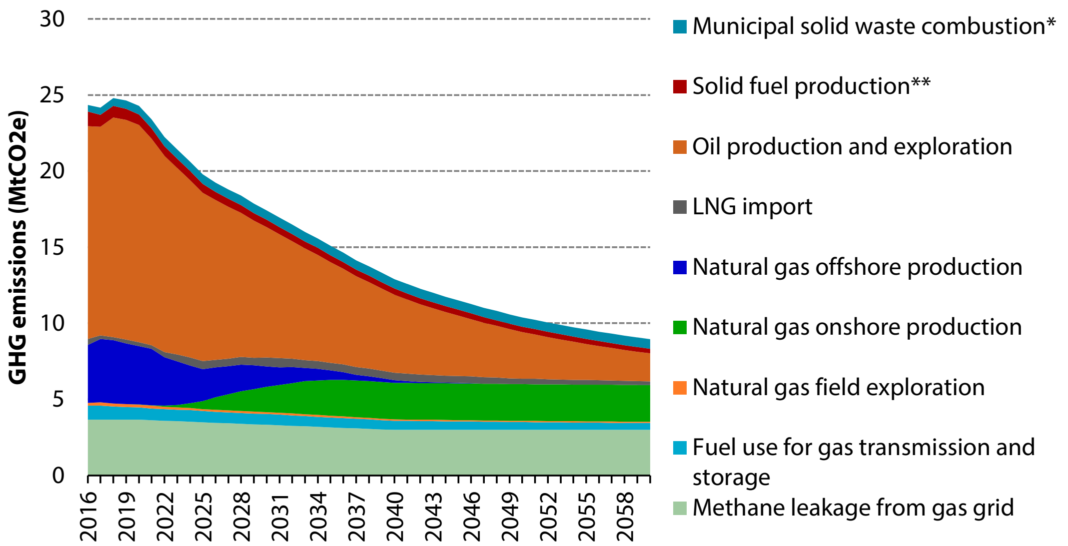
Abatement technologies considered include electricity or hydrogen connections to offshore platforms, flare gas recovery, small scale on-site carbon capture and leak detection and repair (LDAR) for reducing methane leakage.

Baseline emissions from these sources are projected to reduce to 10 $MtCO_2e$ in 2050 (Figure B4.4). This is primarily a result of decreasing offshore oil and gas production, but with a small contribution from ongoing investment in the Iron Mains Replacement Programme. These falls are partially offset by a projected increase of 2 $MtCO_2e$ from new onshore petroleum development (based on National Grid scenarios). Overall, this implies that by 2050, methane leakage from pipelines and the gas grid is projected to contribute 29% of projected emissions, with similar size contributions from onshore and offshore oil production and smaller emissions from Municipal Solid Waste combustion and methane leaks from closed coalmines.

The research found that the lowest cost abatement options are gas recovery, reduced venting with flare and LDAR. The research identified 3 $MtCO_2e$ of abatement potential from continuous monitoring at a cost of around £90/tCO_2e. CCS and fuel-switching to hydrogen and electricity account for 3 $MtCO_2e$ and 2 $MtCO_2e$ of abatement potential in 2050 respectively (based on the report's central rollout rates).

Rollout rates were determined based on an estimated Technology Readiness Level measuring the maturity of the technologies, with both year of first deployment and year of maximum deployment calculated on this basis.

Figure B4.4. Baseline emissions from UK fossil fuel production and fugitive emissions, 2017-2060



Notes: *and flue gas desulphurisation. **including emissions from closed coal mines, but excluding most production of coke.

Source: Element Energy (2019) *Assessment of Options to Reduce Emissions from Fossil Fuel Production and Fugitive Emissions, report for the Committee on Climate Change.*

(b) Current Government ambitions

Current long-term Government ambitions include greater deployment of fuel-switching (to hydrogen, electricity or bioenergy), CCS and more improvements in energy efficiency and resource efficiency:

- The Government's Industrial Clusters Mission aims to establish the world's first net-zero carbon industrial cluster by 2040 and at least one low-carbon cluster by 2030, which would require some fuel-switching and CCS. This is supported by some nearer-term policies and ambitions:
  - The Government's Carbon Capture, Use and Storage (CCUS) Action Plan set out a plan to enable deployment of the UK's first CCUS facility in the UK, commissioning from the mid-2020s.
  - The Government's Clean Growth Strategy set the ambition to phase-out installation of high carbon fossil fuel heating in business buildings off the gas-grid during the 2020s.
  - The Industrial Energy Transformation Fund will invest up to £315 million in decarbonising industry, through energy efficiency and low-carbon technologies.
- The Government has set an ambition to improve business energy efficiency by 20% by 2030. In our June 2018 Progress Report we estimated that this would provide around as much energy efficiency in 2030 as our cost-effective path to an 80% emissions reduction target in 2050.
- Through the Resources and Waste Strategy, the Government set a strategic framework for the UK to develop into a zero avoidable waste economy by 2050. Policies for resource efficiency in the 2020s include extending producer responsibility by changing product designs, adopting sustainable materials, and adapting distribution models.
- The process of replacing the old iron gas distribution network with plastic pipes (the Iron Mains Replacement Programme) is set to continue through to 2040 and will help reduce methane leakage, potentially by around 40% between 2020 and 2040.[127]

(c) Challenges in avoiding emissions from industry

Achieving high levels of abatement in industry will be challenging. The challenges include cost, the length of replacement and refurbishment cycles, capital constraints, need for infrastructure, technical limitations and behaviour:

- **Cost and competitiveness**. The cost of abatement (in £/tCO_2e) varies across measures. Broadly, energy and resource efficiency, reducing methane venting and leakage, CCS on ammonia production and the use of industrial electric heat pumps are among the cheaper industry options. Other CCS and fuel switching are more expensive, with our analysis suggesting that hydrogen options may be cheaper than electrification (with the exception of heat pumps). These costs could affect the competitiveness of parts of industry. The design of the policy framework to reduce UK industry emissions must ensure it does not drive industry overseas, which would not help to reduce global emissions, nor the UK economy. Abatement costs are considered in more detail in Sections 3 and 4 and policy design in Section 5.

[127] Element Energy and the Sustainable Gas Institute (2019) *Fossil Fuel Production and Fugitive Emissions, report for the Committee on Climate Change.*

- **Refurbishment and replacement cycles**. Industrial equipment and assets typically have long lifetimes. This limits the rate that new technology can be introduced, unless existing assets are scrapped before the end of their life, or there is an option for technology to be pre-prepared for a change (such as a hydrogen-ready gas boiler for space heating). In general, to avoid missing low-carbon investment opportunities, it is important to prepare abatement in line with refurbishment cycles, but there can be further complications.
  – Different equipment on the same site can have different end-of-life dates, but they need to be changed simultaneously (for example, if a site needed to switch to hydrogen).
  – There may be no view to refurbish or replace, but rather to extend the life of an asset as far as possible. For example, for offshore oil and gas fields that have a limited remaining economic life, the economics of investment in abatement technologies may be even more challenging than for fields with longer remaining lifetimes.
- **Infrastructure**. Some abatement will need provision of infrastructure outside the control of specific industries. For example, to take full advantage of the potential abatement from industrial CCS, there will need to be adequate CO_2 transport and storage infrastructure. Similarly, if there is to be widespread fuel switching to hydrogen, a hydrogen distribution network will be required.
- **Capital constraints**. Many of the opportunities in energy-intensive industry have substantial upfront requirements for capital and can have long payback periods. For firms to plan and finance abatement opportunities, there will need to be long-term certainty about a mechanism to reflect the value of abatement.
- **Technical limitations**. Some technologies are not yet commercially available, in particular hydrogen-use technologies, such as hydrogen boilers. This will constrain how quickly these can be deployed.
- **Consumer behaviour**. Some resource efficiency improvement measures require consumers to change their behaviour (for example, by buying new clothes less frequently).

3. Scenarios for minimising emissions from industry

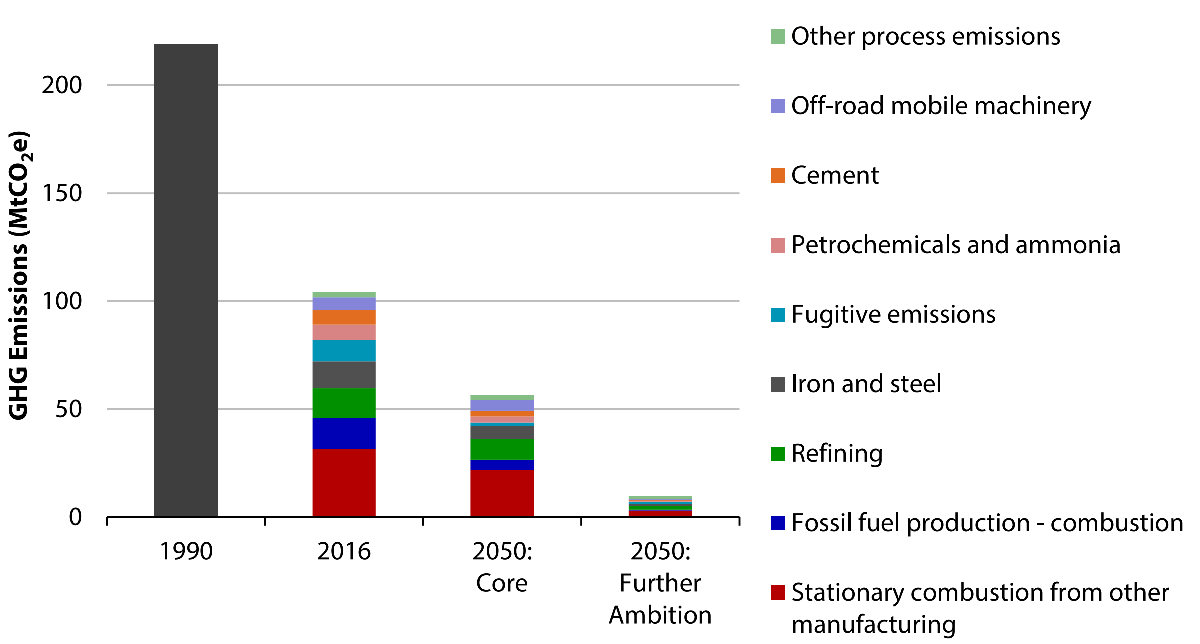
(a) Opportunities for cutting emissions towards zero

In this section we summarise the options to reduce emissions, based on our assessment of the measures outlined earlier (Figure 4.4).[128] We split these options into 'Core', 'Further Ambition', and 'Speculative':

- Core options are those low-cost low-regret options that make sense under most strategies to meet the current 80% 2050 target. For most, the Government has already made commitments or begun to develop policies (although in many cases these need to be strengthened).
- Further Ambition options are more challenging and/or more expensive than the Core options, but are all likely to be needed to meet a net-zero target.
- Speculative options currently have very low levels of technology readiness, very high costs, or significant barriers to public acceptability. It is very unlikely they would all become available. Some of these options would be required to reach net-zero GHG emissions domestically.

Figure 4.5 shows how these options would reduce emissions from the industry sector.

Figure 4.5. Scenarios for very deep emissions reductions from industry



Sources: CCC analysis, National Atmospheric Emissions Inventory.

[128] Figure 4.4 outlines how measures were considered in the analysis and where there was limited consideration.

Core options

Our 'Core' options would reduce industry emissions to 56 $MtCO_2e$ by 2050. Our core options include:

- Energy efficiency improvements drawn from the Max Tech scenario of the Industrial Decarbonisation and Energy Efficiency Roadmaps to 2050.[129] These included a variety of measures that are specific to each sector but can be broadly grouped into: energy and process management, best available and innovative technology, waste heat recovery and use, and clustering industries with waste heat together with industries that could use this waste heat. These measures represent 5 $MtCO_2e$ of abatement in 2050.
- Resource efficiency improvements based on the medium scenario (Box 4.4), representing a total of 5 $MtCO_2e$ of abatement in 2050.
- Carbon capture and storage (CCS) on emissions from the ammonia and cement sectors and on blast furnaces in the iron and steel sector, representing 6 $MtCO_2e$ of abatement in 2050. This scenario assumes that CCS deployment at scale starts from 2030, with second generation CCS technologies (that have lower cost than first generation technologies).
  - It assumes that 90% of flue stream emissions are captured, where capture is applied. Capture is applied to almost all ammonia and cement emissions, but only applied to 60% of iron and steel sector emissions.
- Electrification of some low temperature heating processes using industrial heat pumps, representing up to 1 $MtCO_2e$ of abatement in 2050.
- Reduced methane venting and leakage through gas recovery, continuous monitoring and flaring where needed,[130] representing 4 $MtCO_2e$ of abatement in 2050.
- Use of biomethane in industry for residual gas demand. We have included 5 TWh of biomethane in industry, delivering 1 $MtCO_2e$ abatement in 2050.

Parts of these Core opportunities are already included in the Government's ambitions (section 2b), albeit with significant policy strengthening required to deliver them. Reducing emissions further towards net-zero will require an increased contribution from these options, including greater deployment of carbon capture and storage and fuel switching.

Further Ambition options

Our 'Further Ambition' options would reduce emissions to 10 $MtCO_2e$ by 2050. Most of this could be needed to deliver the UK's existing 2050 target and it will all almost certainly be needed for a net-zero target. Costs are outlined in Table 4.3. Our 'Further Ambition' options include:

- CCS in sectors with non-combustion process emissions (cement, lime, ammonia and glass) and sectors which use 'internal' fuels produced by their feedstock (the iron, petrochemicals and refining sectors). This represents around 22 $MtCO_2e$ of abatement in 2050.
  - This scenario assumes that CCS deployment at scale starts from 2025, with first generation CCS technologies (that have higher cost than second generation technologies).

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[129] Parsons Brinckerhoff and DNV GL (2015) *Industrial Decarbonisation and Energy Efficiency Roadmaps to 2050 - report for DECC and BIS.*
[130] For health and safety purposes in emergencies.

- It assumes that 90% of flue stream emissions are captured, where capture is applied. Capture is applied to almost all emissions in all the above sectors, apart from the refining sector, where it is applied to 90% of emissions sources.

- Industrial BECCS was only considered to a very limited extent in our analysis, in sectors where biomass is already used. The greenhouse gas removal achieved by these options is accounted for in the analysis of Chapter 10.
- Widespread deployment of hydrogen, electrification or bioenergy for stationary industrial heat/combustion in those manufacturing sectors not treated with CCS as identified above.
  - The hydrogen and electrification represents around 19 $MtCO_2e$ of abatement in 2050, reducing emissions from stationary industrial heat/combustion in those manufacturing sectors not treated with CCS to 4 $MtCO_2e$.[131]
  - Use of biomethane in industry for residual gas demand, in line with the core option above, reduces emissions further to 3 $MtCO_2e$ in 2050.
  - Further deployment of fuel switching technologies can be achieved by 2055. This is not achieved by 2050 because of assumed constraints on deployment rate (considered further in Section 3b).
- Widespread deployment of hydrogen or electrification for off-road mobile machinery to 90% of the fleet by 2050. This represents around 4 $MtCO_2e$ of abatement in 2050.
- Reduced methane venting and leakage through gas recovery, reduced emissions completions, continuous monitoring, flaring where needed[132] and closure of parts of the gas grid. This represents around 4 $MtCO_2e$ of abatement in 2050.
- Emissions from fuel combustion in oil and gas production are reduced through a mix of CCS and electrification, with more CCS offshore and more electrification onshore. This represents around 5 $MtCO_2e$ of abatement in 2050.
- Resource efficiency improvements based on the high scenario from work by the University of Leeds and University of Manchester (Box 4.3). This is an ambitious scenario and we assume is accompanied by action on resource efficiency by other countries. It represents a total of 9 $MtCO_2e$ of abatement in 2050.
- Energy efficiency improvements drawn from the Max Tech scenario of the Industrial Decarbonisation and Energy Efficiency Roadmaps to 2050, as outlined in the Core options (5 $MtCO_2e$ of abatement in 2050).

'Speculative' options

Our 'speculative' options, are additional to the further ambition options, and include:

- An increase in carbon capture rates on parts of sites that are fitted with carbon capture.[133] In this option, CCS captures 99% rather than 90%.[134,135] This option provides an extra 2 $MtCO_2e$ of abatement. Applying CCS on brick production provides an extra 0.1 $MtCO_2e$ of abatement.

[131] Before consideration of biomethane abatement.
[132] For example, for health and safety purposes in emergencies.
[133] In refineries, we assume that 90% of the plant (by emissions) is fitted with carbon capture.
[134] Apart from on brick production.
[135] This draws on evidence from IEAGHG (March 2019) *Towards zero emissions CCS from power stations using higher capture rates or biomass.*

- Faster deployment of hydrogen and electrification technologies, requiring more scrappage, or potentially by installing hydrogen-ready equipment. Pace of deployment is considered further in Section 3b. This option provides an extra 2 $MtCO_2e$ of abatement in 2050.
- More electrification of compression on offshore platforms, by connecting the platforms to the electricity grid using cables, provides an extra 0.2 $MtCO_2e$ of abatement.

Alternative options to deliver the abatement in Core, Further Ambition and Speculative scenarios

In many cases there would be alternative technical or behavioural approaches that could deliver the emission reductions in our scenarios. It may not be necessary to decide between them now.

Hydrogen, fossil-fuelled CCS, BECCS, and electrification will compete to reduce emissions from industrial combustion. Our Core, Further Ambition and Speculative scenarios identify where at least one technology can reduce a particular source of emissions. However, the scenarios have not fully considered which technology currently appears most cost-competitive. It is likely that some of the industrial combustion emissions abated by CCS could be abated cost-effectively by hydrogen, electrification or BECCS. Similarly, some of the industrial combustion abated by hydrogen or electrification, could be abated cost-effectively by CCS or BECCS.

(b) Timing for cutting emissions towards zero

The fifth carbon budget (covering 2028-2032) already requires significant progress towards these net-zero scenarios. The cost-effective path that the Committee has identified, and that can be delivered through existing policy with some strengthening, includes:

- 3 $MtCO_2e$ of abatement from carbon capture and storage by 2030
- 5 $MtCO_2e$ of abatement from switching to low-carbon fuels by 2030
- 5 $MtCO_2e$ of abatement from energy efficiency by 2030.

With a committed and well-designed policy effort it would be possible to deliver the Further Ambition options set out above by 2050 and further deployment of the measures outlined could be achieved by 2055:

- By 2050, it should be possible to achieve the full potential identified in our Further Ambition Scenario for the deployment of carbon capture and storage in the cement, refining, iron and steel, ammonia and petrochemicals sectors; CCS and electrification for emissions from oil and gas production, and hydrogen or electrification for off-road mobile machinery.
  - The Further Ambition Scenario assumes that CCS deployment starts at scale from 2025 and that all plants reach one replacement or refurbishment date between 2025 and 2050 at which they are fitted with CCS. This is a very stretching scenario. In practice, for some sites, the timing to fit CCS may be less specific, with retrofit being practically or economically feasible at a number of points in a plant's life. Even with this flexibility, we expect that developing regional 'cluster'-based infrastructure to enable CCS deployment is on the 'critical path' for achieving net-zero emissions. This is also because of the large amount of CCS required by 2050 and long lead-times for developing CO_2 infrastructure.
- In our Further Ambition Scenario, 85% of emissions from stationary industrial heat/combustion in those manufacturing sectors not treated with CCS have switched to hydrogen or electricity by 2050, extending to 95% by 2055.

- This scenario assumes that deployment of hydrogen technologies and electrification starts from around 2025 with half of all refurbishments and replacements in clusters being low-carbon; by 2030 almost all refurbishments and replacements in clusters are low-carbon and by 2035 almost all refurbishments and replacements nationwide are low-carbon.[136] After 2045 an accelerated deployment of fuel-switching is adopted,[137] which results in higher costs of abatement as assets are scrapped up to 20% before their expected lifetime.
- An alternative route to reaching the deployment of fuel-switching technologies in our Further Ambition Scenario in 2050, would be to install hydrogen-ready (or low-carbon-ready) technologies from the mid-2020s. This would reduce the need to scrap assets towards 2050. However, we do not know now that these technologies will be possible or available.

- Full implementation of the resource efficiency and energy efficiency measures accounted for in our modelling could be achieved by 2050.
- Full deployment of options to reduce methane venting or leakage could be achieved by 2040.

This assessment allows for the various limiting factors on a realistic speed of change:

- The rate of technology deployment is no faster than natural stock turnover rates of the existing technology until 2045 for all technologies.
- CO_2 transport and storage infrastructure is assumed to be unavailable until 2025.
- Hydrogen pipeline infrastructure availability is assumed to increase incrementally. Hydrogen via pipelines is assumed to be available at scale in some clusters from 2025, the remaining clusters in around 2030 and wider industry outside of clusters from around 2035.
- Hydrogen boilers, heaters and kilns/furnaces are assumed to be become commercially available in the second half of the 2020s.

There are complicated geographical interactions between some of these factors. For example, sites that could be ready to deploy a hydrogen boiler in 2030, but are not yet near to a hydrogen supply network, may not be able to fuel switch at that point. In some of these cases, it could be cost-effective to implement some limited early scrapping of assets. Alternatively, if technology permits, 'hydrogen-ready' technology[138] should be deployed in anticipation of hydrogen roll-out.

Delayed deployment of hydrogen production and pipeline infrastructure, CO_2 transport and storage infrastructure, or low-carbon heat/combustion technologies, may mean that less decarbonisation of industry is possible and/or a greater role for scrappage of high-carbon assets is required.

In our Further Ambition Scenario, emissions are reduced to 10 $MtCO_2e$ in 2050. Looking beyond 2050, the additional scope for reducing emissions from stationary industrial heat/combustion means industry could contribute an extra 2 $MtCO_2e$ towards an economy-wide decarbonisation in this scenario after 2050.

[136] Deployment of hydrogen boilers starts in 2025, hydrogen heaters in 2026 and hydrogen kilns/furnaces in 2027, reflecting different dates of commercialisation. There are similar lags for the 2030 and 2035 dates.
[137] At 75% faster than the natural rate of refurbishment and replacement.
[138] That is still able to operate with an existing fuel such as natural gas.

(c) Summary table of the opportunities to reduce emissions from industry towards zero

Table 4.3. Opportunities to reduce emissions from industry towards zero

Segment	Current emissions	Further Ambition residual emissions in 2050 ($MtCO_2e$)	Earliest date to reach zero or minimum Further Ambition emissions	2050 cost £/tCO_2e for abatement (further ambition)	2050 cost £/tCO_2e without efficiency measures (further ambition)	2050 cost £/tCO_2e without efficiency measures (core)
Iron and Steel	13	0.7	2050	102	174	81
Cement	7	0.5	2050	94	131	84
Refining	14	1.8	2050	132	165	-
Ammonia	2	0.1	2050	18	30	30
Petrochemicals	5	0.2	2050	113	184	-
Stationary combustion from other manufacturing sectors*	32	3.0	2055	119	156	2
Combustion associated with fossil fuel production	14	0.5	2050	291	299	-
Fugitive methane and CO_2	10	1.2	2040	32	33	55
Off-road mobile machinery	6	0.5	2050	102	105**	-
Other process (non-combustion) emissions***	2	1.2	2050	113	152	0

Source: CCC analysis.
Notes: Emissions in 2050 include all GHGs; £/tCO_2e cost figures represent levelised costs of abatement of the measures in place in 2050, and are averaged across multiple abatement measures applied to the same emission source. *Includes all manufacturing sectors not listed in the rows above, such as food and drink and paper and pulp. **Due to scarce data on off-road mobile machinery, hydrogen Heavy Good Vehicles were used as a proxy to estimate costs. ***Includes process emissions from brick, glass and some chemicals.

4. Costs and benefits of achieving very deep emissions reductions in industry

Our overall approach to assessing costs and benefits is summarised in Chapter 1 of this report and set out in full in Chapter 7 of the accompanying advice report.

Some of the low-carbon options included in our net-zero scenario for the industrial sector, such as energy and resource efficiency, would avoid costs compared to the high-carbon alternative, whilst others will be more expensive.

Together, these costs imply an annual cost for cutting industrial emissions to 10 $MtCO_2e$ of £8 billion in 2050 (in real 2017 prices, 0.2% of expected 2050 GDP), [139] compared to a theoretical scenario with no climate change policy action at all. The annual cost builds to this level over time, starting small in the early 2020s and growing steadily as larger proportions of industry switch to low-carbon technology, typically at the end-of-life of their existing capital stock.

Overall investment in new and existing UK industry could increase in the Further Ambition scenario, relative to the counterfactual. For this to occur, government and industry will need to develop an attractive investment environment, based on competitive advantages and stable policy. This investment could lead to socio-economic benefits from employment in the industrial sectors. The value of employment and activity in the sector may be amplified where it provides a key foundation to local communities.

There would also be health benefits from improved air quality. These are set out across the economy in Chapter 7 of our advice report.

The next section considers how the scenarios can be delivered, including the need to design policy to ensure UK industry is not competitively disadvantaged.

5. Delivering very deep emissions reductions in industry

(a) What is needed to deliver the Further Ambition Scenario

Delivering our Further Ambition Scenario will require Government leadership on funding mechanisms, preparing for abatement in line with refurbishment and replacement cycles, infrastructure, innovation and technology development, and social and behavioural change. Table 4.3 summarises our assessment of the degree of challenge there will be in achieving the uptake of the main abatement measures in our Further Ambition Scenario. Figure 4.6 summarises the timing for when key changes would need to occur:

- **Funding mechanisms**. Significant levels of investment and finance will be required in our Further Ambition Scenario. We estimate that the additional annualised capital cost of the capital stock in 2050 will be £3 billion. To provide this investment and cover around £5 billion additional annual operational costs in 2050, industry will require clear stable policy that reflects the value of abatement. This will require appropriate funding mechanisms and policy design (subsection 5b). In our June 2018 Progress Report to Parliament we recommended that Government:
  - Develop and implement the framework to support decarbonisation of heavy industry by the end of 2022.

[139] In line with our Further Ambition Scenario.

  - Put in place a mechanism to support CO_2 transport and storage infrastructure and initial industrial CCS projects by end 2021.

  These actions are a minimum under our Further Ambition Scenario and we will review these for our annual Progress Report to Parliament in July 2019.

- **Preparation for abatement in line with refurbishment and replacement cycles.** To meet our Further Ambition Scenario it will be necessary to install low-emission technology at industrial sites, typically timed around refurbishment and replacement cycles. These long cycles will likely necessitate starting deployment at scale soon. Fitting hydrogen-ready or capture-ready equipment may provide a small amount of flexibility around linking these up to infrastructure. In our scenario, the date from which all new equipment is required to be low-carbon varies from 2025 to 2037 depending upon the subsector and application. Government should urgently establish a detailed understanding of constraints on pace of deployment of low-carbon technologies across sites and policy should be designed to account for these constraints. Consideration of 'low-carbon-ready technologies' (e.g. hydrogen-ready boilers) should be a high priority for Government, since it will significantly affect the required pace of deployment and requirement for scrappage.

- **Infrastructure**. Options to use CCS and to switch to hydrogen will be limited by the rate of deployment of infrastructure. To deliver our Further Ambition Scenario, CO_2 transport and storage infrastructure should be operational in at least one industrial cluster by 2026 and available to all major industrial clusters soon afterwards, alongside hydrogen for all clusters where it is the best fuel-switching option for some sites in the cluster. A network to provide hydrogen to industry outside of the main industrial clusters should be established by 2035, or potentially slightly later if 'hydrogen-ready' appliances can be deployed in industry prior to this date.

  - It will be important for BEIS to identify when those industrial sites that will require CCS would need to fit CCS in order to fit with their refurbishment cycles, and what that implies for the dates by which CO_2 transport and storage infrastructure needs to be available for different clusters. This may necessitate more CCS infrastructure being rolled out at particular clusters earlier.

- **Innovation and technology development.** Innovation will be essential across technologies:

  - Industrial hydrogen-using technologies, across heat and off-road mobile machinery, are not yet commercially available, and require development if our Further Ambition Scenario is to be delivered. Innovation in BECCS and electrification will also be important, with these options likely to play a role in some sectors and applications. Innovation across these technologies is urgent given the need to prepare for abatement in line with refurbishment and replacement cycles. These constraints also mean that the development of hydrogen-ready technologies is an urgent priority.

  - Innovation into higher capture rates will also be important, as higher abatement from CCS will offset risks of under-delivery elsewhere.

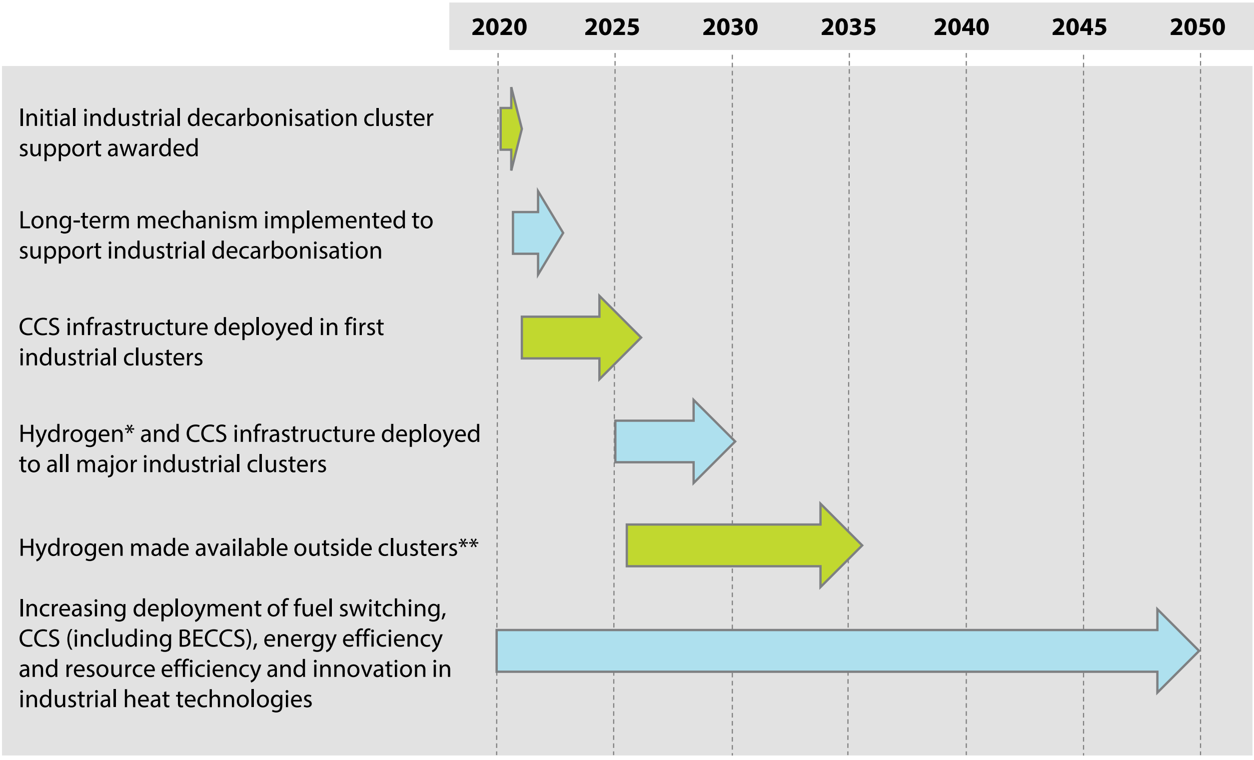
- **Social and behavioural change** will be required to deliver some of the improvements in resource efficiency outlined in Box 4.3, which are included in our Further Ambition Scenario. These measures include consumers using products (such as clothes and appliances) for longer and increased reuse and recycling.

Table 4.4. Assessment of degree of challenges for key abatement options in the Further Ambition scenario for the industry sector

Emissions segments	Abatement option	Barriers and Delivery risks*	Funding mechanisms	Co-benefits and opportunities	Alternative options
Iron and Steel, Refining, Cement, Ammonia, Petro-chemicals, and other process emissions	CCS	Pace of deployment - given stock turnover rates. 🔴 Support for transport and storage infrastructure. 🟡	Consumer, industry or taxpayer funded, depending upon risk to competitiveness 🔴	Clean growth, regional jobs, air quality 🟢	For combustion emissions, BECCS, hydrogen and electrification
	Energy efficiency	Payback periods and capital constraints. 🟢			
	Resource efficiency	Consumer behaviour inertia. 🔴 Manufacturers' behaviour inertia. 🟡			
Stationary combustion from other manufacturing sectors, and off-road mobile machinery	Hydrogen technologies	Pace of deployment - given stock turnover rates. 🔴 Hydrogen supply pipe (and trucking) network. 🔴 Development of hydrogen use technologies at pace. 🔴			CCS, BECCS and electrification (including electrification of off-road mobile machinery)
	Energy and resource efficiency	As above for resource and energy efficiency. 🟡			
Combustion associated with fossil fuel production	CCS and electrification	Lack of incentive to invest (and falling cost-effectiveness) as fields come to end of lives. 🔴			
Fugitive methane and CO_2	Gas recovery, reduced emissions completions, continuous monitoring.				Leakage detection and repair

Source: CCC analysis.
Notes: *Barriers and delivery risks include supply chains. The rating of measures in the table is based on the following criteria: 'barriers and delivery risks' are rated as 'red' if there is evidence that a given measure is particularly hard to implement, and 'green' or 'amber' otherwise; 'funding mechanisms' are rated as 'red' if the delivery of a given measure has high costs and these have a negative impact on businesses' competitiveness or are regressive on households, and 'green' or 'amber' otherwise; when there is evidence of positive 'co-benefits and opportunities' these are rated as 'green', otherwise no rating is given.

Figure 4.6. Timing of key decisions and changes to deliver the net-zero scenarios for industry



Notes: * Where it is the best fuel-switching option for at least some sites in the cluster.
** The end of the arrow could potentially occur slightly later if 'hydrogen-ready' appliances can be deployed in industry prior to switching the gas supply to hydrogen.

(b) Policy design for driving deep emissions reductions from industry

This report does not aim to identify a full policy package to deliver the scenarios set out above. However, there are important high-level policy implications that should be understood by Government and Parliament when considering the setting of a UK net-zero emissions target.

In particular, for industry, the Government must urgently establish an overall framework to support long-term industrial decarbonisation, as committed to in the Government's Clean Growth Strategy, if it is to enable decarbonisation towards the Committee's recommended net-zero target. Delay will mean less decarbonisation of industry is possible or a greater role for scrapping assets.

The design of the policy framework to reduce UK industry emissions must ensure it does not drive industry overseas, which would not help to reduce global emissions, and be damaging to the UK economy. This will require either consumers or taxpayers to bear much of the cost of decarbonisation of industrial subsectors or sites that are at risk of carbon leakage.

The Government should also help to ensure that the UK realises the benefits of ambitious decarbonisation. By providing an attractive investment environment, including stable policy, the UK can become a leader in production of low-carbon goods, attract increased investment in productive new and existing industries, and develop new businesses and products. This should involve encouraging subsectors and technologies where the UK may have a competitive advantage.

Designing policy mechanisms and avoiding carbon leakage

Designing policy to encourage deep decarbonisation in industry may require new policy mechanisms, as it is unlikely that carbon prices under the EU emissions trading system (or a UK equivalent) will rise high enough with sufficient lead-time (and stability) to incentivise the range of changes required to meet our Further Ambition scenario.

These will need to support decarbonisation in both industries at risk of carbon leakage (typically where they are carbon intensive and in a sector with high levels of international trade) and those not at risk. Policies for sectors at risk of carbon leakage will require costs to be passed directly on to taxpayers or consumers (households or businesses not at risk of carbon leakage). Policies for sectors not at risk could also be funded directly through industry.

There are a range of possible options for decarbonising industry in a way that avoids carbon leakage, where consumers or the taxpayer bear the cost:

- **Emissions trading combined with issuing free allowances**, offers an existing route. However, the system would need to be managed to ensure that the stability and level of the carbon price provided sufficient incentives for decarbonisation. In addition, the system of awarding free allowances would need to manage the risk of windfall profits, once the carbon price was above the cost of abating a sites emissions.
- **Mechanisms similar to those used in existing energy markets.** A recent review of business models by Element Energy for BEIS has set out a number of policy options, which are largely taxpayer funded and draw on comparable existing policies (Box 4.5).
- **Creation of a low-carbon market**. Demand for low-carbon goods could be created through certification and regulation of end uses, creating a premium price for low-carbon goods. In this case the user (consumers) could bear the cost. Alternatively, such a market could be driven by public procurement, in which case Government and taxpayers would bear the cost.
- **Border-tariff adjustments** would raise the price of high-carbon imported goods. This could enable deep decarbonisation in sectors that would otherwise be at risk of carbon leakage. It would also send a strong signal to the other manufacturing countries to decarbonise their production. Under this approach industry and consumers would pay for the emissions reductions.
- **Sectoral agreements** would involve the whole of an international sector agreeing a pathway for decarbonisation to ensure that one country's firms in a given industry sector are not at a competitive disadvantage to those in other countries. This will tend to work better in industry sectors in which there is a small number of firms. This would involve industry bearing the costs of decarbonisation while also avoiding carbon leakage.

It may be that for an interim period, industrial decarbonisation of trade-exposed sectors can be funded by taxpayers, but this is unlikely to be fiscally sustainable in the longer term given increasing decarbonisation over time. As other countries take action to meet their commitments under the Paris Agreement, there would need to be a transition away from taxpayer funding. We will consider these options in further work.

Box 4.5. Report on industrial carbon capture business models for BEIS

A recent review of business models by Element Energy for BEIS has set out some potential options (for supporting industrial carbon capture), which largely draws on comparable existing policies:

- **Contract for difference CO_2 certificate strike price**: The emitter with carbon capture is paid (or refunded) the difference between a CO_2 strike price contractually agreed, in £/tCO_2 abated, and the prevailing CO_2 market certificate price. The quantity of CO_2 'abated' is determined relative to an industry benchmark to ensure that best available technologies are deployed where possible and the deployment of high emissions technologies is not incentivised through CO_2 revenue. The costs would likely be borne by taxpayers.
- **Cost plus open book**: The emitter is directly compensated through government grants for all properly incurred operational costs and any emitter capital investment is paid back with agreed returns. The costs would be borne by taxpayers.
- **Tradeable tax credits**: Tax credits would offer reductions in the tax liability of firms which implement low-carbon measures, in £/tCO_2 abated, and may taper through the contract. The credits must be tradeable to allow full realisation of their value and a government buyback guarantee may be required, as well as capital support. The costs would be borne by taxpayers.
- **Regulated asset base (RAB) model**: A RAB model values assets used in the performance of a regulated function, for example UK gas distribution, and sets tariffs to pass the costs of these assets on to consumers. The RAB model is thought to be primarily applicable for hydrogen production for heat, where the cost recovery is through gas consumer bills. However, in this case, the consumers of hydrogen could often be energy-intensive industry, leading to the need for another mechanism to avoid passing costs onto industry at risk of carbon leakage.
- **Tradeable CCS certificates + obligation**: Tradeable CCS certificates are awarded, per tCO_2 abated, and obligated parties are obliged to surrender a set number of these certificates, which may increase over time. This policy type might result in costs being borne by industry or taxpayers.

The review did not focus on mechanisms for support of other deep industrial decarbonisation, such fuel switching to hydrogen or electricity, however, the policy approaches above may also be applicable for these technologies.

Source: Element Energy (2018) *Industrial carbon capture business models: Report for BEIS.*

The Committee's annual progress reports to Parliament include our detailed progress assessments. Our June 2018 report identified a number of areas where policy strengthening was required to deliver existing ambition. These are a necessary condition to support the increased effort required to deliver a UK net-zero emissions target – we will report on progress against them in July 2019.

Chapter 5: Transport

Introduction and key messages

This chapter sets out the scenarios for the surface transport sector that inform the Committee's advice on reviewing long-term emissions targets for the UK, Scotland and Wales. It draws on new research on the costs of zero-emission cars, vans and HGVs, as well as the costs and likely roll-out rates of the supporting refuelling infrastructure.

The key messages from this chapter are:

- **Background.** Cars, vans and heavy goods vehicles (HGVs) are the most significant sources of greenhouse gas (GHG) emissions in this sector. GHG emissions from surface transport account for 23% of total UK GHG emissions in 2017 and are predominantly CO_2.
- **'Core' measures.** Cars and vans can switch, cost-effectively, to electric vehicles, representing 100% of new sales in 2040, in line with current Government policy. Buses can also switch to electricity and hydrogen fuel. Demand for transport can be reduced by encouraging walking, cycling and the use of public transport instead of car travel and by supporting freight operators to make improvements in logistics. These changes could reduce emissions by 79% by 2050, compared to a 1990 baseline.
- **'Further ambition' measures.** Our Further Ambition Scenario additionally involves:
  - The end to sales of non-zero emission cars, vans and motorcycles being brought forward to 2035, and regulatory approval of non-zero emission vehicles limited to 2050 at the latest.
  - HGVs transitioning to zero emission options including hydrogen and electrification throughout the 2030s.
  - A more ambitious programme of rail electrification and the roll-out of hydrogen trains.
  - More ambitious targets set for demand reductions through switching to walking, cycling and public transport, reducing car mileage by 10%, and through logistics improvements for freight, reducing HGV mileage by around 10%.
  - Combined, these measures reduce emissions by 98% by 2050, compared to a 1990 baseline.
- **Costs and benefits.** The electrification of cars, vans and motorbikes, and demand reduction options, are cost-saving. Whilst the costs of HGV vehicles and infrastructure are currently highly uncertain, there is potential for these to be cost-saving relative to higher carbon alternatives as well. These scenarios have significant co-benefits in terms of air quality improvements, health benefits, congestion reduction and noise reduction, as well as economic opportunities in manufacturing zero emission vehicles.
- **Delivery.** The following priority actions should be taken as soon as possible to support the transition to zero emission technologies across road transport:
  - Commit to end the sale of conventional cars and vans by 2035, including ending the sale of hybrid and plug-in-hybrid vehicles. End the use of petrol and diesel vehicles (including hybrid and plug-in-hybrid vehicles) on UK roads by 2050.
  - Announce plans for the continuation of financial incentives for electric vehicles, through a commitment to continued grant schemes or through greater differentiation in the tax system, e.g. vehicle excise duty (VED), VAT and fuel duty, which will still be required in the near-term to support the early market.

– Continue development of charging infrastructure provision, especially improving reliability of current provision and rolling out of chargers in towns and cities to provide for people without off-street parking.
– Trials of zero emission HGVs with associated infrastructure within the UK.

We set out our analysis in five sections:

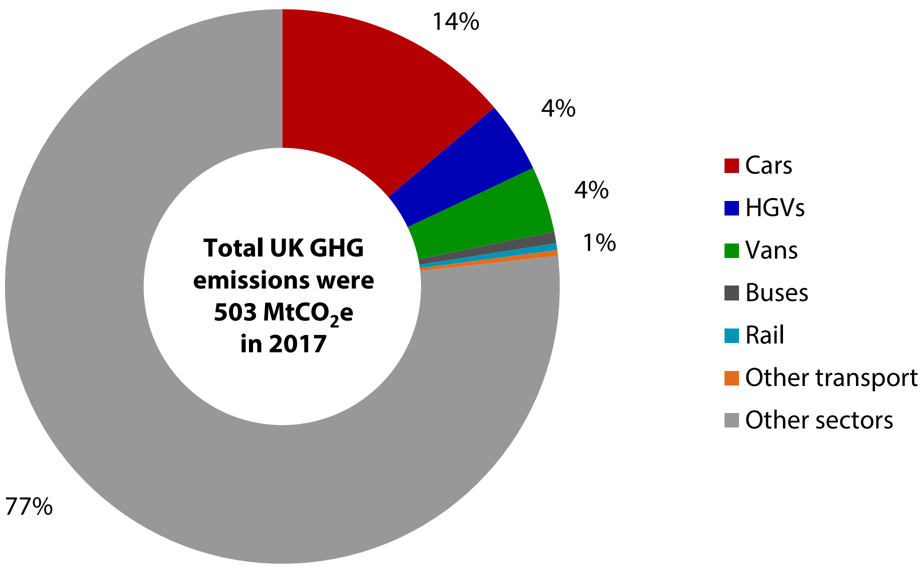
1. Current and historical emissions from surface transport
2. Reducing emissions from surface transport
3. Scenarios for minimising emissions from the surface transport sector
4. Costs and benefits of achieving very deep emissions reductions in the surface transport sector
5. Delivering very deep emissions reductions in the surface transport sector.

1. Current and historical emissions from surface transport

Greenhouse gas (GHG) emissions from surface transport in the UK were estimated to be 117 $MtCO_2e$ in 2017. Transport continues to be the largest-emitting sector in the UK, accounting for 23% of total GHG emissions. Cars, vans and HGVs remain the three most significant sources of emissions, accounting for 94% of surface transport emissions (Figure 5.1).

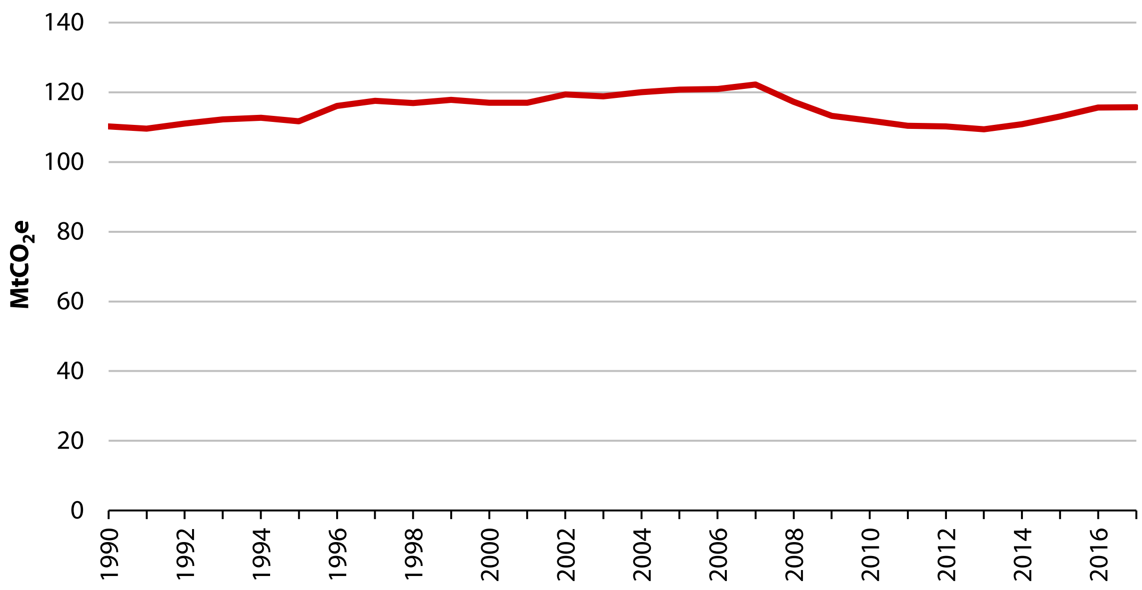
Emissions in 2017 were 3.6% higher than in 1990. They were constant from 2016 to 2017, after three consecutive years of emissions increases (Figure 5.2).

Figure 5.1. Current emissions from the surface transport sector (2017)



Source: BEIS (2019) *Final UK greenhouse gas emissions national statistics 1990-2017.*
Notes: Other transport includes mopeds and motorcycles, LPG fuelled vehicles and other road vehicle engines.

Figure 5.2. Emissions from the surface transport sector since 1990



Source: BEIS (2019) *Final UK greenhouse gas emissions national statistics 1990-2017.*

2. Reducing emissions from surface transport

(a) The current role of low-carbon sources

In 2017, approximately 0.3% of car and van miles were driven without direct carbon emissions, using electricity. In addition, in 2017/18, 3.1% of road fuels were biofuels:

- In 2018, electric vehicles (EVs) accounted for 2.5% of new cars sales. This represents a 22% increase on 2017. It includes both battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs) whose market shares were 0.7% and 1.9% respectively. Between 2010 and 2018, a total of 199,000 electric vehicles have been registered, comprising 138,000 plug-in hybrids and 61,000 pure electric.
- In 2017, 2.3% of vehicle-kms were driven using biofuels.[140]

(b) Options for reducing emissions further

Under current commitments, emissions from surface transport will reduce by 27% by 2030, relative to 1990:

- In the Department for Transport's Road to Zero strategy, the UK Government committed to pursuing a future approach in the event the UK leaves the European Union that would be at least as ambitious as current arrangements for vehicle emissions regulation. In January 2019, the EU finalised new targets to cut CO_2 emissions from new cars by 37.5% from 2020/21 levels by 2030 and by 31% for vans. The EU has set standards to reduce emissions from

[140] Department for Transport (2019) *Renewable Transport Fuel Obligation statistics: period 10 (2017/18), report 6, Final Report.*

trucks, compared to 2019 levels, by 15% in 2025 and 30% in 2030. The means of replicating these standards in UK legislation have not yet been set out, but any domestic standards should be at least as ambitious.

- The Government has also set targets for at least 50%, and potentially as many as 70% of new car sales to be electric vehicles by 2030, and up to 40% of new van sales. It also plans to end the sale of new conventional petrol and diesel cars and vans by 2040. The Scottish Government has made a commitment to "phase out the need to buy" new petrol and diesel cars or vans by the earlier date of 2032.
- The Road to Zero strategy also included a voluntary commitment by the freight industry to reduce HGV GHG emissions by 15% by 2025, from 2015 levels.
- The Cycling and Walking Investment strategy, which covers England only, aims to double cycling from 2013 to 2025, and to increase levels of walking. Scotland has a Cycling Action Plan with a target for 10% of everyday journeys to be by bike by 2020.[141] Wales is currently reviewing ambition for active travel and plans to set challenging targets.[142] Northern Ireland has an ambition for 40% of all journeys less than one mile, 20% of journeys between one and two miles and 10% of journeys between two and five miles to be cycled by 2040.[143]
- In February 2018, the Department for Transport set an ambition to phase out diesel-only trains by 2040.

Reducing emissions further towards net-zero will require an earlier end to petrol and diesel new car sales, shifts in travel away from car journeys to walking, cycling and more extensive use of public transport, a shift towards using zero-emission HGVs for freight transport and improved logistics efficiency:[144]

- Whilst the average lifetime of a vehicle operating on UK roads is 14 years, some can remain on roads for 20 plus years. In order to ensure all petrol and diesel vehicles leave the fleet by 2050, all non-zero emission vehicles sold before 2035 could be certified for use on UK roads no later than 2050.
- Motorcycles and mopeds, whilst representing a relatively small proportion of transport emissions (<1%), can cost-effectively be replaced by electric versions over similar timescales to cars and vans.
- There is potential to go further in replacing car journeys with walking and cycling trips. The National Travel Survey for England showed that 58% of car trips in 2017 were under five miles, representing 14% of total car mileage. Many of these trips, representing up to 10% of car mileage, could be completed by walking, cycling, using an e-bike or via public transport.
- The full potential of buses (zero emission where possible), trams and light rail could be exploited to reduce demand for car travel in the near-term. Increasing walking, cycling and the use of public transport has many co-benefits, including improved noise levels, air quality, public health and reductions in congestion.

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[141] Transport Scotland (2017) *Cycling Action Plan for Scotland 2017-2020.*
[142] Welsh Government (2019) *Prosperity for All: A Low-carbon Wales.*
[143] Department for Regional Development, Northern Ireland (2015) *Northern Ireland Changing Gear: A Bicycle Strategy for Northern Ireland.*
[144] Additional types of vehicles are covered in other chapters of this technical report, including agricultural vehicles within the agriculture chapter and off-road mobile machinery within the industry chapter.

- Zero-emission options for freight transport include hydrogen HGVs, electrified HGVs which use pantographs to charge constantly via overhead electrified lines on catenaries, and electrified HGVs which use extremely fast chargers located at motorway service areas during driver breaks. With demonstrating and testing of zero-emissions options within the next few years, a move towards the mass market in the late 2020s and strong take-up in the 2030s, HGV emissions can reduce to near-zero during the course of the 2050s.
- Increased uptake of measures to improve logistics efficiency of HGVs, including the use of urban consolidation centres and extending delivery times to shift deliveries to times outside of peak congestion, can further reduce demand for freight transport.
- The roll-out of electric and hydrogen buses and coaches could reach 100% market share by 2040 with accelerated take-up in the next two decades.
- There are options to reduce emissions from trains through further electrification and replacement of diesel with hydrogen trains. Electrification of at least 54% of track km on lower-speed urban and regional lines with hydrogen fuel cell powered trains replacing diesel trains on other lines is feasible by 2040.
- Aircraft support vehicles such as baggage belts, passenger stairs, catering tractors and aircraft tugs can also be electrified. A number of prototypes have already been developed by industry.

Box 5.1. EV supply chain risks and opportunities

To facilitate a more ambitious transition to zero-emission vehicles it is imperative that vehicle manufacturers supply a sufficient range of EV models to meet increasing demand. The scale of the transition from petrol and diesel vehicle production to high volume electric vehicle production is challenging and will require that policy, industrial and supply chain issues be resolved:

- At present there are indicators that vehicle manufacturers are not producing enough EVs to meet demand, leading to long waiting times for vehicles, as they are maximising their returns on investments in R&D and the production of conventional vehicles. There need to be much stronger policy and regulatory frameworks to provide industry with the certainty and incentives to transition to zero-emission vehicles.
- The skills and manufacturing methods to produce electric powertrains are significantly different to those of conventional car production. Electric vehicles have fewer parts than petrol and diesel vehicles and are mechanically less complex, meaning they are simpler to assemble. However, car manufacturers will need to either manufacture battery cells and packs in house or set up new supply chains with battery manufacturers. Engineers designing vehicles and production lines will need to develop an understanding of battery chemistry and management systems. Manufacturers will need time and support to adjust.
- There are several key raw material inputs of lithium-ion batteries, such as lithium, graphite, cobalt and nickel, all of which will be required in far greater quantities in the future. The size and quantity of batteries required for electric vehicles could put pressure on new unfamiliar parts of these supply chains. There is concern that the supply of raw materials for lithium ion batteries could act as a bottleneck to electric vehicle roll-out.
    - The European Federation for Transport and Environment carried out a life-cycle review of the raw materials used in battery manufacturing. The availability of raw material does present concerns, however these can be mitigated by diversifying supply, advances in battery technology and recycling. With cobalt in particular, there are ethical issues related

Box 5.1. EV supply chain risks and opportunities

to mining practices, as over half of global supply comes from the Democratic Republic of the Congo. Overall, however, they conclude that the available resource of critical metals and rare earth minerals will not constrain the supply of EVs.

  – Whilst these commodities are sensitive to changes in price as demand changes, they represent a small proportion of overall battery costs. Recent battery price sensitivity analysis from Bloomberg New Energy Finance found that a 50% increase in the cost of lithium would lead to less than a 4% increase in the cost of a battery pack. Similarly, if the price of cobalt were to double they estimate this would only increase the battery pack cost by 3%.

- The demand for electric vehicles and associated inputs is expected to increase world-wide. In order to benefit from the supply of a full range of EV models, the UK should position itself at the forefront of countries with strong policy around phasing out conventional petrol and diesel sales.
- There is an opportunity for the UK automotive manufacturing sector to become a world leader in the development and production of ULEVs. Early investment in EVs will help to deliver this. Vivid Economics found that a transition to 100% market share of EVs by 2030 is likely to increase investment in the electric vehicles industry, with potential to increase UK production from around 16,000 EVs today to around 880,000 EVs per year and adding 89,000 jobs in the EV industry.

Source: Vivid Economics for WWF (2018) *Accelerating the EV transition: environmental and economic impacts;* Bloomberg New Energy Finance (2018) *Electric Vehicle Outlook*; McKinsey (2017) https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/trends-in-electric-vehicle-design

(c) Challenges in avoiding emissions from different parts of the surface transport sector

There are some sources of emissions in the surface transport sector that are relatively easier to decarbonise – with lower costs and fewer barriers:

- Passenger cars made up 60% of emissions from surface transport in 2017, but technological developments imply that this sector can quickly electrify. Barriers to the adoption of electric vehicles - higher upfront costs, anxiety about the range covering daily trips and the availability of charging infrastructure - can each be addressed.[145] A rapid transition to electric vehicles is already occurring in Norway, where EVs made up 60% of new car sales in March 2019:[146]
  – Under current Government subsidies, the total cost of owning an electric vehicle can still come at a cost premium relative to a petrol or diesel vehicle.[147] However, this cost premium is declining at an increasing rate and is expected to reach cost parity in the mid-2020s. Our analysis indicates that EVs will also have a lower subsidy-free purchase price before 2030. An electric drive train is mechanically simpler with fewer moving parts than conventional vehicle drivetrains and is therefore expected to require less maintenance.

[145] Department for Transport (2016) *Public attitudes towards electric vehicles: 2016.*
[146] Reuters (2019) https://uk.reuters.com/article/uk-norway-autos/tesla-boom-lifts-norways-electric-car-sales-to-58-percent-market-share-idUKKCN1RD2B7
[147] The total cost of ownership calculation includes purchase cost, fuel cost (at retail fuel prices), and maintenance and vehicle tax. The assumed annual mileage is 10,800 km. Our analysis is based on a privately owned VW e-golf compared with the petrol and diesel versions of the same car.

Once the industry adjusts to the new skills required to service electric vehicles, we can expect this element of costs to be to cheaper over the lifetime of the vehicles.

  - There has been a limited choice of EVs, with only 20 zero emission models available in the UK market to date.[148] This is expected to improve with the introduction of new models in the years from 2019 to 2025, with several promising industry announcements. Volkswagen Group have announced they plan to release 70 new all-electric models over the next decade.[149]
  - The range of battery electric vehicles is also increasing, with nine models having over 200 miles of range in March 2019, up from only five models in June 2018.[150]
  - The number of charging connectors of all types has increased from 16,700 in June 2018 to 20,900 in March 2019.[151] The rapid charger network has also expanded from 3,500 connectors in 1,100 locations to 4,800 connectors in 1,400 locations over the same time period.

- Van owners are more likely to use a van as part of their business or job, and are therefore more likely to consider the total lifetime cost of the vehicle, including fuel and maintenance, before making a purchase. With current Government incentives, fully electric vans are already more cost-effective for certain duty cycles.[152] When van models with sufficient range are available in large volumes, the van market could shift to electric vehicles more rapidly than the passenger car market:
  - Companies including UPS and Gnewt Cargo already operate large electric van fleets in the UK. However, these companies report difficulties in upgrading the power connections at their depots to be able to simultaneously recharge vans overnight. These barriers must be addressed to enable widespread adoption.
  - An expansion of public rapid charging infrastructure is also likely to be required.
- Electric motorcycles face different challenges to electric cars and vans. Although the battery sizes that can be installed on a motorcycle are much smaller, the average distance travelled on a motorcycle trip is only around 11 miles and the weight transported is much lower.[153] Electric motorcycles also benefit from advancement in the wider electric vehicles market and deployment of charging infrastructure. There have been fewer electric motorcycle models coming to market to date but we expect this to change, with several announcements by major manufacturers.
- For smaller HGVs, generally focused on urban and regional delivery, relatively short and predictable duty cycles in slower stop-start traffic make a switch to plug-in hybrid or zero emission vehicles relatively easy compared to longer haul and heavier HGVs. Air quality concerns in busy urban centres will also drive zero-emission HGV uptake, particularly in those

148 Next Green Car (2019) www.nextgreencar.com
149 Business Green (2019) https://www.businessgreen.com/bg/news/3072457/vw-revs-up-electric-ambitions-by-50-per-cent
150 Comparison uses NEDC range estimates, except where NEDC range estimates are not available, in which case WLTP is used.
151 Zap-map (2019) www.zap-map.com
152 CCC total cost of ownership analysis of a Nissan NV-200 electric and diesel van, with an assumed annual mileage of 21,570 km.
153 Department for Transport (2017) *National Travel Survey: Motorcycle use in England.*

cities with clean air zones, enabling operators to avoid fees whilst also enjoying reduced fuel costs.

- Walking, cycling and public transport is highly cost-effective and needs to be supported through the promotion of active travel choices, building walking and cycling infrastructure and increasing the coverage of public transport. This modal shift has a number of co-benefits other than reducing emissions, such as reduced congestion, improved air quality and health benefits. These need to be communicated effectively to encourage this societal shift to take place.
- Improvements to logistics operations, whilst potentially in need of support whilst schemes are in early stages, are generally considered financially viable from the perspective of a commercial operator. Delivery time constraints should be relaxed to enable more off-peak deliveries and the reprioritisation of land use to enable development of urban consolidation centres will support this measure.
- Given that buses have predictable routes, it is possible for fleet operators to assess when they can be electrified and to install only minimal necessary charging infrastructure.

Other sources of emissions are more challenging:

- For longer haul and larger, heavier HGVs, the mass and the volume taken up by the batteries or hydrogen storage tanks required to complete journeys make this a relatively difficult vehicle to decarbonise. There are also relatively few vehicles available, given that most zero emission larger HGVs are at the early trial and prototype stage. In terms of the scale of remaining emissions this is the most significant area.
- Recent rail electrification projects have proven to be more expensive than initial cost estimates. Hydrogen trains have only recently entered operation in Germany, and there is yet to be a trial on UK railways, which operate using a different loading gauge to Europe.
- Given the diversity of vehicles that operate airside at airports, there is some uncertainty about whether all types of these vehicles can fully electrify by 2050.

(d) The strengthened evidence base used in this report

We have drawn in this report on the evidence published in and alongside recent Committee reports – advice on the fifth carbon budget and reviews of Hydrogen and Biomass:

- The Committee's review of the uses of biomass in a low-carbon economy indicated that the best uses for biomass are those which permanently sequester carbon, such as using wood in construction and Bioenergy with Carbon Capture and Storage.[154] Use of biofuels in surface transport should be phased out during the 2030s.
- The Committee's review of the uses of hydrogen in a low-carbon economy found that hydrogen is best used selectively alongside widespread electrification.[155] Battery electric vehicles are well placed to fully decarbonise passenger cars and vans. Hydrogen could play an important role as a zero emission option for long-haul heavy duty vehicles including buses, trains and lorries.

We have also commissioned and undertaken new analysis for this report:

[154] Committee on Climate Change (2018) *Biomass in a low-carbon economy.*
[155] Committee on Climate Change (2018) *Hydrogen in a low-carbon economy.*

- Falling battery costs can be expected to reduce the costs of EVs significantly. Our analysis suggests that EV upfront costs will become comparable with conventional vehicles before 2030, without the need for subsidy. However, several studies suggest this date could be much sooner (Box 5.2). EVs have significantly lower running costs due to their high efficiency and the lower cost of electricity compared to petrol and diesel.
- The ability of the supply of EVs to match increased demand is critical in enabling the transition. Our analysis has been informed by an assessment of the potential difficulties automotive manufacturers may face when increasing EV production volumes. This has included an evidence review and consultation with industry experts and organisations. Whilst these scenarios present certain challenges for industry they are possible to overcome given appropriate planning and support (Box 5.1).
- We have drawn on the zero emissions HGV cost dataset developed for the Energy Technologies Institute by Element Energy. We have also commissioned our own research to develop cost estimates for the scale of refuelling infrastructure likely to be required by zero emission heavy duty vehicles for three potential technology options: hydrogen heavy duty vehicles; electric heavy duty vehicles accompanied by on-road catenaries to recharge the vehicles as they drive; and electric heavy duty vehicles accompanied by extremely fast high-powered charging infrastructure (Box 5.3).

Our findings and assumptions are in line with those of other recent assessments:

- The Energy Transitions Commission report 'Mission Possible' found that electric drivetrains were likely to dominate in the heavy-duty vehicles sector, certainly for short and medium distance trips and potentially for long-haul as well.[156] Battery developments for the passenger car and van industry will lead to battery cost reductions which are likely to result in lower total ownership costs for new electric trucks during the 2020s. However, in the long-haul sector, hydrogen trucks may have a competitive advantage due to the faster speed of refuelling and size of the batteries that may be required.
- The European Federation for Transport and Environment has published a roadmap that sets out how to decarbonise European transport.[157] To achieve net zero emissions from road transport in 2050, the most efficient way to decarbonise vehicles, from cars to HGVs, is by electricity, such that lower efficiency fuels such as hydrogen are used only when no other alternatives exist. Deploying higher fuel taxes and road charges, as well as encouraging car sharing, walking, cycling and the use of public transport, could reduce emissions, whilst also tackling congestion and making cities more liveable. Freight will need infrastructure to facilitate the use of electricity and cities will need zero-emission freight strategies.
- Scania, a manufacturer of commercial vehicles, have published a pathways study looking at how to remove fossil fuel usage from commercial transport by 2050.[158] They estimate that battery electric trucks could reach total cost of ownership parity with diesel trucks as early as 2027, whilst fuel cell vehicles could reach parity in 2047. In fact, for buses and urban distribution applications, electric vehicles in Sweden have already reached cost parity. Electric highways (overhead electric wires to enable HGVs to charge as they drive) can help enable widespread electrification of trucks, especially over the coming decade when battery

[156] Energy Transitions Commission (2018) *Mission possible: Reaching net-zero carbon emissions from harder-to-abate sectors by mid-century.*
[157] Transport and Environment (2018) *How to decarbonise European transport by 2050.*
[158] Scania (2018) *The Pathways study: Achieving fossil-free commercial transport by 2050.*

pack costs are relatively high and further energy density improvements have yet to be commercialised. Electric highways can also reduce lifecycle emissions from trucks by reducing the size and quantity of batteries required by electric HGVs. The study found that the total costs of the whole system were lower (when including infrastructure, vehicles and fuel) but that four to five times more infrastructure investment would be required relative to the present situation.

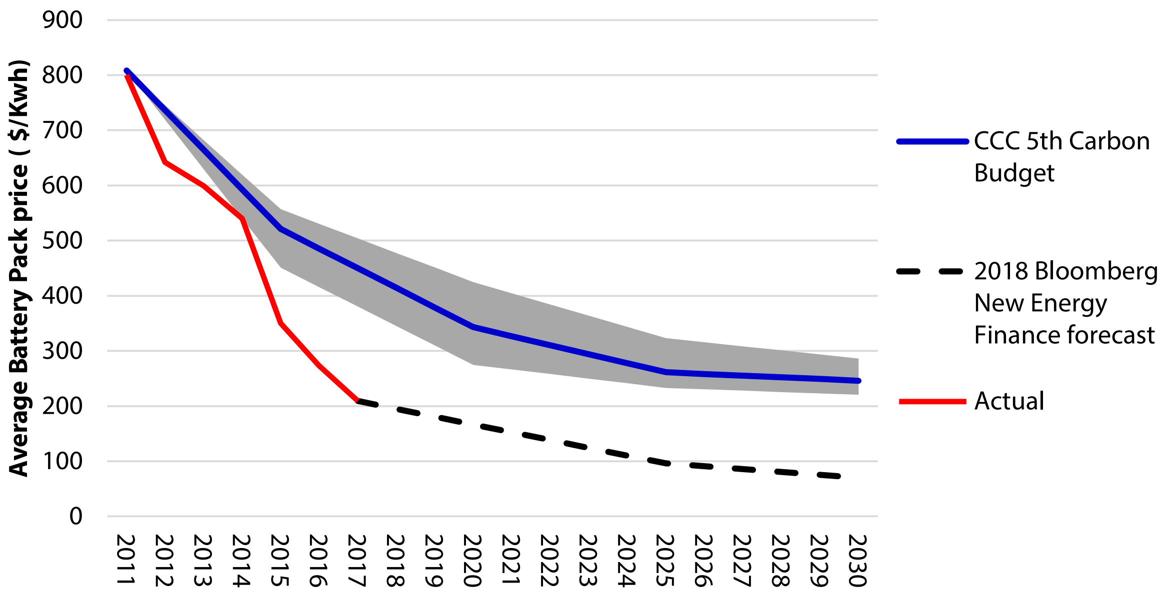
- A McKinsey Centre for future mobility report on electric trucks suggests that commercial fleets could rapidly go electric, as zero emission trucks reach total cost of ownership parity and the infrastructure becomes increasingly cost-competitive. Adoption can be enabled by the regulatory environment, via country-wide emissions standards and local clean air zones charging more polluting trucks for access.

We reflect this new evidence along with our existing evidence base in our scenarios in section 3.

Box 5.2. Battery costs

Our projections for battery costs have been updated using Bloomberg NEF battery cost forecasts. There has been a greater improvement in efficiency and cost of batteries than our previous analysis suggested, which has reduced projected costs (Figure B5.2):

Figure B5.2. Average battery cost for electric vehicles - Actual and forecast to 2030



Source: BNEF (2018) *Electric cars to reach price parity by 2022; CCC* (2015) *Sectoral scenarios for the Fifth Carbon Budget.*

- Advancements in battery technology and manufacturing methods have increased the energy density of batteries and reduced costs per kWh of energy sooner than anticipated. Costs are forecast to decrease even further.
- As battery costs have fallen, car manufacturers have tended to increase battery size and range of EVs to address range anxiety, rather than reducing up-front costs. Once sufficient range has been

Box 5.2. Battery costs

achieved we expect further cost savings to be reflected in lower up-front purchase costs. Our modelling suggests that electric vehicles will reach upfront cost parity with conventional vehicles in the second half of the 2020s. However, several other studies have suggested this date could be much earlier.

- Whilst the majority of daily driving can be completed by electric vehicles with only 50 miles of range, electric vehicle buyers also consider whether their vehicle will be able to drive longer distances, even if only occasionally required. Evidence suggests that a range of around 370 km (230 miles) is enough to completely offset range anxiety. The average electric range of BEVs has increased as battery costs have declined and is now expected to reach 300 km (190 miles) by 2030. To reflect this trend we have updated the range assumptions in our modelling, with the range of pure electric vehicles now increasing to 450 km (280 miles) on average in 2050.

Taken together with projected fuel costs, our analysis suggests that new electric cars and vans are likely to become cost-effective during the 2020s from a societal perspective (i.e. including the cost of the vehicle and the cost of fuel (excluding taxes) over the lifetime of the vehicle, discounted at the social discount rate of 3.5%.

Source: Department for Transport (2013) *National Travel Survey 2012*; Cenex and Oxford Brookes University (2013) *Assessing the viability of EVs in daily life;* CCC (2015) *Sectoral scenarios for the Fifth Carbon Budget;* Deloitte (2019) *New market. New entrants. New Challenges. Battery Electric Vehicles;* BNEF (2017) *Electric cars to reach price parity by 2022.*
Notes: 2012 is the latest year for which the National Travel Survey was performed across Great Britain.

Box 5.3. Costs of zero emission heavy goods vehicles and associated refuelling infrastructure

Zero emission HGV technologies have been developing quickly in recent years.

- The costs of hydrogen fuel cell HGVs have previously been assumed to be heavily dependent on the uptake of hydrogen cars and vans. However, hydrogen fuel cells used for HGVs are significantly different to those used in cars and vans as HGVs drive more hours a day than lighter vehicles. Given that electric vehicles are expected to remain the more cost-effective option for cars and vans internationally, substantial take-up of hydrogen cars and vans is not expected in the near-term, hence it is likely that hydrogen HGVs will use specialised stacks that have longer lifetimes. Many of the components of hydrogen fuel cell stacks for HGVs are not yet produced at large-scale, so can be expected to reduce in cost significantly as volumes ramp up. Procurement across Europe for fuel cell buses will assist with cost reductions. There are, however, large variations in estimates of hydrogen fuel cell costs for HGVs by different organisations.
- We have estimated costs of HGV batteries using the costs of batteries in large cars (in £/kWh), scaled up by the kWh required to power much larger HGVs. Given improvements in the energy density of batteries, by 2030 the volume taken up by batteries could be equivalent to the volume taken up by a standard 350 bar hydrogen storage tank installed on a vehicle, meaning that the volume required to store the fuel on a hydrogen and an electric HGV could be approximately equivalent. Hydrogen would still have advantages in that it would offer faster refuelling times and would weigh less than batteries. Higher pressure tanks at 750 bar or liquid hydrogen storage would also enable more fuel to be stored in the same space.
- Given that hydrogen fuel cells can be used with batteries to create hybrid options, there are many ways to optimise vehicles by partnering different size fuel cells and batteries. For example, long haul HGVs are unlikely to meet energy requirements using batteries unless there is some sort of

Box 5.3. Costs of zero emission heavy goods vehicles and associated refuelling infrastructure

charging whilst on the move, so hydrogen fuel cells provide the bulk of the energy to the electric motor, paired with a very small battery to capture energy from regenerative braking and support high power demands (e.g. hill starts). However, for municipal utility trucks, given the shorter distances involved, a balanced split between a larger battery partnered with a smaller fuel cell can be more cost-effective, given the relative costs of electricity and hydrogen.

- For the vehicles studied in this report, the hydrogen storage and battery size and weight were built into a computer modelled design for a truck to ensure that the volume taken up by the zero emission technology was not impractical.

Given this improved knowledge on zero emission HGV costs, the Committee commissioned research from Ricardo to model infrastructure costs for three different zero emission technology options – hydrogen fuel cell HGVs; electrified HGVs with on-road recharging via pantographs and catenaries; and electrified HGVs combined with very fast high powered chargers.

- The main barriers to deploying a large-scale hydrogen refuelling station infrastructure are the currently high capital costs of equipment, including compressors, chillers, dispensers and storage, and the need to upskill construction workers in order to build the infrastructure. Given a commitment to a nationwide roll-out with sufficient time to develop skills, the demand would drive down costs and these barriers could be removed. Refuelling stations can be constructed within 12-18 months, assuming that the process for gaining planning permission can be streamlined.
- In Germany, the roll-out of on-road recharging overhead wires is currently being trialled, with each km installed taking approximately one month. However, the length of time this may need to take in the UK could differ, given the potentially different regulations set by the motorway operator on motorway construction work and the availability of trained installation personnel and special vehicles. Estimates by different organisations of how much of the German motorway network may be electrified by 2050 range from 4000 to 10,400 km. For context, the whole motorway network in Great Britain is approximately 3,700 km. There are concerns that if the infrastructure is damaged if there is a storm or an accident, HGVs may have to drive into other lanes, but given that all HGVs using this infrastructure will require either sufficient range or an alternative fuel source to travel on roads not covered by the overhead wires, this should not cause significant problems provided only a small portion of the infrastructure is affected.
- A significant proportion of the costs of deploying very fast high-powered chargers arise from the power network upgrades required. The main uncertainties to rolling out a refuelling network of this type arise from uncertainty over the need for substation upgrades, which is highly dependent on the cooperation of the Distribution Network Operator and can take a long time to process. Other sources of delays include the need to get planning permission from local authorities and the need to get a wayleave when necessary to install cables across third party land, which can delay projects for months with no clear process or timelines. Charging points themselves can be installed within 6-8 weeks, but these other issues can mean deployment must be planned at least six months in advance. Future work is required to address how these delays can be minimised.

Given all of these considerations, it should be feasible to roll-out any of these three options over the required timescales to support a transition of the HGV fleet by 2060. Therefore, it is important to consider system-wide costs. Ricardo considered the following scenarios (all scenarios, excluding the baseline, include some electrification of small rigid HGVs):

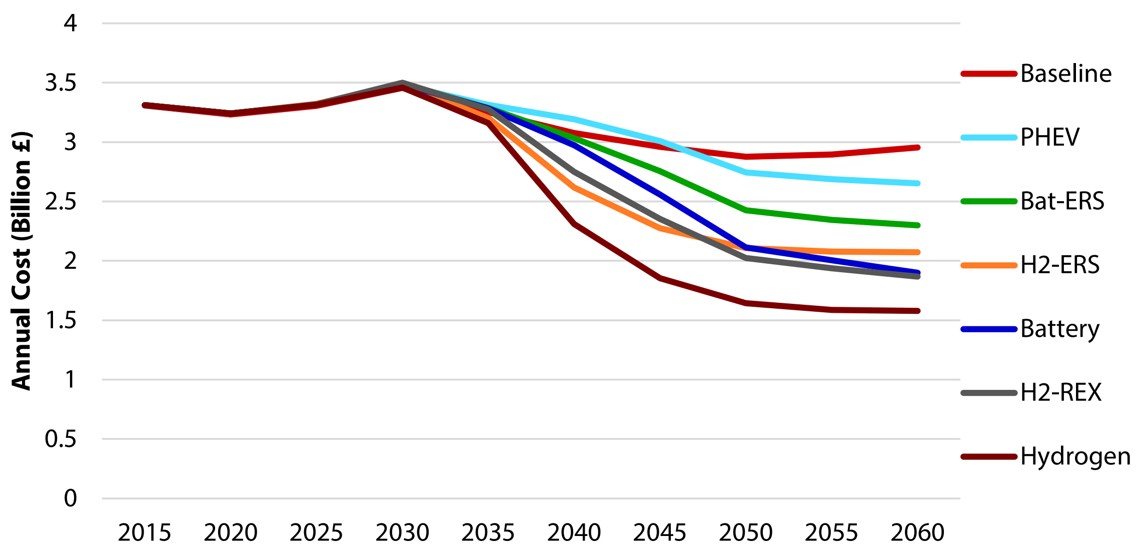
- Baseline represents continued use of petrol and diesel vehicles. Costs for maintaining this network are assumed to be included in fuel costs.
- Hydrogen represents the use of hydrogen to fuel all large and some small HGVs

Box 5.3. Costs of zero emission heavy goods vehicles and associated refuelling infrastructure

- Battery represents the electrification of all HGVs and includes the cost of extremely fast chargers to top up HGVs on driver breaks and overnight.
- Battery-ERS represents the installation of on-road overhead electric wires to refuel the large HGVs on motorways and major roads as they drive, with vehicles driving on batteries when off this network.
- H2-ERS represents the installation of on-road overhead electric wires to refuel large HGVs as they drive on motorways and major roads, with vehicles driving on hydrogen fuel when off this network.
- H2-REX assumes that large HGVs primarily drive using batteries, but have a hydrogen fuel cell range extender for longer journeys.
- PHEV assumes that large HGVs primarily drive using batteries but have a diesel range extender for longer journeys.

Installing extremely fast chargers at motorway service areas appears to be the most expensive option when looking at infrastructure alone (Figure B5.3a).

Figure B5.3a. Cumulative capital expenditure (excluding taxes) for different HGV refuelling infrastructure options.

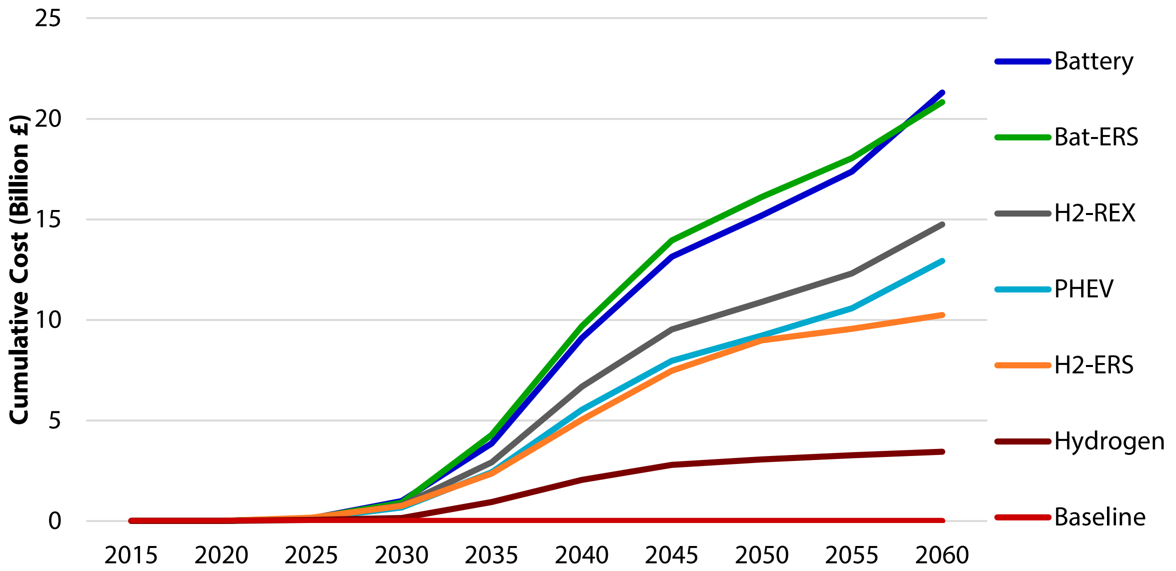


Source: Ricardo for the CCC (2019) *Zero emission HGV infrastructure requirements.*

When the annual costs of fuel (excluding taxes) and infrastructure (including capital and operational costs) are considered together (Figure B5.3b), the hydrogen scenario appears to be the most cost-effective option for zero emission vehicle refuelling infrastructure. Of the zero emission options, installing on-road electric overhead wires to recharge HGVs as they drive appears to be the most expensive option. Plug-in hybrid HGVs are more costly. All potential lower emission options are estimated to be cost saving relative to the baseline.

Box 5.3. Costs of zero emission heavy goods vehicles and associated refuelling infrastructure

Figure B5.3b. Annual costs of zero emission HGV fuel and infrastructure (including infrastructure capital and operational expenditure)



Source: Ricardo for the CCC (2019) *Zero emission HGV infrastructure requirements.*

In estimating the most cost-effective option for reducing emissions from HGVs to zero, it is also important to consider the costs of the vehicles themselves. For larger HGVs, all three zero emission options outlined here were found to be cost-saving by 2050 in £/tCO_2e (including vehicles, fuel (excluding fuel taxation), and capital and operational infrastructure costs). Hydrogen and electric hybrid large HGVs were found to have costs between -£100-£50 £/tCO_2e depending on the type of vehicle. For smaller HGVs, given the expense of ensuring each small electric HGV has a depot charger, abatement costs were estimated to range between £100-£150 £/tCO_2e. There is the potential to achieve lower abatement costs by optimising the capabilities of each vehicle (in terms of battery and hydrogen fuel cell sizing) to minimise vehicle and infrastructure cost together.

Large uncertainties remain in the potential development of the costs and capabilities of zero emission HGVs and infrastructure. Moreover, a coordinated approach is needed across mainland Europe to ensure international freight can continue to operate effectively in the UK. Given these uncertainties, now is not the time to pick a particular zero-carbon option for HGVs. The Government should focus on removing regulatory barriers in each of these options and proceed with trials and pilots in the near-term to further develop the evidence base.

Source: Element Energy for the Energy Technologies Institute (2017) *HDV - Zero emission HDV Study Report;* Ricardo for the CCC (2019) *Zero emission HGV infrastructure requirements;* Department for Transport (2018) *Road lengths statistics.*
Notes: Electricity network upgrade costs for the infrastructure are excluded from this analysis, but can likely be achieved in parallel with network reinforcements for electric car and van charging.

3. Scenarios for minimising emissions from the surface transport sector

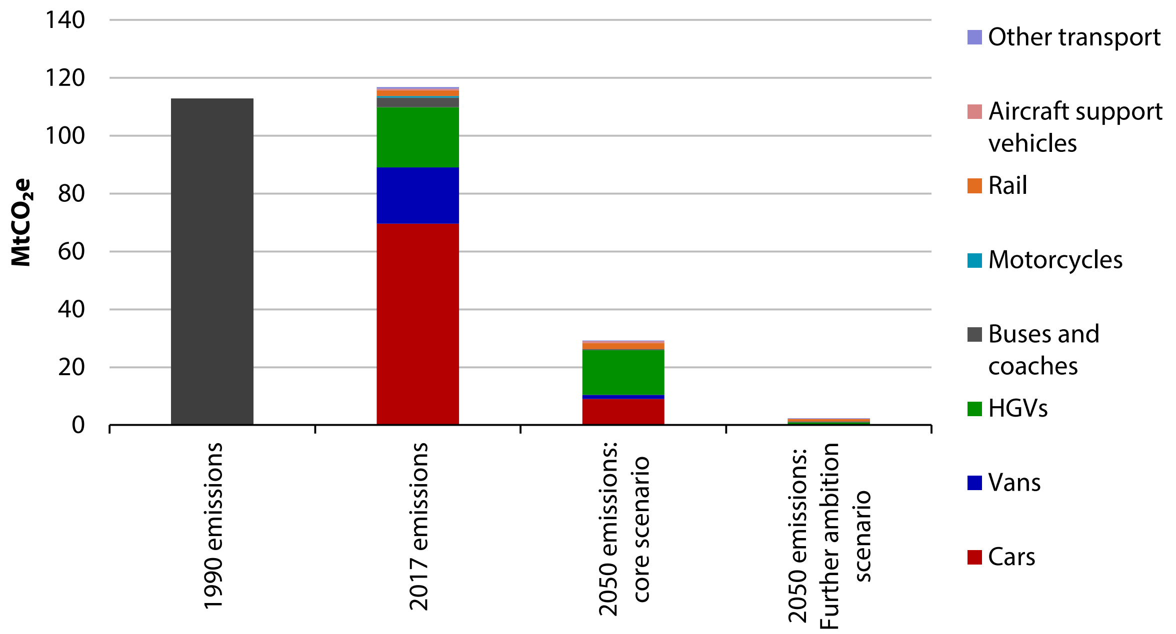
(a) Opportunities for cutting emissions towards zero

As set out in Chapter 1, we have classed the options for cutting emissions towards zero in three categories:

- Core options are those low-cost low-regret options that make sense under most strategies to meet the current 80% 2050 target. For most, the Government has already made commitments or begun to develop policies (although in many cases these need to be strengthened).
- Further Ambition options are more challenging and/or more expensive than the Core options, but are all likely to be needed to meet a net-zero target.
- Speculative options currently have very low levels of technology readiness, very high costs, or significant barriers to public acceptability. It is very unlikely they would all become available. Some of these options would be required to reach net-zero GHG emissions domestically.

Figure 5.3 shows how these options would reduce emissions from the surface transport sector.

Figure 5.3. Scenarios for very deep emissions reductions from the surface transport sector



Source: CCC analysis.
Notes: Other transport includes urea from air quality treatment from remaining diesel vehicles and emissions from lubricants.

Core options

Many of the Core opportunities in the surface transport sector are already included in the Government's plans, although strengthened policies will be required to deliver these existing commitments:[159]

- In-line with previous Government commitments in the Road to Zero Strategy, our Core scenario assumes an end of sales of all conventional cars and vans by 2040 (i.e. an end to the sale of vehicles solely powered by fossil fuels, with only fully electric and plug-in hybrid cars and vans eligible for sale post-2040). Given the lifetime of cars and vans, only around 80% of the fleet would be zero-emission vehicles in 2050, leaving around 9.8 million petrol, diesel and plug-in hybrid vehicles on the road.
- In October 2016, the Government extended the plug-in van grant to cover all HGVs weighing more than 3.5 tonnes. The grant will provide up to £20,000 for the first 200 such vehicles. However, at the time of publication of the Road to Zero strategy in July 2018, no vehicles over 3.5 tonnes had applied for the grant. Uptake of ultra-low emission small HGVs must increase in the Core scenario.
- A plug-in motorcycle grant currently provides 20% of the purchase price for zero emission mopeds and motorcycles, up to a maximum of £1,500. This will continue to be necessary until zero emission motorbikes reach cost parity with petrol models.
- Government strategies to increase cycling and walking already exist in England, Scotland, Wales and Northern Ireland. The Transforming Cities Fund also aims to invest in infrastructure to improve public and sustainable transport connectivity in some English cities. In our Core scenario, we assume that 5% of car miles can be shifted to walking, cycling and public transport.
- With the support of the Freight Transport Association and the Road Haulage Association, the Government has agreed a target with industry for a 15% reduction in emissions from HGVs by 2025 from 2015 levels. This target can be achieved by a mixture of logistics measures, improved fuel efficiency and ultra-low emission vehicles. To achieve the Core scenario, km from HGVs must be reduced by 6-8% through improved logistics efficiency.
- The Government has provided £48 million of funding to accelerate uptake of low emission buses and the supporting infrastructure. In our Core scenario, uptake of low emission buses and coaches must reach 80% of sales by 2050.

Further Ambition options

Our Further Ambition options would reduce emissions close to zero. This could be needed to deliver the UK's existing 2050 target and will almost certainly be needed for a net-zero target:

- Our Further Ambition Scenario assumes the end of sales of conventional cars and vans is brought forward to 2035 at the latest and that this also applies to PHEVs. In addition, from 2030, regulatory approval for fossil fuel cars, vans and motorbikes is limited to 2050.
- In order to reach near zero emissions from the road transport sector by 2050, roll-out of zero emission HGVs must accelerate to reach nearly 100% of sales in 2040. Smaller rigid HGVs will likely electrify, but there are multiple options available for larger rigid HGVs and articulated HGVs. These can decarbonise by a transition to hydrogen HGVs, electrified HGVs with

[159] CCC (2018) *Reducing UK emissions: 2018 Progress Report to Parliament.*

pantographs recharged by on-road catenary systems or electrified HGVs with extremely powerful chargers located at motorway service areas.

- We assume 10% of car miles can be shifted to walking, cycling and public transport. A national strategy to address the decline in bus usage is required. The opportunities offered by bus rapid transit, trams and light rail should also be exploited to not only reduce emissions but cut congestion in busy urban centres.
- Further logistics improvements to reduce HGV km by approximately 10% can be achieved by a variety of measures including expanded use of urban consolidation centres and extended delivery windows.
- Our Further Ambition Scenario assumes at least 54% of rail track-km is electrified by 2040. Rail electrification is most cost-effective on the busiest lines, where there are operational benefits to its deployment. Hydrogen trains are assumed to be deployed on all trains operating at speeds under 75 miles per hour on lines that aren't electrified by 2040, focusing on less busy regional lines where electrification is unlikely to be cost-effective. Several key freight corridors must also be electrified, and trains that cannot be fully decarbonised must hybridise. These measures combined reduce emissions from rail by 55% by 2050.
- Aircraft support vehicles must be regulated to ensure they electrify. Whilst these vehicles are relatively diverse, the short range required and ready access to charging at airports, and the existence of prototypes, indicates that they can predominantly electrify by 2050.

Alternative options to deliver the Further Ambition Scenario

In many cases there would be alternative technical or behavioural approaches that could deliver emissions reduction and it may not be necessary now to decide between them:

- Greater reductions in travel demand via more ambitious estimates of the ability to shift trips from cars to walking, cycling and the use of (electrified or hydrogen fuelled) public transport might mean that fewer electrified vehicles are required. Wider availability of electric bikes and electric scooters could persuade those who find walking or non-electric cycling difficult to choose these options over the car. Electric cargo-bikes also offer opportunities for people who have to carry large or heavy items.
- The introduction of Connected Autonomous Vehicles (CAVs) could enable a faster transition to electric vehicles, if operated by businesses as fleets of taxis. As these vehicles would be used more intensively than cars owned by private consumers, they would reach cost parity sooner. They could also generate resource efficiency benefits from production if fewer vehicles are needed on roads. However, use of these vehicles could increase demand for car travel as they can be used by people unable to drive and could present an attractive alternative to the use of public transport. This transition must be managed carefully to avoid adverse impacts on not only emissions but also congestion.
- Shared 'on demand' fleets of electric vehicles with increased occupancy could reduce global energy demand for transport, as well as reducing the number of electric vehicles on the road.[160] New vehicles, which can be thought of as 'taxi-buses', could be sized between the standard size for a car and public transport and can be thought of as a form of public transport that is better calibrated to the demand for each route. High capacity, high

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[160] Grubler et. al (2018) A low energy demand scenario for meeting the 1.5°C target and sustainable development goals without negative emission technologies. *Nature Energy*, 3, 551-527.

frequency public transport routes would still be required in busy urban centres, but could be based on rapid-transit buses to exploit road space freed up by reduced car congestion.

- Deep reductions in HGV km driven by societal changes in the way we produce and consume goods could offer an alternative to switching part of the fleet to zero emission vehicles. Options that could drive these changes include increasing the longevity of appliances, electronics and clothes, repairing and refurbishing them where necessary, or a reduction in consumption combined with a focus on reusing goods, locally growing food and driving down volumes of waste. There is also potential for growth in the use of 3-D printing technologies to additionally improve logistics efficiency.

Speculative options

It may be possible to address any remaining emissions in the surface transport sector using hydrogen, given further technology developments, or through electrification where this appears to be more cost-effective. It may also be possible to replace any remaining fossil fuels with synthetic fuels but these are likely to be very expensive:

- There is a possibility that any remaining fossil fuels used in the surface transport sector could be replaced with synthetic fuels, made from electrolytic hydrogen and CO_2 captured from the air via Direct Air Capture (DAC). Given the high expected cost of DAC in providing the feedstock CO_2, the low thermodynamic efficiency of the process and the need for multiple processing stages it is likely that costs of synthetic fuels will be very high even if the input electricity comes from low-cost renewables (see Chapter 5 of the advice report). It is likely that any CO_2 captured through DAC will provide emissions reductions at lower cost when combined with carbon capture and storage (CCS) rather than it being inefficiently recycled into a fuel (see Chapter 10 of this technical report for consideration of the removals potential for Direct Air CO_2 Capture and Storage - DACCS). If there are technological advances in hydrogen storage, hydrogen trains could cover all of the remaining railway network not covered by electrification.

(b) Timing for cutting emissions towards zero

The fifth carbon budget (covering 2028-2032) already requires significant progress towards these net-zero scenarios. The cost-effective path that the Committee has identified, and that can be delivered through existing policy with some strengthening, includes:

- Around 60% of new cars and van sales are plug-in hybrids and battery electric vehicles by 2030, as well as 40% of small HGVs.[161] 25% of new bus and coach sales are electrified and 25% switch to hydrogen.
- Conventional vehicle improvements can deliver real-world emissions reductions of 37% for cars, 33% for vans and 24% for HGVs between 2010 and 2030.
- Limited biofuel use in the 2020s and 2030s to deliver around 11% of road fuel by energy in 2030, with an increasing proportion coming from sustainable, advanced feedstocks, including waste materials.
- Demand for passenger car travel is moderated, especially in urban areas, by encouraging people to switch to walking, cycling and using public transport.

[161] CCC (2015) *Sectoral scenarios for the Fifth Carbon Budget: Technical report.*

- Freight operators reduce their fuel consumption and emissions through improved logistics, driver training and the use of fuel saving technologies fitted to existing vehicles, such as aerodynamic improvements.
- Increased rail electrification and deployment of battery electric trains on track unsuitable for overhead cables.

With a committed and well-designed policy effort it would be possible to deliver the Further Ambition options set out above in full between 2020 and 2050:

- Bringing forward the end of sales of conventional cars and vans to at least 2035, including an end to the sales of PHEVs, and limiting the use of fossil fuel cars, vans and motorbikes delivers a faster take-up of zero emission vehicles and lower residual emissions by 2050. Certifying vehicles with a petrol or diesel engine to drive for a limited length of time can ensure that vehicles sold before 2035 do not continue to drive on UK roads beyond their average lifetime, resulting in zero emissions from cars, vans and motorcycles in 2050.
- Sales of zero emission HGVs during the 2020s must be significantly greater in our Further Ambition Scenario. Sales of battery electric and plug-in hybrid small rigid HGVs would need to reach 45% market share in 2030 and zero emission large rigid and articulated HGVs would need to reach 10% market share.
- Bus and coach sales must be fully zero emission by the year 2040, with about 50% of new vehicle sales being zero emission by 2030.
- Increased modal shift to walking, cycling and public transport to reduce demand for car travel should ramp up during the early 2020s. Similarly logistics improvements for HGVs should be in place by 2030.
- At least 54% of track-km should be electrified by 2040. Hydrogen trains should begin to be deployed on UK rail in the 2020s, with the aim of maximum roll-out being achieved by 2040, in line with the Government ambition to have no diesel-only trains on tracks by 2040.
- Electrified aircraft support vehicles should be rolled out in the 2020s and 2030s.

This assessment allows for the various limiting factors on a realistic speed of change, without requiring significant levels of early capital scrapping:

- To avoid vehicle scrappage it is important to consider the expected lifetime of a vehicle. The average lifetime of a passenger car is around 14 years but there is a significant proportion of vehicles which remain in use far longer than this. This means that an end to the sale of petrol or diesel vehicles in 2040 is too late to ensure that the whole fleet is electric by 2050.
- Over 14% of motorcycles are currently over 20 years old, with around 7% of motorcycles (representing 92,000 vehicles) currently over 40 years old.[162] For the purposes of our analysis, we have assumed that motorcycles leave the fleet after 20 years in line with cars and vans. In reality some motorbikes will remain in the fleet for much longer, although the exact usage patterns of these older motorcycles has not been assessed. There may be a need to regulate to ensure that older diesel motorcycles do not continue to be driven well past the 2050s.
- Small and large rigid HGVs remain in the UK fleet for 13 years on average, with many remaining on UK roads 20 years after sale. Articulated vehicles are more short-lived, operating for six years on average. This drives the need to aggressively roll-out zero emission

[162] Department for Transport (2018) *Vehicle Licensing Statistics.*

technologies in the 2030s, so that longer-lived HGVs are no longer operating on UK roads by 2050.

- Buses and coaches operate on UK roads for 16 years on average. This results in a need to deploy zero emission technology as quickly as possible in this sector, with the added advantage of bringing much needed improvements in air quality in urban centres.
- Trains have long lifetimes, of the order of 20 years.[163] Therefore, there may need to be some retrofitting of trains to become hydrogen trains, bimodal trains (a train that operates on electricity when on electrified track and diesel elsewhere) or at the least, diesel hybrids, to avoid scrapping them early. The retrofit market for trains is currently developing, with several early examples of conversion. A collaboration between Fuel Cell Systems Ltd, the University of Birmingham and Hitachi Rail Europe has completed a modelling exercise to show that hydrogen fuel cell technology can be retrofitted to existing diesel trains.[164]

(c) Summary table of the opportunities to reduce emissions from the surface transport sector towards zero

Table 5.1 shows emissions from each type of surface transport in 2050 and their associated abatement costs.

Table 5.1. Opportunities to reduce emissions from transport towards zero

Source	**2030 5CB residual emissions ($MtCO_2e$)**	**Further Ambition residual emissions in 2050 ($MtCO_2e$)***	**Earliest date for Further Ambition emissions**	**2050 cost £/tCO_2e****
Cars	32.8	0	2050	-£39
Vans	10.0	0	2050	-£64
Buses	2.3	0.3	2050	£198
HGVs	14.5	0.9	2050	-£39
Motorcycles	0.5	0	2050	-£22
Rail	1.6	0.9	2050	N/A
Aircraft support vehicles	0.6	0	2050	£137

Source: CCC analysis.
Notes: Emissions in 2030 and 2050 include all GHGs; £/tCO_2e cost figures represent levelised costs of abatement of the measures in place in 2050, and are averaged across multiple abatement measures applied to the same emission source. As rail is generally switched to zero emission options when cost-effective from an operational perspective, the abatement costs have not been calculated here.

[163] Rail Delivery Group (2018) *Long term Passenger Rolling Stock Strategy for the Rail Industry.*
[164] Fuel Cells Bulletin (2017) *UK project shows that fuel cells can be retrofitted to power trains.*

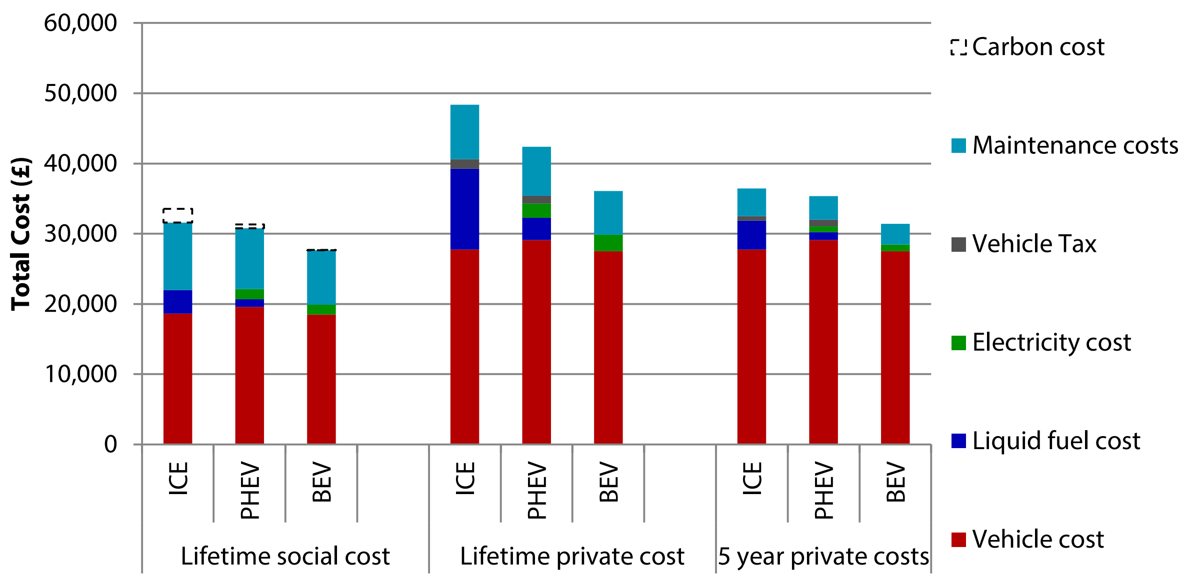
4. Costs and benefits of achieving very deep emissions reductions in the surface transport sector

Our overall approach to assessing costs and benefits is summarised in Chapter 1 of this technical report and set out in full in Chapter 7 of the accompanying advice report.

Some low-carbon options included in our net-zero scenario for surface transport would be cheaper than the high-carbon alternative, whilst others are likely to be more expensive:

- By 2030, a new battery electric car will be cost saving compared to a petrol or diesel car over the lifetime of the vehicle, even when including the costs of developing a public recharging network and upgrading power networks to deal with the increased demand for electricity, and accounting for the need to replace exchequer revenue from fuel duty:
  - A new medium sized battery electric car in 2030 is estimated to have lower capital cost by around £160 compared to an equivalent conventional car, whereas a new plug-in hybrid car will have a capital cost premium of around £910.
  - In 2030, a new medium sized battery electric car will save around £1,930 in discounted fuel costs (before fuel taxes and ignoring the cost of carbon emissions) over a 14 year lifetime and a plug-in hybrid will save around £810.
  - The cost of a home charger is included in the upfront cost of an electric vehicle, expected to be £180 in 2030. The required investment into public charging infrastructure is not expected to be significant per vehicle (more detail on the level of infrastructure required by 2050 can be found in section 5(a) covering what is needed to deliver these scenarios).
- Given expected reductions in the cost to purchase an electric vehicle and projected fuel costs, our analysis suggests that new electric cars are likely to become cost-effective during the 2020s from a societal perspective (i.e. including the cost of the vehicle and the cost of fuel (excluding taxes), discounted at the social discount rate of 3.5%).
- By 2030, we estimate, on the same basis, that a new battery electric van will be also be cost-saving compared to a petrol or diesel van over the lifetime of the vehicle:
  - The average new battery electric van will have lower capital costs of around £510 and a new plug-in hybrid van will have an upfront capital cost premium of around £410.
  - In 2030, the average new battery electric van will save around £4,860 in discounted fuel costs (before fuel taxes and ignoring the cost of carbon emissions) over a 14 year lifetime and a plug-in hybrid will save around £4,300.
  - The fuel savings from switching to an electric van are more significant than for cars, due to higher annual mileage. Therefore, our analysis suggests that new electric vans are likely to become cost-effective in the mid-2020s from a societal perspective (i.e. including the cost of the vehicle and the cost of fuel (excluding taxes), discounted at the social discount rate of 3.5%.)
- Figure 5.4. shows a cost comparison for BEV, PHEV and petrol or diesel vehicles from a social perspective over the lifetime of the vehicle, over the lifetime of the vehicle for a private consumer and over a five year timespan for a private consumer. Electric vehicles are cheaper in 2030 even when costs are evaluated over only a five year period.

Figure 5.4. Conventional and electric car costs from a private and social perspective in 2030



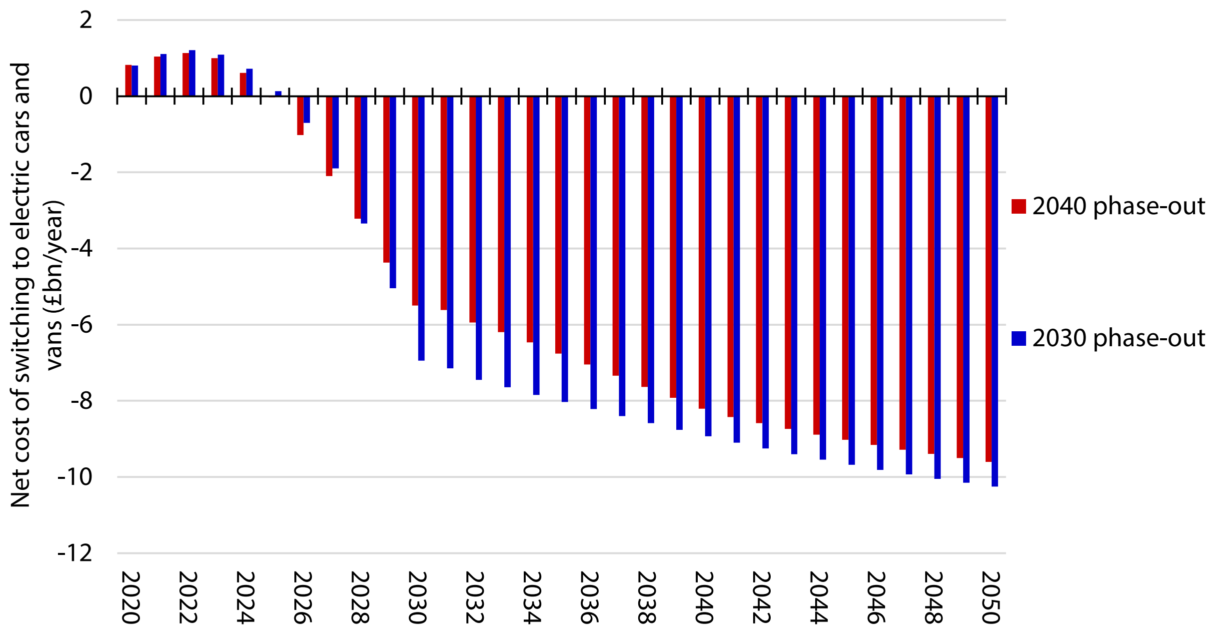
Source: CCC analysis.
Notes: Costs are for a new medium sized car in 2030 in 2018 prices. The vehicle lifetime is assumed to be 14 years. Private vehicle costs include VAT and the manufacturer margin. Private fuel and electricity costs include fuel duty, VAT and the additional costs of low-carbon power generation and power network reinforcement. We use a discount rate of 3.5% for social costs and 7.5% for private costs.

- Abatement costs for all new electric cars and vans fall below the Government's current projected carbon values during the 2020s. After 2030 our analysis suggests costs will continue to fall for BEVs but opportunities to reduce the costs of PHEVs will lessen.
- There are opportunities for conventional vehicle efficiency improvements but these will reduce after 2030. These have a positive economic cost in 2030 and beyond, reinforcing the need to switch to electric vehicles.
- Indicative estimates of abatement costs for zero emission HGVs show that large hydrogen HGVs become cost-effective from a social perspective compared to the Government's current projected carbon values during the 2020s. However, there are still large uncertainties around the costs of zero emission HGV infrastructure, vehicles and fuel. Overall capital costs of infrastructure deployment for zero emission HGV refuelling are likely to be between £3-16 billion cumulatively in the time period up to 2050.
- Travel demand reduction from cars, vans and HGVs has a zero resource cost to the economy. There could be welfare impacts arising from these changes in behaviour but these are likely to be minimal, and dependent on how societal preferences over different travel modes change over time.

Together, these costs imply a total annual saving compared to a theoretical counterfactual without any action on emissions of £0.5 billion (in real 2018 prices, 0.01% of expected 2050 GDP) for cutting emissions from surface transport to close to zero in line with our Further Ambition Scenario in 2050.

Electric vehicles are likely to be cost saving compared to petrol and diesel vehicles by 2030. On this basis, the cumulative costs of passenger transport in the UK from 2018 to 2050 may be lower if the end to sales of cars and vans with petrol and diesel engines is brought forward to 2030, compared to 2040. Figure 5.5 shows the cumulative costs (vehicles, fuels (excluding taxation) and infrastructure) of cars and vans given a decision to end sales in 2030 and a decision to end sales in 2040. It would be desirable to aim for 100% of new car and van sales to be electric by the earlier date, but there is uncertainty about the ability of car manufacturers to supply this volume of electric vehicles.

Figure 5.5. Cumulative costs of cars and vans given a decision to end the sales of vehicles with petrol and diesel engines in 2030 and in 2040



Source: CCC analysis.
Notes: Costs are compared to continued use of petrol and diesel cars, and are the subsidy free total lifetime (14 years) costs relating to all new vehicles bought in that year. Includes upfront vehicle cost, refuelling cost (discounted at 3.5%), and costs of charging infrastructure, electricity generation and network expansion. To better represent vehicles available in the future we assume the costs and efficiencies of petrol and diesel cars also develop over time. As a result, these figures are not directly comparable to others in this advice. Until 2028 costs are slightly higher for a 2030 phase-out date, which is largely due to electric vehicles being more expensive until this point and greater charging infrastructure requirements. Costs for a 2035 switchover date are not shown, but are slightly higher than for a 2030 switchover.

The scenario would also bring significant co-benefits through improved air quality and reduced noise from the deployment of zero emission vehicles and could create further economic opportunities in the UK. Measures to improve walking and cycling have associated health benefits and logistics measures contribute to reduced congestion. There is potential for electric vehicles to provide electricity back to the grid at times of high demand, reducing the need for extra storage or back-up capacity. These co-benefits are set out across the economy in Chapter 7 of our advice report.

Costs of decarbonising surface transport are likely to peak before 2050, given the need to build out a refuelling infrastructure network and that the capital costs of vehicles will likely fall as demand grows:

- Significant infrastructure investment, including public electric refuelling infrastructure for cars and vans, and either hydrogen refuelling stations, electric catenaries or extremely fast chargers for HGVs, is likely to be needed during the 2020s and 2030s. This will enable infrastructure to be deployed prior to significant uptake, to give confidence to consumers and fleet operators that they will be able refuel as part of their daily travel:
  - Previously, the Committee has published the costs of electric vehicle charging infrastructure networks required to support electric vehicle uptake in our fifth carbon budget assessment. This work has been expanded to cover the costs of converting 100% of the vehicle fleet to electric vehicles by 2050.
  - The total cost of a public electric refuelling infrastructure network for cars and vans to top up and enable those without off-street parking to charge, is approximately £9.3 billion for the chargers themselves (spread over the years between now and 2050). Initial results also indicate it is cheaper to deploy a mixture of 22 kW, 43 kW and 150 kW chargers, rather than a mixture of 7kW, 43kW and 150 kW chargers, but these results need to be explored further.
  - A rapid charging network for longer journeys would cost around £300 million to 2050. This network will consist of a mix of 43 kW, 150 kW and 350 kW chargers.
  - The likely costs of upgrading the electricity grid and associated power networks are covered in the power sector chapter. The impact of these has been taken into account in the costs presented in this chapter through the electricity price.
  - HGV refuelling infrastructure will likely require capital investment of between £3 and £16 billion to 2050, depending on the choice of technology. Hydrogen refuelling stations are the cheapest option purely from an infrastructure perspective, whereas installing ultra-rapid chargers to refuel HGVs during the driver's rest breaks appears to be the most expensive for infrastructure costs alone. Initial work to look at the costs of infrastructure, vehicles and fuel costs indicates that hydrogen, electrification (accompanied by on-road overhead wires for HGVs to charge as they drive) and electrification (accompanied by ultra-fast chargers) are all likely to be cost saving by 2050, compared to continued use of diesel. There are large uncertainties and it is too early to assess which technology is most cost-effective at this stage.
- The upfront costs of vehicles are likely to decline due to economies of scale and technological developments during the transition period as volumes of sales ramp up. This may mean the highest capital expenditure occurs significantly before 2050.

The next section considers how the scenarios can be delivered, including the need to design policy to ensure UK industry is not competitively disadvantaged.

5. Delivering very deep emissions reductions in the surface transport sector

(a) What is needed to deliver the scenarios

Delivering the level of emissions in our Further Ambition Scenario will require strong and effective Government leadership at all levels, supported by actions from people and businesses.

Table 5.3 summarises our assessment of the degree of challenge for the major opportunities to reduce emissions across a number of dimensions, in line with the approach set out in Chapter 1. Figure 5.6 sets out the timing for when key changes need to occur:

- A strong regulatory framework is needed to give industry the certainty and confidence to invest in zero emissions technologies and for consumers to adjust their purchasing decisions and behaviours.
- The early market for zero emissions vehicles needs be supported through time-limited financial incentives, either through continuation with current grant schemes or through taxation. This will help accelerate EV uptake, support the industry and help address some of the knowledge barriers about owning an EV. Local authorities can also play a role by providing softer incentives such as access to bus lanes, free access to congestion charging or clean air zones and free parking. Early policy intervention in Norway has helped to accelerate EV take-up (Box 5.4).

Box 5.4. Experience in accelerating electric vehicle uptake in Norway

In Norway, electric vehicle uptake has been accelerated by early policy interventions including setting a 2025 goal for all new cars to have zero emissions, more ambitious new car CO_2 targets than the EU, fiscal incentives (including import tax, VAT and road toll reductions, half price transport on ferries, free parking), and allowing electric vehicles to use bus lanes. These generous tax advantages have been in place since 2001 and brought the cost of electric vehicles into line with petrol and diesel vehicles, despite higher upfront capital costs, much earlier than in other countries. This demonstrates the importance of supporting the early market for electric vehicles with a combination of financial incentives and interventions that improve the ease of use of the vehicles.

Source: Ecofys for the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety of the Federal Republic of Germany (2018) *Incentives for Electric Vehicles in Norway: Fact Sheet.*

- A high uptake of plug-in vehicles will require roll-out of supporting infrastructure, which will need to serve many different requirements for charging.
- Table 5.2 compares numbers of public chargers required by 2050 to the number of chargers currently in place today.

Table 5.2. Required electric vehicle chargers in 2050 compared to current infrastructure

Types of charger	Number required by 2050	Number currently in place in April 2019
22 kW	56,000	11,500
43 kW	51,000	4,400
150 kW	105,000	-
350 kW	2,100	-

Source: CCC analysis; Zap-Map (2019) www.zap-map.com
Notes: An extrapolation was performed from modelling work published in SYSTRA for the CCC (2018) *Plugging the gap - An assessment of future demand for Britain's EV public charging network.*

- If large numbers of plug-in vehicles need to recharge in the same place at the same time, such as commercial fleets recharging in a single depot, it may be necessary to upgrade the local power distribution network. The extent to which this will be necessary is currently uncertain and will depend on the extent to which smart recharging technology can be deployed. This technology would allow plug-in vehicle recharging to respond to electricity prices and to peaks in local power demand and can reduce the costs of infrastructure upgrades and provide a valuable demand-smoothing service. Plug-in vehicles could perform an additional service by allowing electricity to be transferred from their battery to satisfy local power demand during a peak period, thereby reducing the need for additional power generating capacity. Such systems are currently in development.
- A consultancy project carried out for the Committee by Vivid Economics assesses the additional power requirements and grid support required to enable electric vehicle charging. Significant distribution network reinforcements could be required, but future-proofing investments by over-sizing network infrastructure whenever it is replaced can reduce costs overall and avoid disruption. This work is considered in more detail in chapter 2 of the technical report.
- The refuelling infrastructure roll-out for HGVs will likely need Government support, especially at the earlier stages. The Government can play a key role in supporting companies to trial and pilot new zero emission HGV technologies in the early 2020s, to establish which technology is the most practical and cost-effective. Given the proportion of HGV journeys that are cross-border, any infrastructure roll-out will need coordination across Europe. The UK can play a key role in demonstrating the technologies to drive further deployment across Europe in the late 2020s. In the 2030s, taxation and levies (both local and national) must be designed in such a way to make switching to a zero emission vehicle cost-effective compared to a conventional diesel truck.
- Rail electrification is likely to be cheapest if expanded as part of a continuous rolling programme. The Railway Industry Association recommends a rolling programme sufficient to keep two or three delivery teams consistently deployed for at least ten years across the UK.

This would develop UK skills in the design and delivery of electrified rail and further reduce current costs towards European norms.[165]

- Hydrogen trains should begin to operate on the UK rail network in the early 2020s. Trials are currently being planned by an Alstom and Eversholt Rail joint venture and by Vivarail. These should be supported by the Government where necessary.
- Innovation plays an important role in these scenarios. Assumed battery cost reductions and energy density developments must materialise in order to deliver these ambitious uptake trajectories. Similarly, for HGVs, buses and trains, hydrogen fuel cell cost reductions must be achieved, alongside improvements in hydrogen storage. New skills in the workforce will also be required in order to accelerate roll-out of infrastructure and ensure new vehicles can be designed, manufactured, serviced and finally recycled at end-of-life.
- There is a larger role for behaviour change in encouraging a shift towards active travel and the use of public transport. Encouraging cycling will also involve substantial expenditure on cycling infrastructure, which should be physically separated from traffic. Driving into urban centres should be discouraged where possible, and traffic calming measures and lower speeds can help give cyclists' confidence, making the activity more inclusive to a wider variety of people. Land use policies can also create a dense city footprint, to ensure destinations are within easy reach by walking and cycling. Seville is an example of a city that has quickly accelerated levels of cycling by providing high-quality infrastructure, even though there was initially no culture of cycling.
- Measures to improve logistics for HGVs may need financial support in the early stages, accompanied by softer incentives at the local level. Local authorities would benefit from more guidance and advice on how to encourage the use of urban consolidation centres, accompanied by case studies which demonstrate the benefits of existing successful schemes. Relaxing delivery timings to ensure that deliveries can take place outside of peak periods can also help achieve greater logistical efficiency. These measures require support and information provision in the near-term to have the greatest effect.
- There are many myths about electric vehicle usage that must be tackled. Misconceptions include whether electric vehicles are more environmentally friendly than conventional vehicles, concerns about where and how you charge your vehicle and how long the batteries in electric vehicles last. Assuming an average electricity grid intensity of 265 gCO_2/kWh (as for UK electricity generation in 2017), electric cars would emit 60 to 65% less CO_2 over their lifetime than diesel cars, including emissions from battery manufacturing and electricity generation.[166] [167] In reality, the UK grid intensity will continue to fall over the lifetime of the car, resulting in greater emissions reductions.

Whilst there are key uncertainties with these options, largely around expected technological development of batteries and hydrogen fuel cell technologies and whether people will change their behaviour to change the way they travel, there are options that can make up any shortfall:

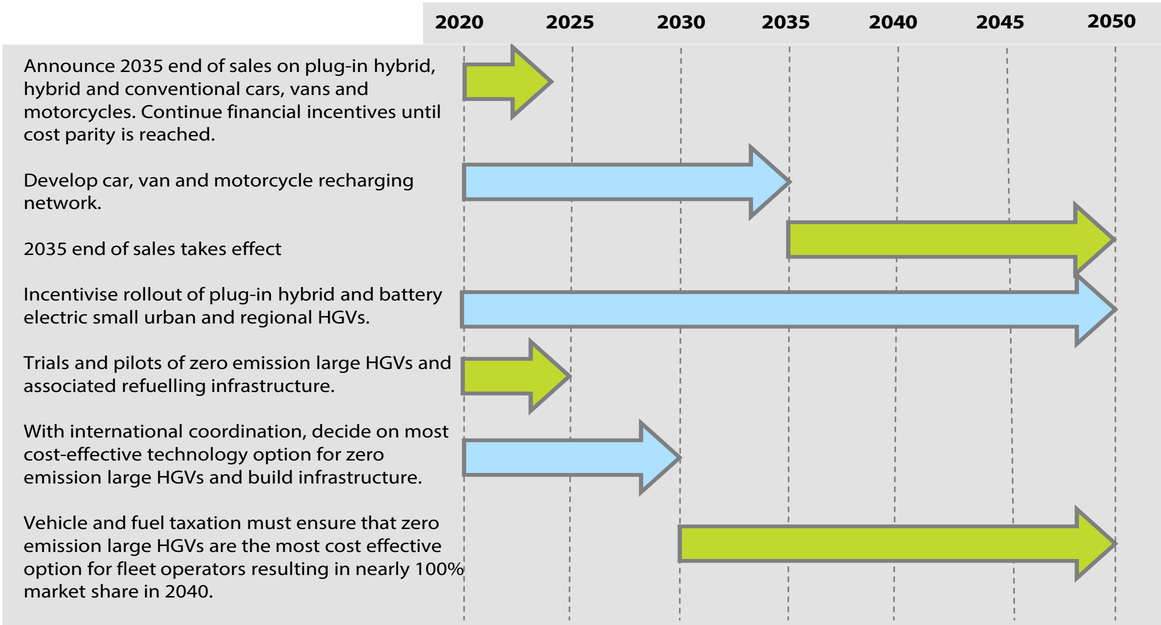
- If electrification does not proceed as quickly as expected in the passenger car sector, there could be scope for some further emissions reduction through increased ambition on shifting car journeys to walking, cycling and use of public transport. Similarly, van journeys can be

[165] Railway Industry Association (2019) *RIA Electrification Cost Challenge.*
[166] CCC (2018) *Reducing UK emissions: 2018 Progress Report to Parliament.*
[167] Transport and Environment (2018) *Electric vehicles: The truth.*

reduced with the deployment of e-cargo bikes and increased logistics efficiency. Increased logistics efficiency can also reduce emissions from HGVs.

- Any remaining fossil fuels in transport in 2050 could be replaced by synthetic fuels, but these are likely to be costly. Some shortfalls in electrification could also potentially be replaced by hydrogen options, for instance for passenger cars and vans.

Figure 5.6. Timing of key decisions and changes to deliver the net-zero scenarios for surface transport



Source: CCC analysis.

Table 5.3. Assessment of abatement options against dimensions of challenge for the transport sector

Source	Abatement measure	Barriers and delivery risks*	Funding mechanisms	Co-benefits and opportunities	Alternative options
Cars	Electrification, Walking, cycling and public transport	Consumer behaviour, Manufacturer supply chains, Infrastructure roll-out.	Consumers	Air quality, noise, public health	Hydrogen
Vans	Electrification	Manufacturer supply chains, Power supplies at depots	Industry	Air quality, noise	Hydrogen, demand reduction through e-cargo bikes.
Buses	Electrification, Hydrogen	Access to capital so bus operators can afford additional upfront costs	Consumers	Air quality, noise	100% electrification or 100% hydrogen
HGVs	Electrification, Hydrogen, logistics improvements	Infrastructure roll-out, Manufacturer supply chains	Industry, Tax-payer funded (for some infrastructure options)	Air quality, noise, congestion	100% electrification or 100% hydrogen
Motor-cycles	Electrification	Consumer behaviour, Manufacturer supply chains	Consumers	Air quality, noise, public health	
Rail	Electrification and hydrogen	Infrastructure roll-out, technology development of hydrogen trains	Tax-payer funded	Air quality, operational benefits	Hybrid trains (limited abatement potential)
Aircraft support vehicles	Electrification	Vehicle development, Variety of vehicles required.	Industry	Air quality	Hydrogen

Source: CCC analysis.
Notes: The rating of measures in the table is based on the following criteria: 'barriers and delivery risks' are rated as 'red' if there is evidence that a given measure is particularly hard to implement, and 'green' or 'amber' otherwise; 'funding mechanisms' are rated as 'red' if the delivery of a given measure has high costs and these have a negative impact on businesses' competitiveness or are regressive on households, and 'green' or 'amber' otherwise; when there is evidence of positive 'co-benefits and opportunities' these are rated as 'green', otherwise no rating is given.

(b) Key policy implications for driving deep emissions reductions from the surface transport sector

This report does not aim to identify a full policy package to deliver the scenarios set out above. However, there are important high-level policy implications that should be understood by Government and Parliament when considering the setting of a UK net-zero emissions target.

In particular for supporting the increased uptake of zero-emission vehicles across all surface transport:

- The Government must bring forward the end of sales of new conventional cars and vans to 2035 at the latest, ideally earlier, and extend this to cover any car or van with petrol or diesel combustion engines. By 2025, the Government must be clear to all consumers that vehicles with a petrol or diesel combustion engine cannot continue to be driven on UK roads by 2050. The scope should also be extended to cover motorbikes.
- Financial incentives will be required in the near-term to support the still early market of electric cars, vans, small HGVs and motorbikes, until cost parity is reached with conventional vehicles from the view of a private consumer, likely in the mid-2020s. Electric car and van charging infrastructure roll-out must be monitored to ensure that sufficient deployment occurs in readiness for significantly higher proportions of the fleet being fully electric.
- Trials of zero emission HGVs and associated refuelling infrastructure should be planned from now until the early 2020s to develop an evidence base to enable decisions to be made on the most cost-effective and practical zero emission option. The Government must prepare to make this decision, with international coordination, in the mid 2020s to enable infrastructure to be developed ready for the deployment of zero emission HGVs in the late 2020s and throughout the 2030s. If this decision is delayed by five years, emissions from HGVs in 2050 could be around 3 $MtCO_2e$ higher, assuming the roll-out trajectory is similarly delayed. Taxation or other measures should be designed to incentivise commercial operators to purchase and operate zero emission HGVs from the 2020s onwards.
- The Government must incentivise walking, cycling and the use of public transport in preference to car usage wherever possible to exploit these opportunities for emissions reductions in the nearer term.
- Opportunities to improve the logistics efficiency of HGVs must be explored, including increased roll-out of urban consolidation centres to minimise journeys into busy urban centres and adjusting delivery times to ensure HGVs can avoid congestion.
- Rail electrification should be planned on a rolling basis to keep costs low and trials of hydrogen trains on UK rail should be supported where necessary.

The Committee's annual progress reports to Parliament include our detailed progress assessments. Our June 2018 report identified a number of areas where policy strengthening was required to deliver existing ambition.[168] These are a necessary condition to support the increased effort required to deliver a UK net-zero emissions target – we will report on progress against them in July 2019.

[168] CCC (2018) *Reducing UK emissions: 2018 Progress Report to Parliament.*

Chapter 6: Aviation and shipping

Introduction and summary

This chapter sets out the scenarios for the aviation and shipping sectors that inform the Committee's advice on reviewing long-term emissions targets for the UK, Scotland, and Wales.

The key messages from this chapter are:

- **Background.** Greenhouse gas (GHG) emissions from aviation and shipping made up 10% of total UK emissions in 2017. CO_2 emissions from international aviation were the largest source, at 7%, making up most of the total. Aviation emissions have more than doubled since 1990, while shipping emissions have fallen by nearly 20%.
- **'Core' measures.** Our Core scenario for aviation stabilises emissions at 2005 levels (i.e. 37.5 $MtCO_2$), in line with current Government policy. This is more than double 1990 levels, and can be achieved with some fuel efficiency improvement and by limiting demand growth to 60% above 2005 levels. Our Core scenario for shipping reduces emissions by around 75% compared to 1990 levels, reflecting current global commitments.
- **'Further Ambition' measures.** Our Further Ambition scenario identifies additional potential to reduce aviation emissions to 30 $MtCO_2e$ in 2050. But emissions remain relatively high given the long lifetimes of aircraft and the challenges in developing and deploying new technologies. Our Further Ambition scenario for shipping reduces emissions to near-zero through more widespread use of alternative fuels (e.g ammonia), which could be possible if a low-carbon supply and global refuelling network develops.
- **Speculative options.** Some options exist to reduce aviation emissions lower than the Further Ambition scenario. We consider two illustrative scenarios for further limiting growth in demand (e.g. to 20-40% above 2005 levels), and through uptake of synthetic fuels to replace jet fuel. These have significant delivery and cost barriers, but could potentially reduce aviation emissions to around 22 $MtCO_2e$ (with demand constraint) or to near-zero (through synthetic fuels).
- **Costs and benefits.** Some of the measures to reduce aviation and shipping emissions are cost saving (e.g. new more fuel efficient aircraft), but some will have positive abatement costs (e.g. alternative fuels). In aggregate achieving the emissions level in the Further Ambition scenarios would cost around £5 billion in shipping in 2050, which is a total annual cost of around 0.1% of GDP. Emissions reduction in aviation could be cost saving, but we take a cautious approach and do not assume this.
- **Delivery.** A mix of UK and international policies will be required to deliver the Further Ambition scenarios in ways that avoid perverse outcomes (e.g. carbon leakage).
  - Both aviation and shipping will need to strengthen the current internationally agreed policies. Aviation should set a global long-term objective for emissions. Shipping should put in place a policy framework to deliver the agreed target for 2050. A more ambitious global target in shipping would be needed to deliver the technical potential that exists in the Further Ambition scenario.
  - The Government should ensure their forthcoming Aviation Strategy and Clean Maritime Plan support innovation, research and deployment to ensure new technologies are brought to market in a timely fashion. The Aviation Strategy will also need to set out an approach to limiting growth in aviation demand. We will set out our recommended approach for aviation in follow-up advice to DfT later in 2019.

We set out our analysis underpinning these key messages in the following five sections:

1. Current and historical emissions from aviation and shipping

2. Reducing emissions from aviation and shipping

3. Scenarios for minimising emissions from the aviation and shipping sectors

4. Costs and benefits of reducing emissions in the aviation and shipping sectors

5. Delivering emissions reductions in the aviation and shipping sectors

1. Current and historical emissions from aviation and shipping

GHG emissions from aviation were 36.5 $MtCO_2e$ in 2017, 7% of the UK total, and shipping emissions were 13.8 $MtCO_2e$, 3% of the UK total (Figure 6.1). The vast majority of aviation emissions are from international flights, particularly long-haul. Shipping emissions are more evenly split between domestic and international journeys, reflecting more options to refuel en route. Almost all aviation and shipping emissions are from CO_2. Some non-CO_2 effects may be important but are short-lived and not currently covered by the international reporting framework (Box 6.1):

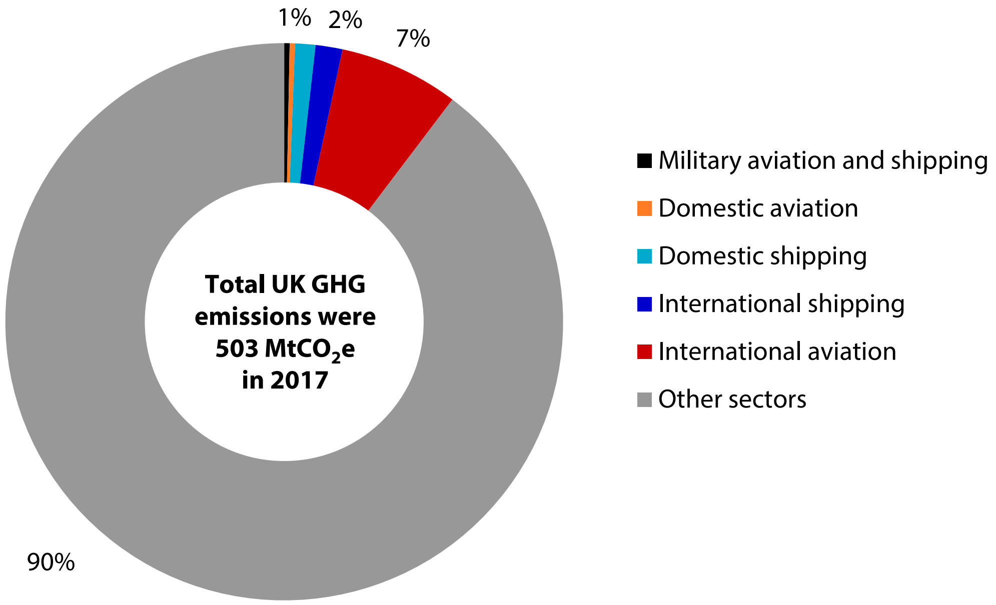
- **Aviation.** The UK emissions inventory measures aviation emissions on the basis of fuel sales. This closely corresponds to emissions from departing flights. In 2017 GHG emissions from departing international flights made up the vast majority (96%) of UK aviation emissions. Domestic flights made up 4% of aviation emissions.
- **Shipping.** In 2017 GHG emissions from international journeys were 57% of shipping emissions, with domestic journeys making up 43% of the total.
- **Non-CO_2 effects.** Almost all emissions (99%) reported in the national inventory from aviation and shipping are from CO_2. The remaining 1% is from non-CO_2 from fuel combustion. Both aviation and shipping have other non-CO_2 effects that are not covered in the emissions inventory reported to the UN. These effects are potentially important but are short-lived (Box 6.1).

Since 1990 aviation emissions have more than doubled, while shipping emissions have fallen by nearly 20% (Figure 6.2). Both sectors were affected by the global financial crisis in the late-2000s:

- **Aviation.** The increase in aviation emissions reflects an increase in passenger demand for flying, which has nearly tripled since 1990. Most passenger demand is for short-haul flights but most kilometres travelled, and therefore emissions, are from long-haul (Figure 6.3). Following the financial crisis there has been some decoupling in demand and emissions growth (e.g. since 2010 passenger demand has grown 4% per year but emissions have only grown 1% per year). However, the extent to which this is a permanent shift is not clear.
- **Shipping.** Shipping emissions were broadly flat between 1990 and 2008, but have fallen by a quarter since then. This largely reflects a reduction in the speed at which ships travel following the global financial crisis.

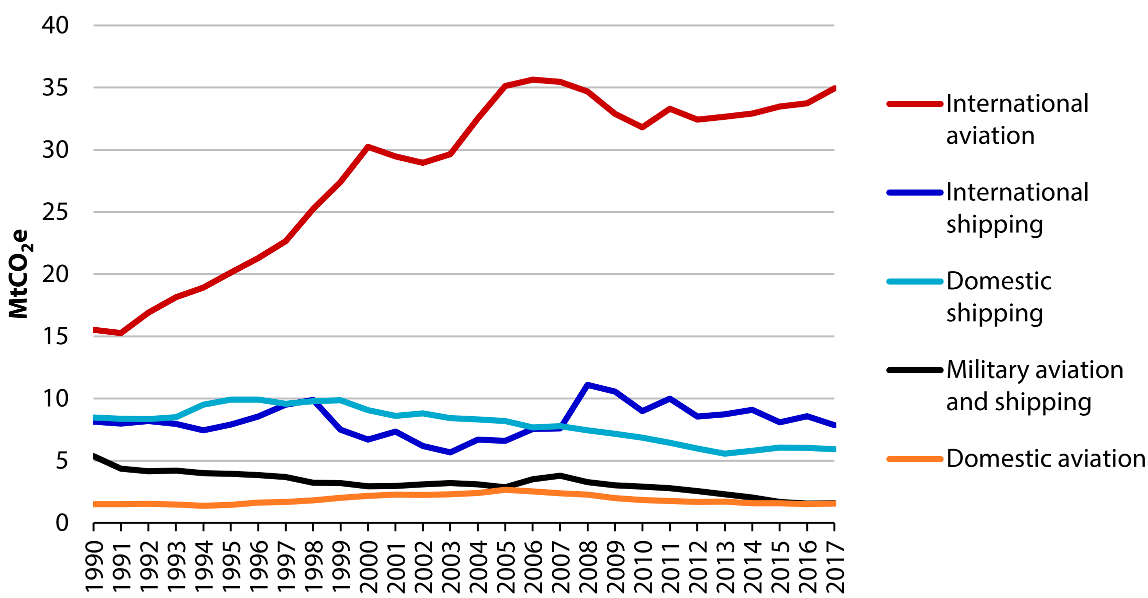
Currently only domestic aviation and shipping emissions are included within carbon budgets. International aviation and shipping emissions are within scope of the 2050 target, and carbon budgets have been set to take this into account.

Figure 6.1. Current emissions from the aviation and shipping sectors (2017)



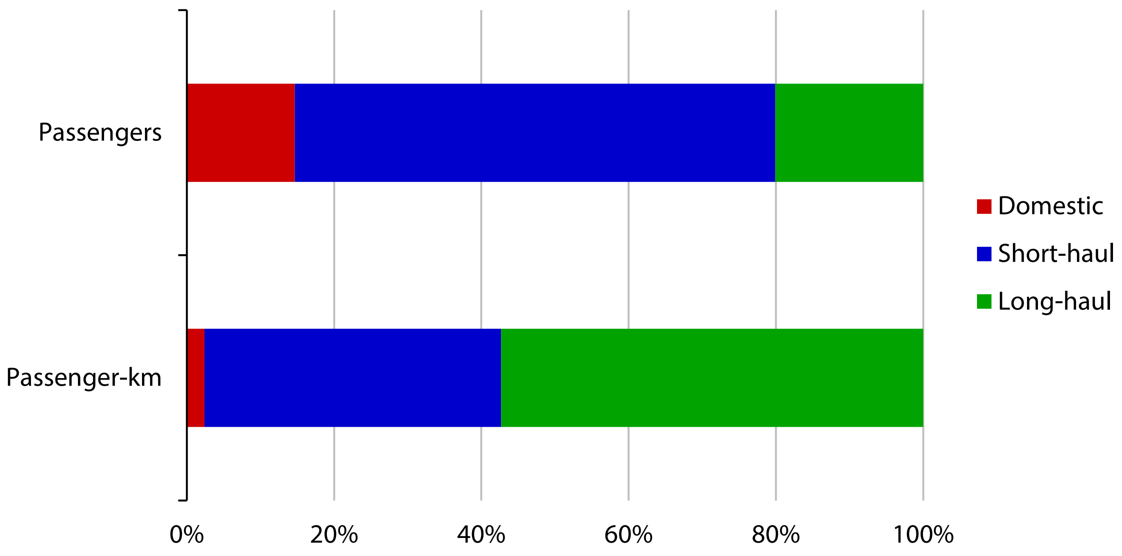
Source: BEIS (2019) *2017 Greenhouse Gas Emissions, Final Figures*.

Figure 6.2. Emissions from the aviation and shipping sectors since 1990



Source: BEIS (2019) *2017 Greenhouse Gas Emissions, Final Figures*.

Figure 6.3. Proportion of aviation demand by domestic, short- and long-haul travel



Source: CCC calculations based on CAA Airport data and DfT analysis of CAA Airport/Airline data.

Box 6.1. Non-CO_2 effects from aviation and shipping

Aviation and shipping both emit very small amounts of regulated non-CO_2 greenhouse gases (methane and nitrous oxide) but also have additional non-CO_2 effects that are not included within the basket of gases covered by the Paris Agreement:

- **Aviation** produces a range of different pollutants that affect the climate in different ways. These include emissions that have a direct cooling effect on the climate, such as sulphates which reflect sunlight and induce low-level cloudiness, and also those that have an overall warming effect on the climate, such as nitrous oxide. Planes can also create contrails (long trails of cloud caused by aircraft flying through supersaturated air) depending on the atmospheric conditions. As these clouds are high in the atmosphere they have a relatively large warming effect on the climate. Overall, non-CO_2 effects from aviation warm the climate and approximately double the warming effect from past and present aviation CO_2 emissions.
- **Shipping** has non-CO_2 effects that come from the emission of sulphate aerosols. These have a cooling effect on the climate by directly reflecting sunlight and through their effects on the brightness and longevity of clouds. Sulphate emissions from shipping are expected to decline in the future due to global regulations to reduce the sulphur content of shipping fuels. These are expected to come into force in 2020.

In both aviation and shipping, these non-CO_2 effects are mainly short-lived, meaning that if emissions were stopped their effects on the climate would rapidly disappear. This is unlike CO_2, for which warming persists long after emissions have stopped.

These non-CO_2 effects can vary substantially depending on the location properties of the atmosphere they are emitted into, unlike for well-mixed greenhouse gases which affect the climate the same regardless of where they are emitted. Therefore, these non-CO_2 effects are not, at the moment,

Box 6.1. Non-CO_2 effects from aviation and shipping

included in national or international emissions inventories and are not addressed explicitly as part of our scenarios for reducing aviation and shipping emissions in the UK.

Efforts to reduce aviation non-CO_2 effects will help to lower peak levels of warming if implemented prior to the date of global net-zero CO_2 emissions (e.g. by 2050-70 for pathways that meet the Paris Agreement) and if not achieved at the expense of additional CO_2 emissions (which would create more warming in the long-term). The trade-off between reductions in non-CO_2 effects and possible increases in CO_2 emissions is currently not clear, but efforts should be made to identify these options and to implement them where possible.

2. Reducing emissions from aviation and shipping

There is a range of technologies that can be used to reduce emissions from aviation and shipping. In this section we set out the options for reducing aviation and shipping emissions, and the further evidence we have considered in this report.

(a) Options for reducing aviation and shipping emissions

(i) Aviation

There are currently no commercially available zero-carbon planes. This is likely to continue to be the case out to 2050, particularly for long-haul flights which are responsible for the majority of aviation emissions. Managing aviation emissions will therefore require actions across a range of areas including more fuel efficient engine and aircraft designs, improved airspace management and airline operations, use of sustainable alternative fuels, and measures to reduce growth in demand:

- **Technology.** There are options to improve fuel efficiency through new engine and aircraft designs. The engine measures we consider include more efficient iterations of conventional jet engines (e.g. ultra-high bypass ratio turbofans) and use of hybrid-electric engines. We also consider use of composite materials and high-aspect ratio wings in aircraft design. We do not include potential from open rotor engines, full-electric propulsion, or blended wing aircraft, all of which are judged to have significant barriers to delivery on a 2050 timeframe. Pure electric aircraft may be an option post-2050, particularly for short-haul flights, but will require breakthroughs in battery energy density to become a commercially viable proposition.
- **Airspace management and airline operations.** Enabling aircraft to fly more direct routes will reduce fuel burn and hence emissions. This will rely on international cooperation (e.g. across the EU) to realise the full benefits. In conjunction with more direct routings, designing aircraft for slower cruise speeds could offer significant fuel savings while maintaining journey times. Other operational measures that could save fuel include use of electric tugs, and reducing the time spent taxiing.
- **Alternative fuels.** Use of sustainable biofuels could help reduce emissions from aviation. Alternative synthetic fuels may be technically possible but are likely to be thermodynamically and economically challenging, and therefore significantly more expensive than other options.

– **Use of sustainable biofuels.** Biofuels could potentially substitute for fossil fuel in aviation, provided that these are developed in a sustainable way that genuinely saves emissions. Consideration should be given as to whether aviation is the most appropriate place to use biomass, given that is likely to be a scarce resource with a range of alternative uses which may save more emissions (including negative carbon emissions through use with carbon capture and storage, CCS).

– **Use of synthetic fuels.** It is possible that synthetic carbon-neutral fuels could be used to reduce aviation emissions to zero. Production of such fuels would entail recycling captured CO_2 (e.g. via direct air capture, DAC) in conjunction with electrolytic hydrogen into a drop-in replacement for kerosene. Given the high expected cost of DAC in providing the feedstock CO_2, the low thermodynamic efficiency of the process and the need for multiple processing stages it is likely that costs of synthetic fuels will be very high even if the input electricity comes from low-cost renewables (see Chapter 5 of the advice report). It is likely that any CO_2 captured through DAC will provide emissions reductions at lower cost when combined with CCS rather than it being inefficiently recycled into a fuel (see Chapter 10 for consideration of the removals potential for Direct Air CO_2 Capture and Storage - DACCS).

- **Managing demand.** Options exist to reduce demand for aviation either indirectly (e.g. through shifting to high-speed rail or use of video calling), or through policies to directly manage demand. Demand may also be lower in future if preferences or social norms change. Potential for emission savings from high-speed rail and video calling are likely to be limited, given that the majority of emissions come from long-haul flights and that 80% of journeys are for leisure purposes.

(ii) Shipping

A range of options exist to reduce shipping emissions, some of which may allow shipping to get to near-zero emissions. These include more fuel efficient ship and engine designs, improved ship operations, and use of alternative fuels:

- **Improvements to fuel efficiency.** These are possible including through measures to reduce water resistance (e.g. more efficient hull coatings), measures to improve energy efficiency (e.g. recovery of waste heat), and through use of alternative sources of propulsion (e.g. kites, Flettner rotors, and sails).
- **Ship operations.** Reducing speeds at which ships travel can significantly reduce fuel use, given that power requirements increase with the cube of speed. This saves fuel even if the journey takes longer. Other operational measures include use of software to plan the most efficient route given expected weather conditions and to optimise ballast and trim.
- **Alternative fuels.** There is potential for fuel switching in shipping to hydrogen or ammonia, both of which would need to be produced in a low- or zero-carbon way (i.e. from zero-carbon electricity or with CCS). These options also have the advantage that they can be retrofitted to existing ships. Biofuels are technically feasible in shipping but not likely to be a priority given other competing uses for this resource. Electrification is possible for ships, but is likely to be limited to relatively short routes given the energy and therefore battery requirements. The potential development of an international market in hydrogen (e.g. as ammonia) shipped from countries with low costs of low-carbon hydrogen production, does raise the possibility of this being the primary way of supplying low-carbon fuel for refuelling at ports.

Alternative fuels offer the largest emission saving, given that these can be retrofitted to existing ships. The remaining potential is broadly equally distributed between fuel efficiency and operational measures.

(b) The strengthened evidence base used in this report

In this report we have drawn on the evidence published in and alongside recent Committee reports, including our reviews of Biomass and Hydrogen:[169]

- **Aviation**. In our recent Biomass review we advised that government should not plan for high levels of biofuel use in aviation in the long-term, given competing potential better uses for this resource. A pragmatic planning assumption would be to aim for up to 10% biofuel use in aviation in 2050. Production of aviation biofuel will need to be in conjunction with CCS to be competitive with competing uses for biomass (e.g. in industry, electricity generation, or hydrogen production).
- **Shipping.** Our Hydrogen review identified hydrogen and ammonia as potential options to decarbonise shipping through use in fuel cells, internal combustion, or dual fuel or hybrid combinations. Low-carbon ammonia can be made directly from electrolysis, or by adding nitrogen to low-carbon hydrogen using renewable energy. Ammonia is likely to be preferred to hydrogen as it is easier to store as a liquid, but further work is required to ensure it can be used safely (Box 6.2). Both hydrogen and ammonia would require a transition to a global refuelling infrastructure and a low-carbon supply of these fuels.

We have also commissioned and undertaken new analysis for this report, and taken into account other new work:

- **Aviation.** We commissioned, jointly with the DfT, a review of the latest evidence on the technological potential to reduce aviation emissions. We have also undertaken internal reviews of the literature and evidence on modal shift and video calling (Box 6.3). We have used this revised evidence base to construct new scenarios for aviation emissions, which we have developed using the DfT's aviation model.[170] These scenarios are based on current and planned airport capacity, including a third runway at London Heathrow.
- **Shipping.** Following agreement in the International Maritime Organisation (IMO) to reduce global international shipping emissions by at least 50% by 2050 compared to 2008 levels, the DfT has committed to publish a new Clean Maritime Plan by spring 2019. In order to support this they commissioned a project to review the potential to reduce shipping emissions, to develop new UK emission scenarios, and to assess the barriers to and economic opportunities from a zero-carbon transition. This work will be published alongside the Clean Maritime Plan.

We reflect this new evidence along with our existing evidence base in our scenarios in section 3.

[169] CCC (2018) *Biomass in a low-carbon economy*, CCC (2018) *Hydrogen in a low-carbon economy*.
[170] For a description of the model see DfT (2017) *UK Aviation Forecasts*.

Box 6.2. Challenges for use of low-carbon fuels in shipping

Use of alternative fuels (e.g. hydrogen, ammonia, or potentially methanol) in shipping presents a range of challenges including ship integration and safety:

- **Ship integration.** From a ship integration perspective, ammonia is generally preferable to hydrogen. Hydrogen is a gas at room temperature, requiring significant space for onboard storage. Liquefied hydrogen requires less storage space, but needs cryogenic conditions which are expensive to run and take up space themselves. Loss of space reduces capacity for carrying cargo. Ammonia is easier to store as a liquid than hydrogen, with a boiling point of -33°C instead of -253°C, so requires less expensive, bulky storage equipment and less cargo is displaced.
- **Safety considerations.** Hydrogen and methanol have low flash points (i.e. the temperature at which the flammable vapour can ignite), and will therefore need to comply with the appropriate safety regulations. Ammonia and methanol are toxic, and will require safe storage and handling. Storing ammonia in liquid form reduces the risk of it leaking as a gas.

Box 6.3. New evidence on reducing aviation emissions

We have commissioned a new project on the potential for reducing emissions from aviation, and have undertaken internal reviews of the potential for modal shift and video calling:

- **Reducing emissions from aviation.** We commissioned a project jointly with the DfT to review the potential for reducing aviation emissions.[171] The project reviewed the evidence on improvements to engines (e.g. ultra-high bypass ratio turbofans, electrification), aircraft designs (e.g. high aspect ratio wings, use of composite materials), airline operations (e.g. aircraft speeds), and air traffic management (e.g. ensuring optimal routing) that could be deployed to 2050 and beyond. The project developed plausible scenarios for how these improvements could be bundled into future aircraft designs for four size categories of aircraft, up to 500 seats. It also estimated the costs of these new aircraft designs and improvements. The key finding is that by 2050 there is potential to reduce aviation emissions by up to around 40% versus a comparable year 2000 aircraft. Fuel savings from these new aircraft would outweigh the additional capital costs, meaning that they are cost saving overall. The abatement costs are therefore negative, at around -£50/CO_2 in 2050.
- **Modal shift from aviation to high-speed rail.** The scope for modal shift between aviation and rail and high-speed rail depends on route distance. Our analysis suggests that journeys up to 800 km offer potential for substitution from aviation to high-speed rail. The types of journeys suitable for modal shift are domestic and some short-haul international routes. The emissions saving potential from these are very limited given that only a small proportion of these journeys are within switching distance. The modal shift assumption applied across our scenarios corresponds to a reduction of between 1% and 5% of domestic and EU demand.[172]
- **Use of video calling.** Given advancements in video capability and availability, these could impact on demand for business air travel. However, in practice the available evidence is unclear whether video-calling acts predominately as substitute or a complement to business travel. The potential for this to reduce aviation emissions is also limited given that business travel only represents around 20% of journeys. In our modelling, we tested this uncertainty with assumptions for the potential impact ranging from a 10% reduction in business air travel demand to a 10% increase. For our main scenario we do not assume any demand reduction from video calling.

[171] ATA and Ellondee (2018) *Understanding the potential and costs for reducing UK aviation emissions.*
[172] CCC (2009) *Meeting the UK aviation – options for reducing emissions to 2050.*

3. Scenarios for minimising emissions from the aviation and shipping sectors

In section 2 we summarised the options for reducing aviation and shipping emissions. In this section we combine these options into scenarios for reducing aviation and shipping emissions to 2050. We also consider the implications for timings of a low-carbon transition.

(a) Scenarios for reducing aviation and shipping emissions

As set out in Chapter 1, we have classified the options for cutting emissions into three categories, 'Core', 'Further Ambition', and 'Speculative':

- **Core options** are those low-cost low-regret options that make sense under most strategies to meet the current 80% 2050 target. For most the Government has already made commitments or begun to develop policies (although in many cases these need to be strengthened).
- **Further Ambition options** are more challenging and/or more expensive than the Core options, but are all likely to be needed to meet a net-zero target.
- **Speculative options** currently have very low levels of technology readiness, very high costs, or significant barriers to public acceptability. It is very unlikely they would all become available. Some of these options would be required to reach net-zero GHG emissions domestically.

Figures 6.4 and 6.5 show how these options would reduce emissions in the aviation and shipping sectors.

Military aviation and shipping emissions are relatively small (1.6 $MtCO_2e$ in 2017, 0.3% of total emissions) and we assume these remain unchanged to 2050.

(i) Aviation

In the absence of a truly zero-carbon plane it will not be possible to reduce aviation emissions to zero. The challenge is therefore to minimise aviation emissions as far as possible:

- **Core scenario.** This is aligned to the planning assumption which underpins the currently legislated 80% 2050 target (i.e. 37.5 $MtCO_2$).
  - This holds aviation emissions constant at 2005 levels, which is over double 1990 levels. This is a generous allocation which requires other sectors to reduce their emissions by 85% in order to meet the 80% target overall. The Government have accepted this planning assumption as a basis for aviation strategy and policy.
  - Aviation emissions at 2005 levels in 2050 could be achieved through a combination of fuel efficiency improvement of around 0.9% per year (e.g. through uptake of more advanced conventional jet engines, and some use of higher aspect ratio wings and composite materials), limited use of sustainable biofuels (i.e. 5% in 2050), and by limiting growth in demand to 60% above 2005 levels.
- **Further Ambition scenario.** This identifies additional opportunities to reduce aviation emissions below the Core scenario, to 30 $MtCO_2e$ in 2050. These include a combination of more ambitious fuel efficiency improvements, and further but still limited uptake of sustainable biofuels.

– **Fuel efficiency improvement** rises to 1.4% per year through deployment of additional measures including some reductions in the design speeds of aircraft, and more widespread use of high aspect ratio wings and composite materials. The scenario includes some deployment of hybrid-electric aircraft in the 2040s, which make up less than 10% of kilometres flown in 2050. There are no full-electric aircraft in the scenario. The scenario also reflects some efficiency improvements in airspace management. We do not assume any savings from more efficient routing, given the need for a global, or at least regional, coordinated solution.

– **Biofuels** use is higher, but still limited, rising to 10% in 2050. Our scenarios are based around supply of sustainable biomass with strong governance to ensure they reflect genuine emission savings. We therefore assume 100% emission saving from these biofuels, in line with the analysis in our 2018 Biomass report.

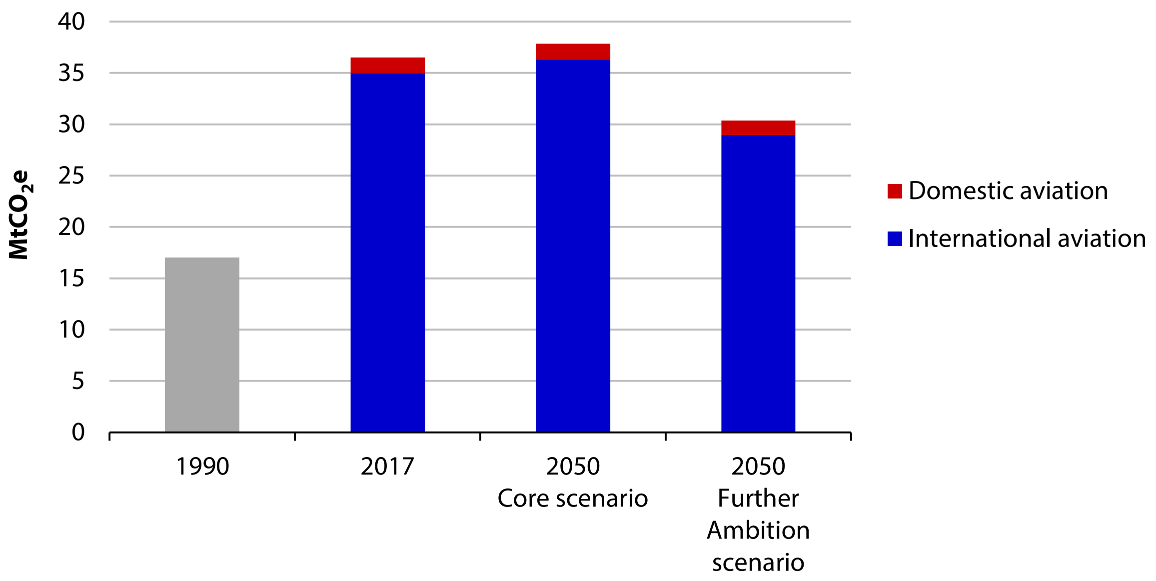
- **Speculative options.** We have identified some Speculative options in aviation that go beyond the Further Ambition scenario on both demand and alternative fuels, but these have significant challenges.

  – **Further demand constraint** is possible in order to limit growth to less than 60% compared to 2005 levels. We illustrate the potential emission savings from additional demand constraint through two scenarios: limiting demand to 40% above 2005 levels by 2050; and a 20% limit. These could save an additional 4-8 $MtCO_2e$ in 2050 respectively, and could, for example, reflect future changes in consumer preferences and social norms, or more ambitious policy to limit growth in demand.

  – **Synthetic fuels** in our Speculative option are produced at an illustrative level sufficient to offset remaining fossil fuel emissions from aviation (technically possible, but likely to be significantly more expensive than paying for the emissions to be sequestered instead).

The resulting 2050 emissions in the Further Ambition scenario are 30.4 $MtCO_2e$. Emissions from international flights are the vast majority of these remaining emissions, at 29.0 $MtCO_2e$. Domestic emissions are 1.4 $MtCO_2e$. The Speculative options have significant delivery and cost barriers, but could potentially reduce aviation emissions to around 22 $MtCO_2$ (demand constraint) or to near-zero (synthetic fuels).

Figure 6.4. Scenarios for UK aviation emissions to 2050



Source: BEIS (2019) *2017 Greenhouse Gas Emissions, Final Figures*, CCC analysis.
Notes: Scenarios are modelled using the DfT aviation model with CCC assumptions.

(ii) Shipping

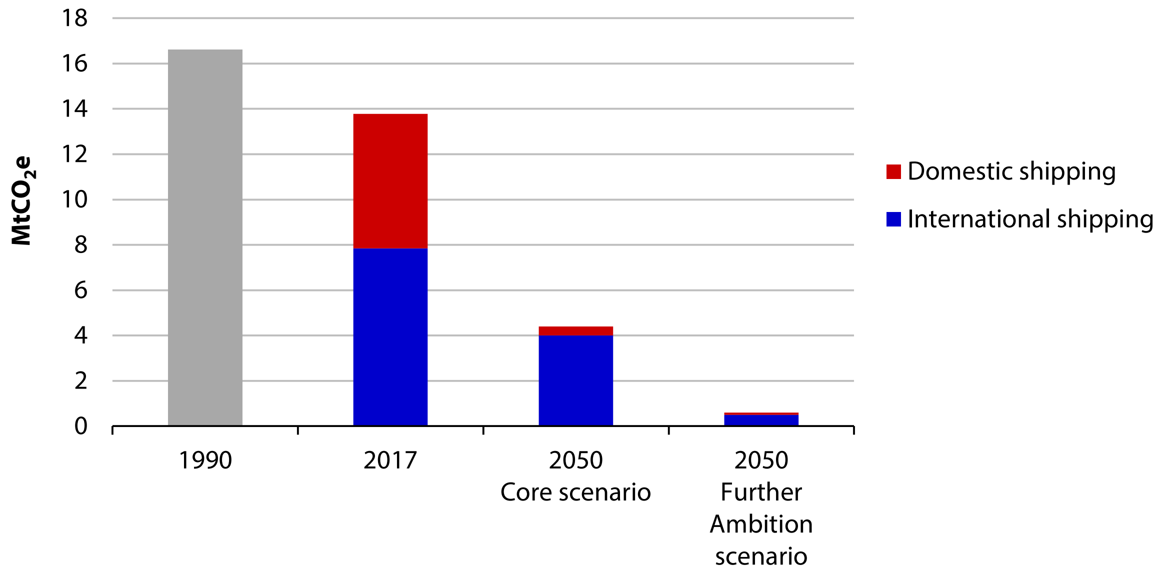
Given that options exist to reduce shipping emissions to near-zero, our scenarios reflect different levels of ambition for the speed at which these options are rolled-out. The Core scenario aligns to the IMO's agreed objective to reduce global international shipping emissions by at least 50% below 2008 levels by 2050. The Further Ambition scenario goes beyond this to reduce shipping emissions to near-zero by 2050.

The Core and Further Ambition scenarios have broadly similar transitions. Both include uptake of energy efficiency measures, many of which are cost-saving to operators. The difference in emissions between the scenarios therefore primarily reflects the speed of uptake of alternative fuels. Across the scenarios ammonia is the most prevalent fuel by 2050, but the level and speed of transition varies:

- In the Core scenario the main transition to ammonia occurs in the mid-late 2040s, and this represents around three-quarters of fuel demand by 2050.
- In the Further Ambition scenario there is a faster transition to ammonia through the 2040s, such that this represents nearly all shipping fuel demand by 2050.

Remaining emissions in the Core scenario are 4.4 $MtCO_2e$ in 2050, of which 4.0 $MtCO_2e$ are from international journeys and 0.4 $MtCO_2e$ from domestic shipping. The Further Ambition scenario reduces total shipping emissions to less than 1 $MtCO_2e$ in 2050, with international emissions of 0.5 $MtCO_2e$ and domestic emissions of 0.1 $MtCO_2e$.

Figure 6.5. Scenarios for UK shipping emissions to 2050



Source: BEIS (2019) *2017 Greenhouse Gas Emissions, Final Figures*, Frontier Economics et al (2019) *Reducing the maritime sector's contribution to climate change and air pollution (Draft outputs)*, forthcoming reports for the DfT.

(b) Timing for cutting emissions from aviation and shipping

Our scenarios for emissions take into account a realistic speed of change for the aviation and shipping sectors. The key factors common to both sectors are the long lifetimes of assets, and the need to develop international supply chains for alternative fuels. Our scenarios do not require early capital scrappage in either aviation or shipping:

- **Long asset lifetimes.** Both aircraft and ships are operational for 20-30 years. Our modelling takes this rate of asset turnover into account. It implies that all new aircraft and ships would need to be zero-carbon from 2030 or before in order for the entire fleet to be zero-carbon by 2050. This is unlikely to be realistic, given development lead times and technology readiness in aviation, and given the potential for retrofit in shipping.
  - In aviation the only potential zero-carbon propulsion system is full battery electric. This is very unlikely to be commercially viable for all flights (including long-haul) by 2030 or even 2050, given current levels of technology and market readiness and time required for safety certification processes. Our Further Ambition scenario has hybrid-electric planes entering the fleet in the 2040s, but these represent less than 10% of total kilometres flown in 2050. This fundamental challenge in a technology-based solution to reducing aviation emissions highlights the importance of managing growth in demand, developing drop-in fossil fuel substitutes, or creating markets for genuinely negative emission removals to offset remaining aviation emissions.
  - In shipping there is scope for a more gradual roll-out of new zero-carbon ships, given the potential for retrofitting existing ships to run on ammonia. The constraints on this are more likely to be related to the capacity and skills required in the sector to deliver the

rate of retrofit and new build necessary to ensure the fleet can run on zero-carbon fuels by 2050.

- **Developing international supply chains.** If shipping, and potentially aviation, are to move to alternative non-fossil fuels (e.g. ammonia or synthetic hydrocarbons) then this will require these fuels to be globally available. That in turn means a global low-carbon supply of the fuels, and a global refuelling infrastructure network. These are both likely to be key barriers. In particular, asset owners may not want to invest in alternative fuel aircraft or ships until a global supply network is in place, but airports and ports may not want to invest in the supporting infrastructure until demand can be credibly demonstrated. Policy may be required to overcome this coordination problem.

(c) Summary table of the opportunities to reduce emissions from aviation and shipping

Table 6.1. Opportunities to reduce emissions from aviation and shipping

Sector	2017 emissions ($MtCO_2e$)	2050 Further Ambition scenario ($MtCO_2e$)	Earliest date for Further Ambition emissions	2050 cost (£/tCO_2e)
Domestic aviation	1.5	1.4	2050	-10
International aviation	35.0	29.0	2050	
Domestic shipping	5.9	0.1	2050	200
International shipping	7.8	0.5	2050	

Source: CCC analysis based on Figures 6.4 and 6.5.

4. Costs and benefits of reducing emissions in the aviation and shipping sectors

Our overall approach to assessing costs and benefits is summarised in Chapter 1 of this report and set out in full in Chapter 7 of the accompanying advice report.

Some of the low-carbon options included in our net-zero scenario for aviation and shipping would avoid costs and therefore be cheaper compared to the high-carbon alternative, whilst others are likely to be more expensive.

Together, these costs imply a total annual resource cost compared to a theoretical counterfactual without any action on emissions of -£0.2 billion in aviation (in real 2018 prices, 0.0% of expected 2050 GDP) and £5.4 billion in shipping (0.1% of expected 2050 GDP), for cutting emissions in line with our Further Ambition scenario in 2050:

- **Aviation.** The options to reduce emissions are anticipated to have a mix of positive and negative resource costs. Technological measures to improve fuel efficiency of aircraft have the largest potential to reduce emissions, and are expected to cost less than standard technologies on a total cost of ownership basis (and from a social perspective that takes account of carbon and other savings) as fuel savings are likely to outweigh higher capital costs (Box 6.3). We assume measures to limit demand growth have no resource cost, but recognise there may be welfare costs depending on the extent to which this reflects a change in preferences or the impact of policy. Sustainable biofuels are expected to have positive abatement costs to society, which we assume are in line with the costs of BECCS (i.e around £125/tCO_2). Overall, the average cost of abatement in aviation in 2050 in our Further Ambition scenario is around -£10/tCO_2e. For our economy-wide analysis we take a cautious approach and do not assume any cost savings.
- **Shipping.** A range of measures to reduce shipping emissions are estimated to be cost saving or cost neutral (e.g. speed reduction and some energy efficiency measures). However, the greatest potential for reducing emissions is from alternative fuels such as ammonia, and these are expected to be relatively expensive. Overall, this means the cost of abatement in shipping could be around £200/tCO_2e in 2050.

Overall costs in both aviation and shipping are expected to build steadily to these levels in 2050, as new technologies and fuels are rolled-out across fleets. Given the long lifetimes of both planes and ships (i.e. over 20 years) this can be expected to be a gradual process, as older less efficient models are replaced by new ones at the end of their lives.

The next section considers how the scenarios can be delivered, including the need to design policy to ensure that perverse outcomes (e.g. carbon leakage) are avoided in these international sectors.

5. Delivering emissions reductions in the aviation and shipping sectors

Aviation and shipping are international sectors, which means that both UK and international policy action will be required to drive decarbonisation. In this section we set out the key changes and policy actions needed to deliver the scenarios.

(a) What is needed to deliver the scenarios

Delivering the level of emissions in our Further Ambition scenarios will require strong and effective Government and international leadership at all levels, supported by actions from people and businesses.

Table 6.2 summarises our assessment of the degree of challenge for the major opportunities to reduce emissions across a number of dimensions, in line with the approach set out in Chapter 1.

- **Aviation.** There are a range of challenges to overcome to deliver the Further Ambition scenario, which will require investment in innovation and low-carbon technologies, as well as social and behavioural changes. Government policy will be needed to make these happen.
  - **Challenges.** Given the international and relatively concentrated nature of the aviation industry (i.e. there are few large-scale engine and aircraft manufacturers, mostly in Europe and the US), many of the technological solutions will require a coordinated global approach (Section 5b). Demand measures have lower technical barriers but face other constraints, particularly around public acceptability. Survey evidence suggests that

although half the UK population do not fly in a given year,[173] appetite to constrain demand can be limited.[174]

  – **Investment and innovation** will be required to deliver the new technologies and practices that will help to reduce emissions. The cost of developing and purchasing new aircraft types can be billions of dollars. The aviation industry currently invests substantially in research and development, in addition to government support. This ongoing investment will need to continue but targeted at low-carbon solutions in future. Key areas for innovation include new aircraft designs (e.g. high aspect ratio wings, use of composite materials) and batteries for use in hybrid-electric aircraft. The aviation industry will also need to champion the use of carbon capture and storage, since this will be critical to delivering emission savings from sustainable biofuels, synthetic fuels, and any negative emissions that are needed to offset residual aviation emissions in 2050.
  – **Societal and behaviour changes.** The Further Ambition scenario limits demand growth to 60% above 2005 levels by 2050. While this is an increase on current levels, it is less than the 90% that is projected to occur under a business-as-usual scenario.[175] Policy will therefore be needed to limit the increase in demand, unless preferences or social norms change significantly. Given that in a given year half the population do not fly and a quarter take two or more flights, this implies scope for rebalancing without removing opportunity to travel.

- **Shipping.** The most significant challenge in delivering the Further Ambition scenario for shipping is to ensure a global supply of low-carbon alternative fuels. Policy is likely to be needed to incentivise uptake of other measures as well, given likely barriers. The largest emissions reduction potential in shipping is from use of alternative fuels (e.g. hydrogen or ammonia). Ensuring this is available will require coordinated action so that ships are able to refuel globally. Other measures such as speed reduction or energy efficiency may have low technical barriers or low costs, but other barriers may exist. For example, a key barrier is that ships are often chartered, so that the owners do not necessarily capture the benefits of any investment to improve fuel efficiency. Non-financial barriers will also be important. These include ensuring that any safety concerns are overcome, and that the skills, knowledge and capacity in the supply chain are developed in order to implement the range of new technologies required for new and retrofit ships.

Figure 6.6 sets out the timing for when key changes would need to occur in order to deliver the Further Ambition scenario in aviation and shipping. The Speculative options (e.g. further limits to demand growth, synthetic fuels) provide contingency to make up for any shortfall should some options fail to deliver as expected.

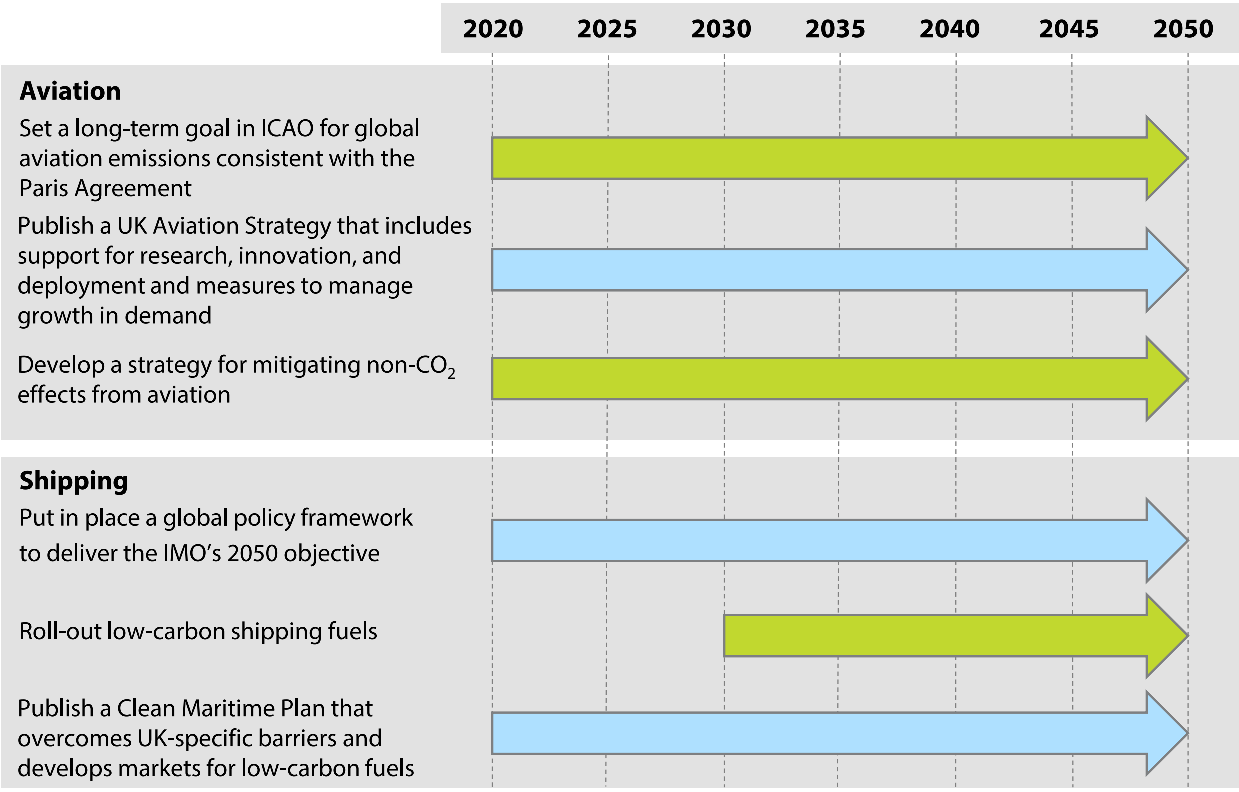
[173] DfT (2018) *National Travel Survey*
[174] 10:10 (2018) *10:10 Climate Action response to CCC Call for Evidence.*
[175] DfT (2017) *UK Aviation Forecasts*

Table 6.2. Assessment of abatement options against dimensions of challenge for the aviation and shipping sectors

Source	Abatement measure	Barriers and delivery risks	Funding mechanisms	Co-benefits and opportunities	Alternative options
Aviation	Limit growth in demand	Policy and consumer acceptability	Consumers	n/a	n/a
	Fuel efficiency improvement	Global policy & industry development	Industry	Opportunities for UK industry	Further demand growth constraint
	Alternative fuels	Supply chains, infrastructure, resource availability	Consumers	n/a	Further demand growth constraint
Shipping	Ammonia	Global policy, supply chains & infrastructure	Industry	n/a	Hydrogen

Source: CCC analysis.
Notes: Rating of measures in the table is based on the following criteria: 'barriers and delivery risks' are rated 'red' if there is evidence that a given measure is particularly hard to implement, and 'green' or 'amber' otherwise; 'funding mechanisms' are rated as 'red' if there are high costs and these have a negative impact on businesses' competitiveness or are regressive on households, and 'green' or 'amber' otherwise; when there is evidence of positive 'co-benefits and opportunities' these are rated as 'green', otherwise no rating is given.

Figure 6.6. Timings of key decisions and changes to deliver the Further Ambition scenarios for aviation and shipping



Source: CCC analysis.

(b) Key policy implications for driving deep emissions reductions from the aviation and shipping sectors

The Government should set a net-zero target for the UK which includes emissions from domestic and international aviation and shipping. We set out below some of the specific implications for aviation and shipping.

(i) Aviation

A net-zero target will require more effort from all sectors, including aviation. The Committee's advice is that a net-zero target for 2050 should cover all sources of GHG emissions, including international aviation and shipping. We will set out our recommended policy approach for aviation in follow-up advice to DfT later in 2019.

Reducing emissions from aviation will require a combination of international and domestic polices, and these should be implemented in ways that avoid perverse outcomes (e.g. carbon leakage). A package of policy measures should be put in place that include carbon pricing, support for research, innovation and deployment, and measures to manage growth in demand:

- **A long-term goal for international aviation emissions.** The International Civil Aviation Organisation's current carbon policy, CORSIA, has an end date of 2035 and will need to be based on robust rules that deliver genuine emission reductions. A new long-term goal for global international aviation emissions consistent with the Paris Agreement would provide a strong and early signal to incentivise the investment in new, cleaner, technologies that will be required for the sector to play its role in meeting long-term targets. This is particularly important in aviation given the long lifetimes of assets. A similar approach has been agreed for global shipping emissions in the IMO, which has set a target for greenhouse gas emissions to be at least 50% below 2008 levels by 2050.
- **Support for research, innovation, and deployment.** Our analysis, and that of industry, suggests the largest contribution to reducing aviation emissions will come from new technologies and aircraft designs. Many of these developments are likely to be cost-effective, given their potential fuel savings. The Government should build on the approach set out in the Aerospace Sector Deal and Future Flight Challenge, and set out a clear strategy to ensure these technology solutions are developed and brought to market in a timely fashion. Synthetic fuels should not be a priority for government policy, but if industry wants to pursue them it should focus on demonstrating that these fuels, used in aviation, would be genuinely low-carbon, and could become cost-competitive and scalable in a global market.
- **Measures to manage growth in demand.** The Further Ambition scenario allows for a 60% growth in passenger demand by 2050 compared to 2005 levels. Without additional policies being put in place government projections suggest demand could be higher than this (e.g. their central case is for around a 90% growth in demand by 2050 compared to 2005 levels). New UK policies will therefore be needed to manage growth in demand. These could include carbon pricing, reforms to Air Passenger Duty, or policies to manage the use of airport capacity. Recent research commissioned by the DfT[176] shows that UK policies to manage demand in aviation would not lead to carbon leakage from the UK to other countries in aggregate, given the relatively small amount of emissions affected. Policies to manage demand can therefore be pursued without significant risk of perverse impacts.

Action should also be taken on non-CO_2 effects from aviation. These cause additional warming but should not be included within targets at this stage given their short-lived effects and uncertainty over how to measure and report their impact in the annual emissions inventory. However, the Government should develop a strategy to ensure that these effects can be mitigated over the coming decades (e.g. by 2050-70 for pathways that meet the Paris Agreement) without increasing CO_2 emissions. Demand measures are one way to reduce these effects.

The Government is aiming to publish an Aviation Strategy later in 2019, and published a consultation on this in December 2018. The consultation commits to regular updates of the Aviation Strategy. These regular reviews will provide an opportunity to respond to a future decision by Parliament to meet the UK's commitments under the Paris Agreement. The final white paper should aim to set more specific time-points for these reviews, and align them to developments in government climate strategy overall.

[176] ATA and Clarity (2018) *The carbon leakage and competitiveness impacts of carbon abatement policy in aviation*.

(ii) Shipping

The IMO has agreed a target to reduce global international shipping emissions by at least 50% by 2050 compared to 2008 levels. It must agree a policy framework for delivering this. A more ambitious global target (e.g. for net-zero shipping emissions in 2050) would be needed to deliver the technical potential that exists in the Further Ambition scenario.

Reducing shipping emissions in line with the IMO's objective will need a combination of policies that incentivise uptake of zero-carbon options, while overcoming the global coordination barriers that are posed by such a transition and avoiding risks of carbon leakage:

- **Incentivise uptake of zero-carbon options.** Options to reduce shipping emissions are a mix of negative cost (i.e. cost saving to operators) and positive cost measures. Broadly, energy efficiency measures that save fuel are negative cost. Alternative fuels are generally positive cost.
  - That cost saving options are not currently being taken up implies there are non-financial barriers (e.g. lack of access to finance, lack of information about potential savings, concerns about safety). Policy should therefore aim to address these barriers, for example through use of regulations.
  - Additional policies (e.g. a carbon price) may be needed to incentivise options which are currently positive cost compared to continuing use of fossil fuels.
- **Overcome global coordination barriers.** If shipping is to reach zero emissions through use of alternative fuels (e.g. hydrogen or ammonia), then this will require a global supply of low-carbon fuel as well a global network of refuelling infrastructure. Policy will be required in order to ensure that this develops in a coordinated manner, which gives ship operators confidence they can refuel on global voyages and gives port operators confidence that a market will exist to supply these fuels to.

The Government is planning to publish a Clean Maritime Plan in spring 2019. The plan should put in place measures which can overcome UK-specific barriers and help develop markets for low-carbon shipping fuels.

Chapter 7: Agriculture, land use, land-use change and forestry

Introduction and key messages

This chapter sets out the scenarios for the agriculture and land use, land use change and forestry (LULUCF) sectors that inform the Committee's advice on reviewing long-term emissions targets for the UK. It draws on new research to identify non-CO_2 emissions abatement in agriculture and from analysis taken from our recent land use report, which considered how transforming the way land is used and managed could deliver deep emissions reduction in agriculture and the LULUCF sector.

Due to the dominance of non-CO_2 emissions in agriculture, getting close to zero emissions will not be possible by 2050.

The key messages from this chapter are:

- **Background.** Emissions in the agriculture sector were 45.6 $MtCO_2e$ in 2017 accounting for 9% of all UK emissions.[177] Since 1990 emissions from agriculture have declined by 16%. The LULUCF sector was a net carbon sink of 9.9 $MtCO_2e$ in 2017 compared to 1990 when it was a small net source of emissions. Emissions from all sources of peatland (estimates ranging 18.5-23 $MtCO_2e$) will be included in the GHG inventory next year.
- **'Core' measures**. In the agriculture sector, core measures rely on low-cost options to reduce emissions from crops, soils and livestock. We assume a medium level of uptake by farmers to reflect the lack of existing policy to reduce emissions. These measures reduce emissions by 15% by 2050 compared to 2017. In the LULUCF sector, the core measure of afforestation, including on-farm, can reduce emissions by 31% compared to 2017.[178]
- **'Further Ambition' Scenario**
  - A stronger policy framework can increase the level of uptake of the same set of measures as in the Core scenario, and the delivery of additional measures to reduce emissions from livestock. The use of fossil fuels in agricultural mobile machinery falls by 90%. A switch to healthier diets away from the most carbon-intensive food can provide further non-CO_2 emissions savings. In this scenario agricultural emissions fall to 26.3 $MtCO_2e$ by 2050.
  - Societal changes towards healthier diets, increasing livestock stocking densities and improving agricultural productivity can release a fifth of land out of agricultural production. This enables more tree planting, energy crops, and the restoration of degraded peat. This reduces emissions further, enabling the LULUCF sector to return to a net emissions sink of 2.5 $MtCO_2e$ by 2050.
- **Speculative options.** More ambitious changes in diets can reduce agricultural emissions further, and release more agricultural land for alternatives use such as woodland creation. For lowland peat that remains in agricultural production, innovative management practices can reduce emissions (e.g. 'wet-farming' and management of the water table). We classify these as speculative as they would require significant consumer behavioural change, including gaining public acceptability on eating alternative protein sources, radical changes on how land is used in the UK and addressing technical challenges around managing the water table.
- **Costs and benefits.** Most on-farm abatement is estimated to be cost saving for farmers, although there is considerable uncertainty around this. Changes in diets are cost-neutral and

[177] The UK total includes emissions from International aviation and shipping.
[178] 2017 value includes the higher level of peat emissions (23 $MtCO_2e$).

afforestation is cost-effective at current carbon values. There is a large range of costs for upland peat restoration, some which are very high. However, restoration has many co-benefits such as improved water filtration and enhanced biodiversity.

- **Delivery.** The following actions should be taken to support deep emissions reduction in agriculture and the LULUCF sectors:
  - Develop a post-Common Agricultural Policy (CAP) framework that incentivises the take-up of low-carbon farming practices and promotes transformational change in land use that rewards land owners and managers for deep emissions reduction and removals and delivering wider ecosystem benefits.
  - Continued investment in R&D, testing and piloting of options to deliver agricultural productivity improvements and enhanced forest productivity. Develop low-carbon agricultural machinery and robotics with artificial intelligence.
  - Provide support to help land managers transition to alternative land uses through skills, training and information. Along with financial support for alternative land uses with high up-front costs and long pay-back periods.
  - Government should introduce consumer-focused policies to encourage healthier diets and reduce food waste more proactively. The public sector should take a strong lead for example, by providing plant-based and lower-meat options in schools and hospitals.

We set out the analysis in the following sections:

1. Current and historical emissions from agriculture
2. Reducing emissions from agriculture
3. Scenarios for minimising emissions from the agriculture sector
4. Costs and benefits of achieving very deep emissions reductions in the agriculture sector
5. Delivering very deep emissions reductions in the agriculture sector
6. Current and historical emissions from the LULUCF sector
7. Reducing emissions in the LULUCF sector
8. Scenarios for reducing emissions and increasing the net carbon sink in the LULUCF sector
9. Costs and benefits of achieving very deep emissions reductions in the LULUCF sector
10. Delivering very deep emissions reductions in the LULUCF sector

1. Current and historical emissions from agriculture

Agriculture emissions were 45.6 $MtCO_2e$ in 2017, 9% of all UK greenhouse gases (GHGs).[179] This is the highest share since 1990, as other sectors have reduced emissions faster than agriculture (Figure 7.1).

In 2017 methane accounted for 56% of agricultural emissions, nitrous oxide (N_2O) 31% and carbon dioxide (CO_2) 12%. These gases have different atmospheric lifetimes. CO_2 and N_2O emissions are long-lived, while methane is short-lived around (12 years). Chapter 2 of the Net Zero advice report sets out how sustained emissions of these gases have different impacts on global temperatures.[180]

In 2017 enteric fermentation from ruminant livestock (cattle and sheep) accounted for 47% of emissions. A quarter was due to agricultural soils, 15% from managing wastes and manures, 9% from mobile machinery, and 1% from stationary machinery.

Emissions have declined by 16% compared to 1990 (Figure 7.2). Successive reform of the Common Agricultural Policy (CAP) in the 1990s and early 2000s, which reduced cattle and sheep numbers, coupled with EU environmental legislation (e.g. Nitrates and Water Framework Directives) have been the main drivers for the decline. Since 2008 emissions have been broadly flat.

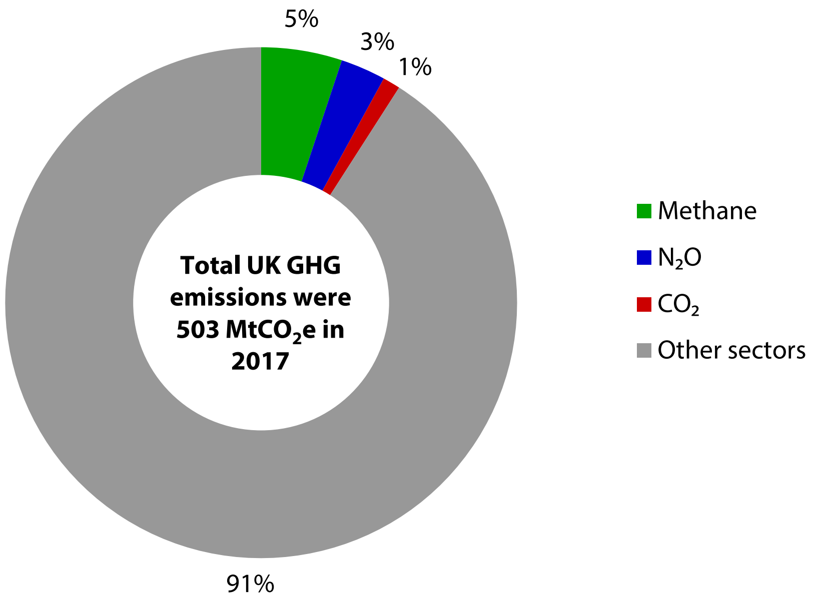
Future estimates of agricultural emissions will increase when the IPCC's revised Global Warming Potential (GWP)[181] values for methane and N_2O are adopted in the GHG inventory by the end of 2024:

- Methane GWP will increase from the current 25 to 28 (or 34 if the feedbacks on the carbon cycle are included).
- N_2O GWP will reduce from 298 to 265, but remain unchanged at 298 if feedbacks on the carbon cycle are included.

On the basis that the carbon feedbacks are included for estimating both methane and N_2O emissions, the new GWP values would result in 2017 agriculture emissions being 20% higher (9.3 $MtCO_2e$) than estimated under the current methodology.

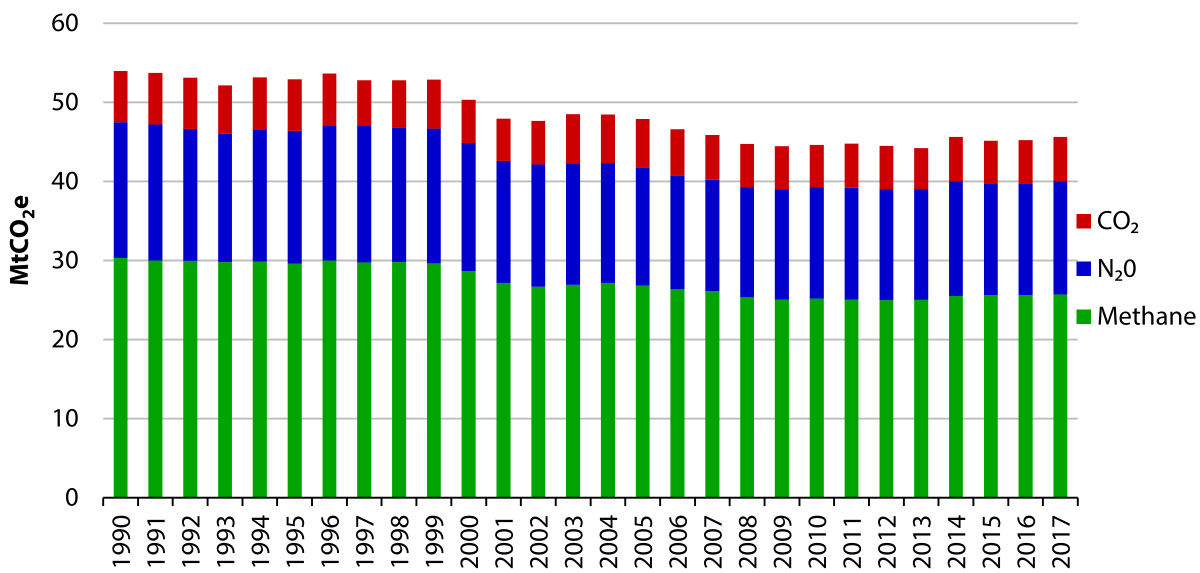
[179] The UK total includes emissions from International aviation and shipping.
[180] CCC (2019) *Net Zero: The UK's contribution to stopping global warming*.
[181] IPCC (2014) *The Fifth Assessment Report (AR5).*

Figure 7.1. Current emissions from the agriculture sector (2017)



Source: BEIS (2019) *Final UK greenhouse gas emissions national statistics 1990-2017*.
Notes: The UK total includes emissions from international aviation and shipping.

Figure 7.2. Emissions from the agriculture sector since 1990



Source: BEIS (2019) *Final UK greenhouse gas emissions national statistics 1990-2017*.

2. Reducing emissions from agriculture

(a) The current role of zero-carbon sources

Retaining an agricultural sector in the UK means it is not possible to reduce agricultural non-CO_2 emissions to zero due to the biological processes inherent in crop and livestock production. Emissions can be reduced through the take-up of a range of low-carbon farming practices (e.g. nitrogen use efficiency practices) and the adoption of technological options (e.g. genetics and breeding). In addition, the adoption of healthier diets away from the most carbon intensive products and reducing food waste can feed through to on-farm GHG emission savings associated with agricultural production.

CO_2 emissions from agricultural stationary (0.3 $MtCO_2e$ in 2017) and mobile machinery (4 $MtCO_2e$) have reduced, but the lack of a low-carbon alternative means that tractors and other field vehicles are still dependent upon fossil fuels:

- Energy is required for a number 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. Electricity accounts for around two-thirds of energy use in stationary machinery, with an increasing share from renewable sources, rising from 12% in 2000 to 49% in 2017. This has been driven by on-farm renewable generation through wind, solar and anaerobic digestion. Over the same period, natural gas use has fallen from 22% to 14% while the use of coal and burning oil as an energy source has disappeared.
- Mobile machinery comprises a wide range of vehicles and machinery such as tractors, combine harvesters, and sprayers. These continue to be fuelled by diesel, although some smaller auxiliary vehicles such as loaders and mixer-feeder wagons are already hybrid-electric.

(b) Options for reducing emissions

Agricultural policy is a devolved matter, and there are no policy measures in place to reduce emissions across all countries of the UK. Action is instead being delivered through various voluntary initiatives:

- In England, the Greenhouse Gas Action Plan (GHG Action Plan) is an industry-led approach to reduce non-CO_2 emissions by 3 $MtCO_2e$ by 2022 against a 2007 baseline. The main mechanism for delivering the Plan is through the provision of information and advice, which focuses on improving efficiencies.
- As part of the Climate Change Plan (CCP), Scotland has set an ambition to reduce agricultural emissions by 9% from 2018 to 2032.[182] This is equivalent to a 0.8 $MtCO_2e$ saving.
- The Welsh Government recently announced ambition to reduce agricultural emissions by 6% from 2016 to 2020, or 0.4 $MtCO_2e$.[183] Over the longer-term it is aiming for a 28% reduction by 2030 from 1990 levels.
- Northern Ireland's Greenhouse Gas Implementation Partnership is a partnership between the government and the agricultural industry, focused on encouraging on-farm action in four key areas: nutrient management, livestock management, improving land and carbon

[182] Scottish Government (2018) *Climate Change Plan: Third report on proposals and policies 2018-2032.*
[183] Welsh Government (2019) *Prosperity for all: A low carbon Wales.*

management and increasing energy efficiency. However, targets for a reduction in emissions have not been set.

Under the Committee's cost-effective path for meeting the fifth carbon budget, UK agricultural emissions fall by around 7 $MtCO_2e$ by 2030. Savings are based on a wider uptake of efficient farming practices for soils and livestock, and improvements in energy efficiency.

Reducing agricultural emissions further towards net zero will require a wider uptake of low-carbon farming practices and technology driven options to decarbonise on-farm energy use. These will need to be combined with a significant societal shift in diets away from beef, lamb and dairy and a reduction in food waste:

- Widespread take-up of low carbon farming practices aimed at reducing soil, livestock and manure management emissions and innovative options such as the use of genetics and methane inhibitors for cattle will be needed to reduce non-CO_2 emissions:
  - **Nitrogen use efficiency**. This could be achieved through a number of measures including loosening soil compaction on cropland, use of precision farming (e.g. variable rate fertiliser application and controlled traffic farming), more use of organic residues (e.g. anaerobic digestates), better accounting for nutrients in livestock manures, and increased use of legume crops.
  - **Livestock measures.** Measures such as improving the feed digestibility of cattle and sheep, improving animal health and fertility, and increasing the feed conversion ratio through the use of genetics can reduce methane emissions. The New Zealand Animal Selection, Genetics and Genomics Network (ASGGN)[184] focuses on scientific research to reduce emissions from ruminant livestock through the use of animal selection, genetics and genomics techniques. It has found that the trait for emitting methane is 20% heritable for sheep, so by breeding lower emitters it was possible to reduce the amount they produced after a few generations.
  - **Manure management.** Practices such as better storage, management and application of animal wastes on land can reduce manure management emissions. Improved management of housed livestock manures can include better floor design and use of air scrubbers, while treating stored slurry with acid can reduce N_2O emissions.
- Decarbonising energy related emissions to zero will require increased energy efficiency in agricultural buildings to reduce energy demand and a switch to low-carbon technologies to displace fossil fuels for heating and cooling buildings and for farm vehicles such as tractors:
  - There is scope to improve the thermal efficiency of agricultural buildings through retro-fit or new-build. Alongside the installation of more efficient technologies for heating and cooling, this can contribute to a reduction in energy demand.
  - Consistent with other non-residential buildings (Chapter 3), the residual level of natural gas used for heating and other processes will need to be replaced by low-carbon alternatives (e.g. electricity or renewables).
  - Agricultural vehicles account for 93% of the emissions arising from machinery use in the sector. Reducing these emissions close to zero requires a shift to low-carbon fuels such as electricity and hydrogen. There is also scope for smaller sized vehicles to be replaced with

[184] The ASGGN is within the Livestock Research Group, which was established by the Global Research Alliance on Agricultural Greenhouse Gases.

battery powered robots for certain on-field applications such as seed drilling and applying crop protection and fertiliser.

- Achieving deep cuts in agriculture emissions will require societal changes away from consumption of the most carbon intensive food products (e.g. beef, lamb and dairy) and reductions in the amount of avoidable food waste along the food supply chain.

Our analysis assumes that the level of food production per capita is at least maintained at current levels in 2050. The behavioural measures around food waste and shift towards healthier diets lead to a change in the composition of agricultural output rather than an increase in imports.

(c) Challenges in avoiding emissions from different parts of the agriculture sector

Some sources of agricultural emissions are easier to reduce, have lower costs and fewer barriers.

Emissions from stationary machinery can be reduced to zero:

- There are opportunities to switch to zero carbon options (e.g. renewables and low-carbon electricity) and reduce energy demand by installing energy efficient systems governing lighting, temperature and ventilation in line with options outlined for non-residential buildings. Reducing energy demand will also deliver efficiency savings in terms of lower energy bills.
- There is also scope to improve the thermal efficiency of the stock of agricultural buildings, especially those housing pigs. In a 2013 survey, over half of pig farmers had pig buildings which were over 20 years old, and 90% were dissatisfied with the state of their stock and wanting to invest.[185] Better performing buildings can also improve animal welfare for pigs and poultry, resulting in lower production costs.

Other sources will be more challenging to decarbonise fully**:**

- Non-CO_2 emissions which arise from biological processes and chemical reaction inherent in crops and livestock production are affected by variable, uncontrolled elements such as climate, weather and soil conditions. There are some low-regret options focused on the adoption of low-carbon farming practices, and we can expect advances in R&D and technology to drive further abatement in the future.
- Currently, use of biofuels is the main low-carbon option for agricultural machinery. Going forward there are opportunities to reduce emissions close to zero by 2050:
  - Several manufacturers have developed electric, hydrogen and hybrid prototypes for the agricultural sector, but these have not yet been commercialised. This sector can draw on advances made to commercialise low-carbon heavy goods vehicles (HGVs) e.g. reduction in battery costs and deployment of hydrogen in buses.
  - The use of field robots fitted with artificial intelligence software could displace the use of field machinery for certain operations, such as drilling seeds, applying fertiliser and crop protection. This could potentially displace a high proportion of emissions associated with fossil fuel field vehicles. Smaller in size and weight to conventional vehicles, these are less costly to buy and operate and can be electric or solar powered. Sufficient 4G coverage in rural areas would be needed to support uptake (Box 7.1)

[185] BPEX (2013) *Pig buildings and associated technology: Industry survey report.*

Box 7.1. Use of field robots

The development of autonomous robots to displace field machinery for a wide range of applications could potentially deliver multiple benefits, that will extend beyond the reduction of fossil fuel use in mobile machinery:

- Robots are cheaper to buy and run, with costs provided by one supplier (Small Robot Company) for a small-sized robot put at £2,000 for spraying and seed drilling. It is envisaged that a fleet of three to four robots (depending on field size) could be deployed at the same time.
- The lighter machinery avoids soil compaction, which is beneficial for soil structure. It also enables field operations to take place in all weathers. This is not possible with conventional machinery, where wet weather can cause significant delay in key farming activities (e.g. sowing of seeds), which can have a detrimental impact on crop yields.
- Use of artificial intelligence allows for more precise application of inputs, while the scope for each plant to be treated individually can improve yields. This could potentially increase productivity and profits.

Around 20 farms are trialling equipment from the Small Robot Company across a wide range of geographical conditions and soil types. This includes Waitrose, which has just started a three-year trial on its wheat fields. The Small Robot Company is aiming for commercial adoption by the mid-2020s.

Deeper emissions reduction rely on societal changes in diets and reducing food waste, which face different challenges:

- **Diet change**: Switching towards healthier diets away from the most carbon intensive foods requires a shift in social and cultural attitudes, and increased awareness of the environmental, animal welfare and health impacts of food. Whilst there is some evidence of a move towards eating less meat and dairy, deep emissions reduction will require more concerted action (Box 7.2).
- **Food waste reduction**: According to estimates by the Waste Reduction Action Programme (WRAP)[186] around 10 million tonnes of food downstream of the farm-gate is wasted each year. Householders account for the largest share (70%), of which 5 million tonnes is deemed to be avoidable (or under the revised definition 'edible').[187] The supply chain comprising manufacturing (17%), hospitality and food service (9%) and retail (2%) make up almost all of the remainder. There is currently no reliable data on the scale of food wasted in primary production. WRAP is working on developing a robust baseline to measure this.

  A combination of information and voluntary programmes have been implemented to reduce waste, such as WRAP's *'Love food hate waste'* campaign, which provides advice and tips to consumers. These have had mixed results in reducing per capita household waste in the UK (Chapter 8).

[186] WRAP (2013) *Household Food and Drink Waste in the United Kingdom 2012.*
[187] WRAP (2018) *Household food waste: restated data for 2007-2015.* This report restates previously published estimates which have been reinterpreted using the most recent international definitions and classifications relating to food waste.

Box 7.2. Recent evidence on changes in diets

There are two key sources of official information about UK diets: the Living Costs and Food Survey (LCF), an annual survey of 5,000 households covering shopping and eating habits; and the National Diets and Nutrition Survey (NDNS), covering 1,000 people's diets each year. These show a long-run decrease in overall meat consumption and a marginal increase in the number of vegetarians:

- Between 1974-2017 there has been a 7% decline in all meat and meat products (g/pw) per person and a 3% decline in the past two decades (LCF). Beef consumption has been flat over the past 20 years, but consumption of lamb has decreased by 58%.
- The proportion of the population classifying themselves as vegetarian rose from 1.6% in 2009/10 to 2.5% in 2015/16 (NDNS).

More recent evidence is from one-off surveys from different sources. These generally show a higher proportion of people who are vegetarian or 'flexitarian' (consciously eat less meat), but they are generally less rigorous in terms of sampling techniques used:

- A Harris survey for the 'Grocer' magazine in 2018 found 12.5% people were non-meat eaters (vegetarian, vegan or pescatarian). This proportion was highest for younger age groups (under 35) and for women.
- A 2018/19 survey by Waitrose also found 12.5% of those surveyed said they vegan or vegetarian, although more than half admitted they sometimes ate meat. A further 21% of people classified as 'flexitarian'.

These trends have been mirrored in the retail sector, which has had strong growth in non-meat products over the past few years:

- In 2018 Waitrose launched dedicated vegan sections in more than 130 stores after increasing its vegan and vegetarian product range by 60%.
- Between 2012 and 2016 there was a 185% increase in the number of vegan products launched in the UK.
- There has been a large increase in dairy alternatives, oat, almond and soya milk. Mintel report that total UK plant-based milk sales rose by a third from 2015 to while traditional milk sales rose just over five per cent.

Source: The Grocer (2018) *Meat-Free Diets: Fad or the Future of Foods?*; Waitrose and Partners (2018) *Food and Drink Report 2018*; The Vegan Society Statistics *Non-dairy-milk-alternatives: soya, oats, rice and vegan,* https://www.wired.co.uk/article/non-dairy-milk-alternatives-oatly-soy-oat-rice-vegan

(d) The strengthened evidence base used in this report

We have drawn on the evidence published in and alongside recent Committee reports, in particular advice on the fifth carbon budget (Section 2 (b)) and the 2018 Land Use report.[188]

- The Committee's Land use report considered how the use and management of land needs to change to meet climate change mitigation and adaptation objectives. It concluded that a future land strategy that delivers the UK's climate goals while balancing other pressures will require fundamental changes to how land is used:

[188] CCC (2018) *Land use: Reducing emissions and preparing for climate change.*

- Deep emissions reduction in agriculture requires higher up-take of low-carbon farming practices and the release of land out of agricultural production for alternative uses.
  - Releasing agricultural land while retaining a strong agriculture sector requires a shift towards healthier diets, a reduction in food waste, an increase in the stocking rates of livestock and improvements in crop productivity (Box 7.3).
  - We use a medium level of ambition for these factors, corresponding to Multi-functional land use (MFLU) scenario from the land use report for this report (Box 7.4).
- The Committee's review of Biomass in the UK[189] concluded that the use of biofuels in surface transport, including in agricultural vehicles, should be phased out in the 2030s, while the use of biomass for buildings should be constrained to niche uses (e.g. hybrid heat pumps off the gas grid) and biomethane injected into the gas grid.

Box 7.3. Measures to improve crop productivity

Cereal crop yields in the UK have risen modestly (e.g. 0.5% annual average increase for wheat, barley and oats) or fallen (e.g. for rye) over the past three decades. Options to deliver sustainable improvements in arable crop yields cover improved management techniques and developing new varieties that are better able to withstand pests, diseases and the impacts of a warming climate:

- **Agronomic practices.** In recent years record global wheat yields achieved in New Zealand of 16.8 tonnes/hectare, and the UK record yield of 16.5 tonnes/hectare in Northumberland provide examples of the impact of adopting best practices, coupled with favourable weather. This relies on selecting crop varieties that are consistently strong performers, having good soil structure and fertility, selecting the optimum planting period, and ensuring good crop nutrition and protection from weeds and pests. Good nutrition involves not only optimum fertiliser use throughout the growing period, but an adequate supply of trace elements (e.g. zinc and copper) to ensure good plant health.
- **Crop breeding.** Funded by the Biotechnology and Biological Sciences Research Council (BBSRC), work under the 'Designing Future Wheat' multi-institute programme is focused on developing new improved wheat germplasm, or living tissue that contain key traits that allow the next generation of wheat to be more sustainably productive and resilient to disease and the warmer climate. Launched in 2017, the programme aims to develop traits that will be made available to commercial breeders that are higher yielding, require fewer inputs such as fertiliser and water, contain essential nutrients and increase resistance and susceptibility to pathogens and pests.

We have also commissioned new analysis for this report.[190] This covers:

- An assessment of the scope for additional cost-effective on-farm abatement of non-CO_2 emissions.
- A revision of the abatement estimates of some of our fifth carbon budget measures to fully reflect the improved methodology for calculating agricultural emissions (i.e. the Smart Inventory).

[189] CCC (2018) *Biomass in a low carbon economy.*
[190] SRUC, ADAS and Edinburgh University (2019) *Non-CO_2 abatement in the UK agriculture sector by 2050.*

- A review of the emissions associated with producing 'alternative' proteins for either livestock or human consumption in order to compare the carbon intensity of these products with existing protein sources.

In addition, we have been able to draw on a limited set of results from new analysis commissioned by Defra as part of their wider project to deliver sustainable growth in agriculture in response to the Government's Clean Growth Strategy (Box 7.5).

We reflect this new evidence along with our existing evidence base in our scenarios in section 3.

Box 7.4. Reducing agricultural non-CO_2 emissions in the land use report

The Committee's land use report considered the scope to reduce non-CO_2 agricultural emissions through the take-up of on-farm management practices (that entails no change in the use of land) and the release of land out of agricultural production for alternative uses:

- Immediate opportunities to deploy cost-effective low-carbon management practices (i.e. better soils and livestock management) could deliver annual savings of 9 $MtCO_2e$ of abatement by 2050. This is broadly consistent with the level identified for the fifth carbon budget estimates by 2050 (8.8 $MtCO_2e$).
- We considered five options that could release land out of agricultural production (while still maintaining existing per-capita levels of agricultural output). The Multi-functional land use scenario (MFLU) assumes the following level of ambition by 2050:
    - Sustainable agricultural productivity improvements with average crop yields increasing by 25% from current levels based on improved agronomy practices and use of breeding.
    - Moving some livestock off upland grazing areas and redistributing these to other grassland, with an overall increase in the stocking rate on the remaining grassland of 10%.
    - Shift to healthier diets entailing a 20% reduction in beef, lamb and dairy consumption by 2050, and a switch to poultry, pork and plant-based foods such as legumes and pulses.
    - Reducing avoidable food waste downstream of the farm-gate by 20% by 2025, with no further reduction. This is consistent with the WRAP's voluntary target.
    - Move 10% of horticultural crops off the land to an indoor production system only.

The combined effect of these assumptions is to release 25% of land out of agricultural production by 2050. Associated with this is a reduction in non-CO_2 emissions due to less cattle and sheep numbers and less grassland and cropland being fertilised. The shift to healthier diets and crop yield improvements have the biggest impact on land released. A reduction in cattle and sheep through diet change has the largest impact on agricultural emissions reducing these by 15% by 2050 compared to the business as usual.

The emissions reductions and carbon removals from using the land released out of agriculture for tree planting, peat restoration and other uses is set out in the LULUCF section.

Box 7.5. New evidence for non-CO_2 abatement in agriculture

We commissioned SRUC, ADAS and Edinburgh University to assess additional measures to reduce agriculture emissions. We also drew on evidence from Defra's Sustainable Intensification project.

We considered seven on-farm measures chosen from a longer list of measures on the basis that that they could provide significant technical abatement and be feasibly deployed by 2050, while avoiding potentially negative impacts on animal welfare. With the exception of high sugar grasses, analysing manure before application, and current breeding goals, current uptake of these measures is assumed to be zero:

- **High sugar content grasses (HSG):** planting HSG into a grassland-based dairy system has the potential to increase the nitrogen content released from the digested grass. This means less nitrogen is lost in urine, thereby reducing N_2O emissions. It is assumed the current uptake is 9% of dairy grassland area, and remaining potential is around 29%. Annualised costs associated with planting the seeds is put at £32/hectare.
- **Analyse manure prior to application:** analysis is undertaken to ensure nitrogen applied to crops and grassland matches crop requirements, thereby minimising N_2O emissions. Current uptake is assumed to be 23% and the remaining potential is for all non-winter sown crops and grassland. This measure is cost-saving.
- **Livestock breeding measures:** breeding programmes aim to select animals with beneficial traits (e.g. to improve health and fertility), which can also lower emissions intensity of production. Uptake can increase using current methods and two further measures. The savings from these measures take account of interactions:
  - Using current breeding goals to improve genetic material. Current uptake is around 25% for the dairy herd and lower for beef cattle.
  - Genetic improvement can be enhanced by using genomic tools in current breeding goals, which requires farmers to collect performance information on the individual animals and feed the information to breeding goal development.
  - Breeding for low methane intensity using genomic tools. Therefore selecting lower-emitting animals for breeding can reduce the methane emissions in subsequent generations.
- **Ruminant feed additive 3NOP (3-nitrooxypropanol):** adding this chemical to diets can reduce enteric emissions by inhibiting the production of methane in the rumen. This was found to reduce enteric methane emissions by 6-40% for dairy and 4-17% for beef cattle. This measure is applicable to all cattle, with uptake dependent on how long livestock are housed as the chemical is added to feed.
- **Nitrification inhibitors:** applied with nitrogen fertiliser, this measure inhibits the proportion of nitrogen that is converted to N_2O. We excluded this measure from our fifth carbon budget estimates as it was not found to be cost-effective against the carbon price. Costs still remain high (£1,500/tCO_2e) so we exclude this measure from our analysis for this report.

We also considered genetic modification of livestock but assigned this as a speculative measure given it is currently not legal within the EU, and yet to be proven.

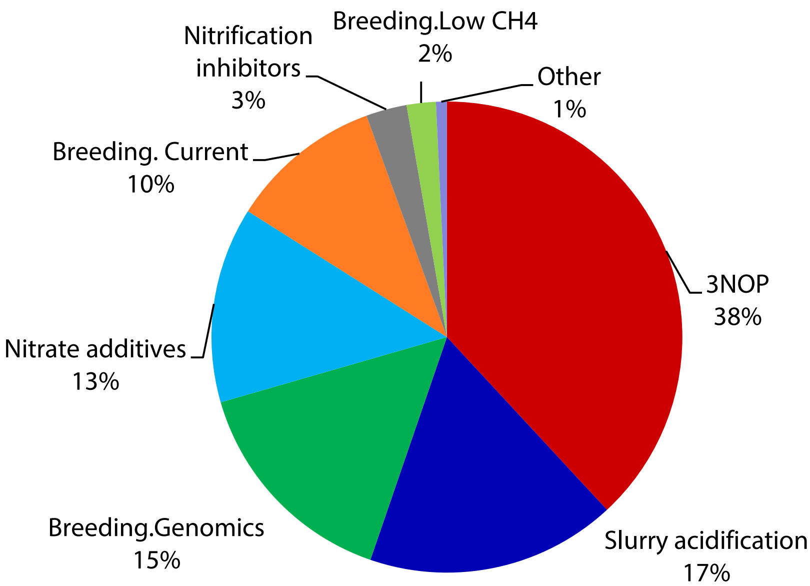
Estimates of emissions savings are based on the current agriculture Smart inventory methodology. This inventory methodology was also used to update the estimates for two measures in the fifth carbon budget: nitrate feed additives and slurry acidification.

Box 7.5. New evidence for non-CO_2 abatement in agriculture

Overall the updated and new analysis identified:

- A maximum technical abatement potential (i.e. before taking account of take-up) of 5.4 $MtCO_2e$ by 2050. 3NOP accounts for 38% of the savings, and the three breeding measures a further 28%, based on the business as usual land area and livestock numbers (Figure B7.5). All measures were less than £200/tCO_2e, with the exception of nitrification inhibitors.
- The emissions savings reduce by 22% after taking account of the reduction in agricultural land area and livestock numbers by 2050 under the Multi-functional land use scenario.

Figure B7.5. Share of maximum technical abatement potential by measure in 2050



Source: SRUC and ADAS (2018) *Non-CO_2 abatement in the UK agriculture sector by 2050;* CCC calculations.
Notes: Other include manure analysis, genetic modification of livestock and high sugar grasses. Emission estimates are based on the area of agricultural land and number of livestock consistent with the baseline in the land use report.

SRUC also undertook a literature review on the emissions associated with producing 'alternative' proteins for either livestock or human consumption to compare the carbon intensity of these products with existing protein sources:

- **Industrial production of microbial proteins:** Dried cells of micro-organisms such as algae, bacteria and fungi can be used as food and feed. The most well-known example of this is Quorn, launched in 1985. Producing mycoprotein is less emissions intensive than meat alternatives: 1.6-3.9 $kgCO_2e$/100 grams of protein compared with 4-41 $kgCO_2e$ for meat alternatives (with poultry the lowest and beef the highest). If used to displace crop-based feed for livestock, agricultural emissions could fall by 50-60%, excluding additional benefits from releasing land out of agriculture to other uses.
- **Insect feed for pigs and poultry:** Insects contain high levels of protein and macro-nutrients and are eaten widely by people in some parts of the world. They could potentially offer an alternative protein source for pigs and poultry. Over half of the emissions from production are due to energy

Box 7.5. New evidence for non-CO_2 abatement in agriculture

use (to regulate temperature, humidity and ventilation), with the remainder from feedstock (which can be minimised if using food waste) and methane emitted from the insects (depending on species type). Emissions intensity per kg of protein of housefly larvae and black soldier fly larvae were found to range 1.4-2.1 $kgCO_2e$ if fed on waste substrate compared to 4-41 $kgCO_2e$ for livestock.

- **Lab-grown meat:** Produced by taking tissue from animals to culture cells in the laboratory, this technology has been proven with creation of the first lab-grown burger in 2013. Compared to the meat alternatives, lab-grown meat has a higher energy use requirement, but assuming future energy sources will be low-carbon, the emissions intensity of lab-grown meat will become much more favourable than beef and lamb. Studies indicate that the current emissions intensity is around a tenth of that for beef, and there would be additional savings from releasing land out of agriculture. The challenge remains in scaling-up affordable production and gaining consumer acceptance.

We consider the scope for alternative proteins in our 'Speculative' scenario below.

Source: Tuomisto, H. L. and Teixeira de Mattos, M. J. (2011*) Environmental impacts of cultured meat production. Environmental Science and Technology 45;* Mattick, C. S., Landis, A. E., Allenby, B. R. and Genovese, N. J. (2015) *Anticipatory Life Cycle Analysis of in vitro biomass cultivation for cultured meat production in the United States. Environmental Science and Technology 49.*

Our findings and assumptions are in line with those of other recent assessments:

- The EU 2050 strategy to achieve carbon neutrality, published in 2018, included scenarios for agriculture that were similar to our analysis for technical on-farm abatement and diet change.[191] Resulting emissions reductions from these scenarios are in line with our assumptions.
- A report by Vivid Economics for the World Wildlife Fund in 2018 contained scenarios for reducing agriculture emissions by around 40%, and a 'collaborative' scenario which goes further on changing behaviour that included a 50% reduction in meat consumption.[192] These are within the range of the scenarios in the Committee's Land use report.

3. Scenarios for minimising emissions from the agriculture sector

(a) Opportunities for cutting emissions towards zero

As set out in Chapter 1, we have classified the options for cutting emissions towards zero in three categories:

- **Core options** are low-cost and low-regret options that make sense under most strategies to meet the current 80% target by 2050. For most, the Government has already made commitments or begun to develop policies (although in many cases these need to be strengthened).

[191] EU (2018) *A clean planet for all. A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy.*
[192] Vivid Economics (2018) *Keeping it cool. How the UK can end its contribution to climate change.*

- **Further Ambition options** are more challenging and/or more expensive than the Core options, but are all likely to be needed to meet a net-zero target.
- **Speculative options** currently have very low levels of technology readiness, very high costs, or significant barriers in gaining public acceptability. It is very unlikely they would all become available. Some of these options would be required to reach net-zero GHG emissions domestically.

Figure 7.3 shows how these options would reduce emissions from the agricultural sector.

Core options

The Core options are based on the set of measures identified in our fifth carbon budget. These cover a variety of on-farm practices to reduce non-CO_2 emissions from soils, livestock, waste and manure management and from reduced energy consumption in stationary machinery.

Many of these measures reflect current Government proposals, ambition in England (the Industry's GHG Action Plan) and in the DAs (Section 2 (b)). In some cases, they represent low-regret options required to meet an 80% target by 2050, where costs and barriers to implementation are relatively low (e.g. practices to improve efficient use of nitrogen).

The level of abatement in the Core scenario (4.9 $MtCO_2e$ by 2050) is less than the level in the Committee's fifth carbon budget cost-effective path (8.8 $MtCO_2e$) because we have assumed a lower level of uptake to reflect the lack of firm policy commitment in place by England and the DAs. The Core scenario results in residual agricultural emissions of around 38.6 $MtCO_2e$ by 2050.

Further Ambition options

Our 'Further Ambition' Scenario reduces emissions in agriculture by an additional 12.3 $MtCO_2e$ (32%) compared with the Core scenario:

- A further 2 $MtCO_2e$ of savings reduce emissions from mobile and stationary machinery to 0.3 $MtCO_2e$ by 2050:
  - Demand for natural gas is replaced with low-carbon electricity by 2050, some of which can be produced on-farm using renewable energy sources such as wind and solar. This is in line with ambition in the non-residential buildings sector (Chapter 3).
  - The majority of agricultural vehicles switch away from diesel and biofuels by 2050. Options include hydrogen and electricity powertrains, and the uptake of robotics. This reduces emissions by 90% which is in-line with ambition for off-road machinery in industry (Chapter 4).
- We assume a higher level of deployment for the on-farm practices than in the Core scenario and for new measures covering livestock identified in the SRUC led-analysis. Abatement savings take account of the reduced area of agricultural land and livestock numbers in the MFLU scenario by 2050. We assume a higher uptake rate by farmers (75% of the maximum technical potential) reflecting a strengthened policy framework. This results in additional savings of 3.8 $MtCO_2e$ by 2050 compared with the Core scenario.
- Moving to healthier diets away from beef, lamb and dairy and reducing avoidable food waste could deliver additional savings of 6.5 $MtCO_2e$ in agricultural non-CO_2 emissions by 2050.[193]

[193] This does not include emissions saved through changes in land use which is considered in the LULUCF section.

- Our Further Ambition Scenario includes a 20% reduction in the consumption of beef, lamb and dairy by 2050. This results in an 8% reduction in cattle and sheep numbers in the UK and a 23% decrease in grassland area by 2050. This results in emissions savings of 5.9 $MtCO_2e$, almost 70% of which is from enteric fermentation.
- Reducing food waste by 20% by 2025 saves around 0.7 $MtCO_2e$ in agricultural emissions by 2050. Savings are lower than for changing diets because of the composition of food that is wasted.[194] Fruit, vegetables, salad and drink account for over 40% of waste by weight which are less carbon intensive than arable crops and livestock. 84% of UK fruit demand is imported and does not produce emissions in the UK.

Combining all the above measures results in residual agricultural emissions of 26.3 $MtCO_2e$ in 2050. This is a 42% reduction compared to 2017 and would leave agriculture as the second largest emitting sector.

Additional work from Defra's Sustainable Intensification project could identify further abatement potential. We will consider results from this work and revisit the abatement savings in our Further Ambition Scenario in our policy report on agriculture and land use later this year.

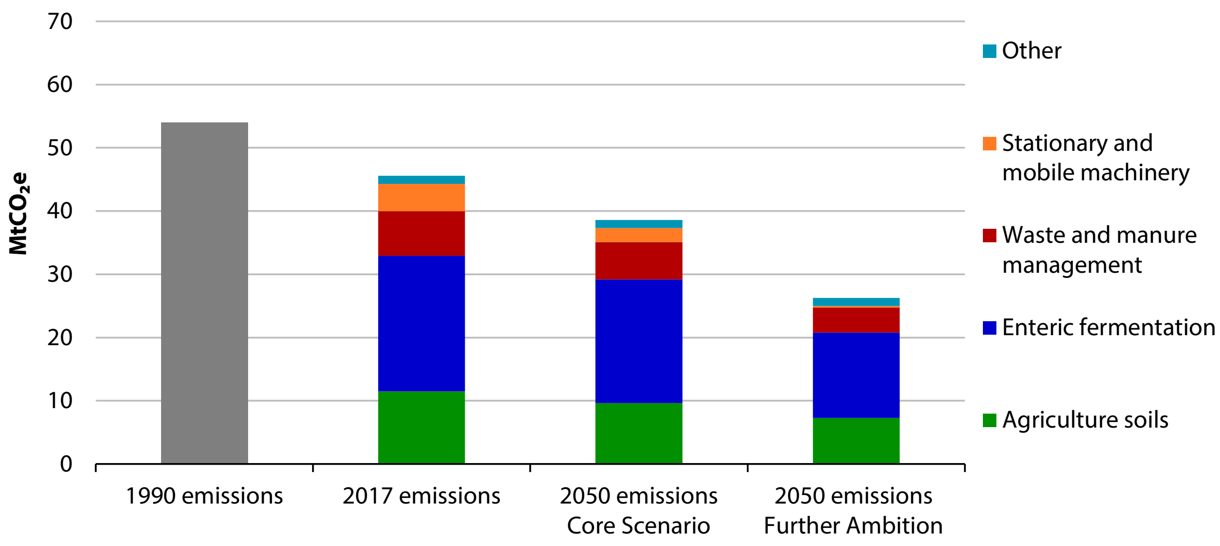
Speculative options

Additional abatement could emerge from a range of options that go further than the measures identified above. These rely on larger societal shifts in diets and food waste and higher adoption of more innovative options which, with time, could become technically feasible and gain wider public acceptability:

- Further livestock breeding measures (e.g. altering the genetic material) could deliver higher savings, but would require animal welfare and wider impact on ecosystems concerns to be addressed.
- A 50% reduction in the consumption of beef, lamb and dairy products could deliver 9 $MtCO_2e$ more in non-CO_2 savings by 2050. Under this scenario, the additional 30% reduction is assumed to be met with 'alternative' proteins produced off-farm (e.g. lab-grown meat and mycoprotein).
- A 50% reduction in food waste across the supply-chain could reduce non-CO_2 savings by an additional 1 $MtCO_2e$.
- Remaining fossil fuels used by agricultural vehicles could be replaced with synthetic fuels, but this is likely to be very expensive.

[194] WRAP (2013) *Household food and drink waste in the United Kingdom 2012.*

Figure 7.3. Scenarios for very deep emissions reductions from the agriculture sector



Source: BEIS (2019) *Final UK greenhouse gas emissions national statistics 1990-2017*; SRUC, ADAS and Edinburgh University (2019) *Non-CO_2 abatement in the UK agriculture sector by 2050*; and CCC calculations.

(b) Timing for cutting emissions towards zero

The fifth carbon budget (covering 2028-2032) already requires significant emissions reduction in agriculture. The cost-effective path that the Committee has identified includes the uptake of many of the measures set out in our Core scenario, but based on a much higher level of uptake (of around 85% compared with 45% in the Core scenario). If achieved this would reduce emissions by 16% (7.2 $MtCO_2e$) in 2030 compared to 2017.

However, achievement of these savings is at risk given the current voluntary approach in England and the DAs.

With a committed and well-designed policy it would be possible to deliver both the Core and Further Ambition options set out above by 2050:

- The post-CAP policy framework currently under development represents the largest opportunity to target non-CO_2 emissions reduction in agriculture. Proposals include:
  - The development of a new regulatory baseline reflecting the 'polluter pays' principle. This should provide an industry-wide standard for low-carbon farming, in addition to retaining the requirement for agricultural land and soils to be in good environmental condition.
  - A new Environmental Land Management Scheme (ELM) will provide public money for the provision of public goods, for actions over the regulatory baseline. Climate change mitigation and adaptation is one of the government's six proposed public goods.
  - Additional mechanisms and sources of funding to incentivise farm managers and land owners to improve environmental outcomes. These could include the use of reverse auctions and tendering to encourage private investment.

- Technology driven solutions, such as crop and livestock breeding options will require increased R&D investment and measures to get these to market in the 2020s.
- The assumption of a 20% reduction in food waste by 2025 is in line with ambition in Wales and Scotland, but would require further policies and measures across all countries to inform and enable producers, firms and consumers to reduce waste. These could include promoting waste avoidance more proactively, increasing availability of portion sizes for smaller households, and communications on avoidance techniques.
- There will need to be an acceleration in the shift towards healthier diets to achieve a 20% reduction in beef, lamb and dairy by 2050. There is a strong role for the retail sector in reducing the meat component in composite foods[195], active promotion and increasing the availability of plant based meals. The public sector should take a strong lead on their own estate (e.g. in schools and hospitals).

This assessment allows for various limiting factors on a realistic speed of change, without requiring significant levels of early capital scrapping:

- The uptake of low-carbon practices by farmers needs to increase beyond current levels in the 2020s and beyond. This will require new measures to address lack of knowledge, experience and skills of using low-carbon farming techniques and practices. Technology driven solutions for example, crop and livestock breeding will require increased R&D investment and measures to get these to market in the 2020s.
- The turnover of mobile machinery stock such as tractors is around 15-20 years, although there are older refurbished stock in the fleet from sales dating back to the1970s and 1980s. Near full decarbonisation by 2050 is possible if sales of new fossil machinery end around 2030. This would require sufficient supply of alternatively fuelled machinery and addressing infrastructure issues such as charging and 4G coverage for robotics.
- Transitioning to electric and hydrogen agricultural vehicles will benefit from market development of the same technologies for large on-road vehicles such as HGVs. However as the global market for agricultural vehicles is smaller than for HGVs, they may not be cost-effective on the same timescale and would require specialist manufacturers to develop them. They would need to be designed to match how they are used on-farm and ensure adequate and fast charging coverage in rural areas.
- Use of hydrogen could overcome some of the limitations associated with electrification, such as running time and power required to lift, pull and drag. This will rely on having a sufficient network of accessible hydrogen refuelling stations, trucking in hydrogen to farms and/or producing hydrogen on-farm from using renewables with electrolysers.
- Robots potentially represent a low-cost alternative to conventional tractors and other field machinery both in terms of up-front and running costs. Precision technologies could also deliver further savings through more efficient use of inputs and crop yield improvements. The need to commercialise this technology for wider adoption by farmers could be supported by the Government's Industrial Strategy, which has the application of digital technology as a key theme.

[195] A composite product is as a foodstuff that contains both processed products of animal origin and products of plant origin.

(c) Summary table of the opportunities to reduce emissions from agriculture towards zero

Table 7.1. Opportunities to reduce emissions from agriculture towards zero

Emissions source	2030 5CB residual emissions ($MtCO_2e$)	Further Ambition residual emissions in 2050 ($MtCO_2e$)*	Earliest date for Further Ambition emissions	2050 cost £/tCO_2e**
Agricultural soils	8.9	7.3	2050	-£82
Enteric fermentation	19.2	13.5	2050	-£118
Wastes and manure management	5.2	4.0	2050	-£167
Stationary and mobile machinery	2.0	0.3	2050	N/A
Other***	1.3	1.3	2050	-

Source: CCC analysis.
Notes: *Emissions in 2030 and 2050 include all residual GHGs (the Further Ambition column includes the emissions savings from diet change and food waste reduction, both of which are zero cost). **£/tCO_2e cost figures represent levelised costs of abatement of the measures in place in 2050, and are averaged across multiple abatement measures applied to the same emission source. *** Liming and urea.

4. Costs and benefits of achieving very deep emissions reductions in the agriculture sector

Our overall approach to assessing costs and benefits is summarised in Chapter 1 of this report and set out in full in Chapter 7 of the accompanying advice report.

Some of the low-carbon options included in our net-zero scenario for agriculture would avoid costs compared to the high-carbon alternative, whilst others are likely to be more expensive:

- Around 84% of the abatement in the Core scenario is cost saving for farmers through efficiency gains. The remaining 16% has a cost averaging £95/tCO_2e by 2050, which is cost-effective at the Government's existing carbon values. These measures include loosening compacted soils, controlled released fertilisers, improving sheep health and the use of nitrates as a feed additive.
- In the Further Ambition scenario, the non-CO_2 savings delivered through higher uptake of on-farm measures are cost-effective, averaging -£122/tCO_2e.
- We expect low-carbon options for stationary machinery such as robotics to be cost saving. The costs associated with transitioning from diesel powered vehicles to electric and/or

hydrogen are more uncertain but some models such as battery electric vehicles could become cost-effective from a social perspective during the 2020s. However there are large uncertainties around zero emissions infrastructure and fuel.

- Diet change and waste reduction measures in the Further Ambition scenario have a zero societal cost, but they could deliver cost-savings to consumers and some producers:
  - Oxford University modelled the costs of meeting the dietary requirements of the EatWell Guide (which has a much higher cut in the consumption of beef, lamb and dairy) and concluded that it could be delivered at no extra cost to the householder.[196]
  - In various studies commissioned by the multi-national group, Champions 12.3,[197] they found that concerted effort to prevent food waste amongst different players in the supply chain (e.g. restaurants, caterers and hotels) reduced costs. For example, a review of over 100 restaurants in 12 countries found that on average for every $1 invested in reducing food waste, the restaurants were able to save $7.[198]

Beyond the reduction of emissions, these measures can deliver additional benefits which have not been included in the above estimates:

- More efficient use of fertiliser can improve air and water quality, while avoiding soil compaction can improve soil function and crop yields.
- Adopting healthier diets can reduce the risk of developing long-term illnesses such as heart disease, Type 2 diabetes and some forms of cancer.

Some of these benefits are set out in Chapter 7 of the Net Zero advice report.

5. Delivering very deep emissions reductions in the agriculture sector

This section considers how the scenarios can be delivered, including the need to design policy to ensure UK industry is not competitively disadvantaged.

(a) What is needed to deliver the scenarios

Delivering the level of emissions in our Further Ambition scenario will require strong and effective Government leadership at all levels, supported by actions from people and businesses.

Table 7.2 summarises our assessment of the degree of challenge for the major opportunities to reduce emissions across a number of dimensions, in line with the approach set out in Chapter 1:

- There will need to be a high uptake of low-carbon farming practices and technologies. Government should ensure that this is fully incentivised through the post-CAP Environmental Land Management (ELM) framework, and include low-regret options in developing a strong regulatory baseline. New measures will also need to address the lack of knowledge, experience and skills of using low-carbon farming techniques and the high up-front costs of some measures.

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[196] Scarborough P, Kaur A, Cobiac L, et al. (2016) *Eatwell Guide: modelling the dietary and cost implications of incorporating new sugar and fibre guidelines.*
[197] Champions 12.3 is a coalition of Champions made up of executives from governments, businesses, international organisations, research institutions, farmer groups, and civil society dedicated to inspiring ambition, mobilising action, and accelerating progress toward achieving the target to halve food waste by half.
[198] Champions 12.3 (2019) *The business case for reducing food waste and loss: restaurants.*

- Innovation plays an important part in these scenarios. Continued investment is needed in R&D, testing and piloting of options to deliver agricultural productivity improvements such as sustainable high yielding crops and improvements in livestock health and diets; low-carbon fertilisers; use of genetics and breeding to improve crop and livestock productivity.
- There will need to be major societal changes towards healthier diets requiring increased public understanding of the climate impacts of our food choices. These will need active promotion from the retail sector in reducing the meat component in composite foods and to increase the range of plant-based meals. The public sector should take a strong lead, for example by providing plant-based and lower-meat options in schools and hospitals. This should be complemented with information and education campaigns to promote the benefits of moving away from red meat and dairy. More detail is set out in an accompanying report to the Net Zero advice report.[199]
- Gaining public acceptability of consuming 'alternative' protein sources including dairy substitutes and novel food sources produced off-farm (e.g. lab-grown meat and micro-algae).[200] This should build on the success to date of mycoprotein, where sales of Quorn products have increased with innovative product design coupled with a strong marketing campaign, appealing to both meat-eaters and vegetarians/vegans.
- Major societal change will also be required in reducing food waste across the supply chain - from farmers to manufacturers, retailers and consumers. These will require measures to promote waste avoidance more proactively, increased availability of portion sizes for smaller-sized households, and communications on waste avoidance techniques.
- Sufficient investment is needed to bring forward options for low-carbon agricultural vehicles and machinery e.g. tractors and robotics. This is a specialised part of the manufacturing sector and clear signals and support from government can provide industry with confidence to enable this transition. The roll-out of adequate infrastructure (e.g. electricity charging and 4G coverage) is likely to require government support.

Figure 7.4 sets out the timing for when key changes need to occur.

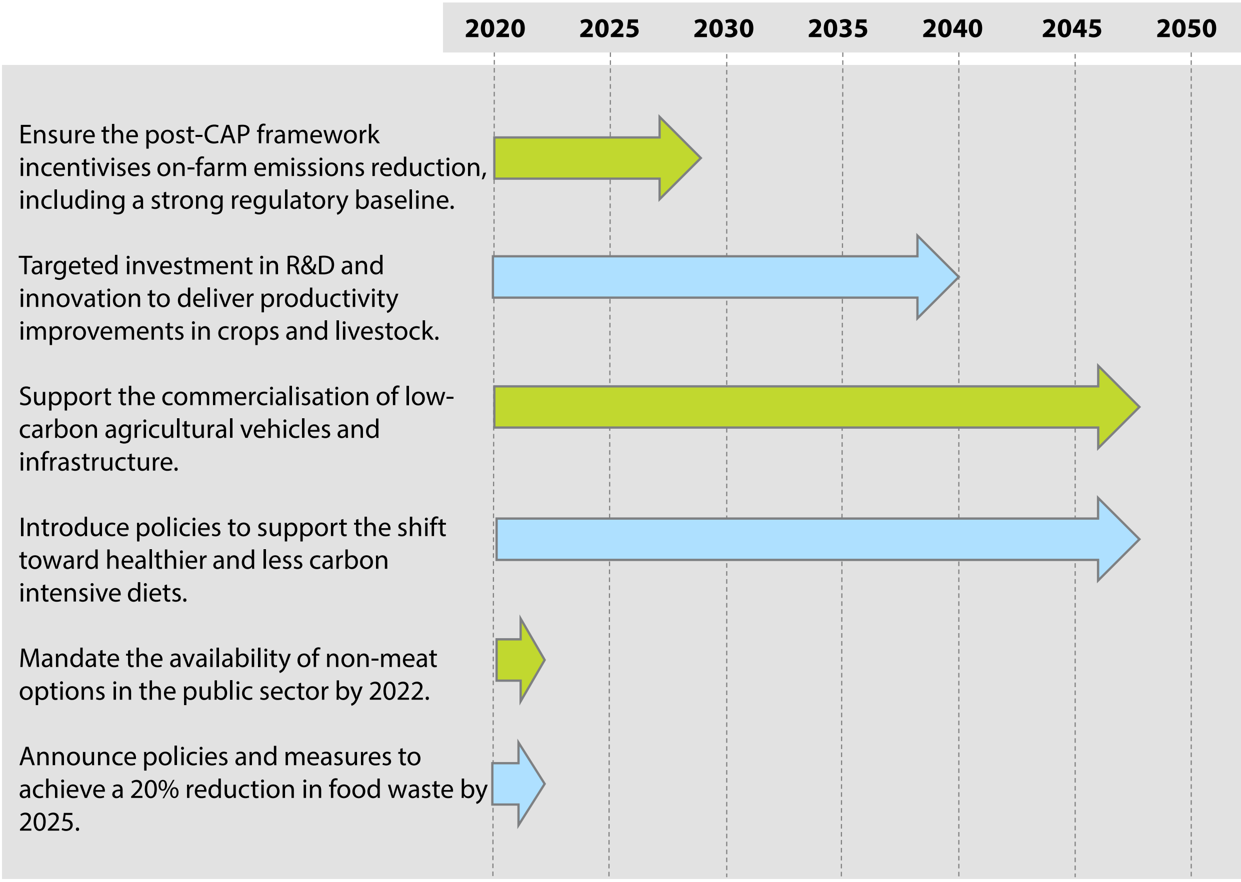
[199] CCC (2019) *Behaviour Change, public Engagement and Net Zero.*
[200] The Oxford Martin School, Oxford University (2019) *World Economic Forum's White Paper: Meat - alternative proteins.*

Table 7.2. Assessment of abatement options against dimensions of challenge for the agriculture sector

Emissions source	Abatement measures	Barriers and delivery risks*	Funding mechanisms	Co-benefits and opportunities
Agricultural soils	Crops and soil management practices	Farmer behaviour	Tax-payer funded Businesses	Air, water and soil quality Crop yields Efficiency savings
Enteric fermentation	Livestock health, diets and breeding	Farmer behaviour	Tax-payer funded Businesses	Livestock yields Efficiency savings
Wastes and manure management	Waste management practices	Farmer behaviour	Tax-payers Businesses	Air quality Efficiency savings
Stationary machinery	Electrification, on-site renewables, energy efficiency	Farmer behaviour	Cost-saving	Efficiency savings
Mobile machinery	Electrification, hydrogen, robotics and digital technology	Commercial deployment of technology, Infrastructure roll-out	Tax-payers Farmers	Air quality Crop yields
Diet change	Reduce consumption of beef, lamb and dairy by 20% by 2050	Consumer behaviour	Cost-saving	Health
Avoidable food waste	Reducing avoidable waste across the supply chain to households	Consumer and supply chain behaviour	Cost-saving	Efficiency savings

Source: CCC analysis.
Notes: The rating of measures in the table is based on the following criteria: 'barriers and delivery risks' are rated as 'red' if there is evidence that a given measure is particularly hard to implement, and 'green' or 'amber' otherwise; 'funding mechanisms' are rated as 'red' if the delivery of a given measure has high costs and these have a negative impact on businesses' competitiveness or are regressive on households, and 'green' or 'amber' otherwise; when there is evidence of positive 'co-benefits and opportunities' these are rated as 'green', otherwise no rating is given.

Figure 7.4. Timing of key decisions and changes to deliver the net-zero scenarios for agriculture



Source: CCC analysis.

(b) Key policy implications for driving deep emissions reductions from the agriculture sector

This report does not aim to identify a full policy package to deliver the scenarios set out above. However, there are important high-level policy implications that should be understood by Government and Parliament when considering the setting of a UK net-zero emissions target.

There is a need to implement a policy framework to translate existing proposals and ambition into firm delivery plans, and outline new policies that can cover the full range of measures we have identified in our Core and Further Ambition scenarios. This is particularly important in agriculture due to the lack of progress in reducing emissions to date and the lack of firm ambition or policy intent by Defra and the DAs. Policies should include:

- A post-CAP framework that incentivises the take-up of low-carbon farming practices and promotes transformational change in land that rewards land owners for the public goods required to deliver deep emissions reduction.
- Innovation and investment in R&D and testing and piloting of options to deliver agricultural productivity improvements, low carbon technologies and options for low-carbon agricultural machinery e.g. tractors and robotics.

- Measures aimed at shifting diets towards healthier alternatives including reducing beef, lamb and dairy products and reducing food waste. This includes information and advice; promotion of alternative food choices by retailers; proactive promotion of waste avoidance; and improved labelling and communications.
- Preparing for potential speculative options will rely on addressing concerns related to animal welfare and the wider impact on ecosystems from more advanced livestock breeding measures; the success of efforts across society to reduce food waste and switch diets; and more research on producing synthetic fuels.

The Committee's annual progress reports to Parliament include our detailed progress assessments. Our June 2018 report identified a number of areas where policy strengthening was required to deliver existing ambition.[201] These are a necessary condition to support the increased effort required to deliver a UK net-zero emissions target. We will report on progress against them in July 2019. The Agriculture and Land Use policy report at the end of this year will set out a more detailed assessment of policy options.

The following sections consider the land use, land-use change and forestry sector.

[201] CCC (2018) *Reducing UK emissions - 2018 Progress Report to Parliament.*

6. Current and historical emissions from the LULUCF sector

The land use, land use change and forestry (LULUCF) sector covers GHG emissions and removals from the use and change in use of different land types in the UK. The main land categories are cropland, forestry, grassland, wetlands and settlements. The inventory also includes carbon stocks of harvested wood products.

The sector was a net carbon sink of 9.9 $MtCO_2e$ in 2017, equivalent to abating 2% of UK GHG emissions. This is a 1% increase in the net sink compared to the previous year. The net sink has strengthened by around 10 $MtCO_2e$ since 1990 mainly due to a strengthening in the net forest carbon sink and a decline in net carbon losses from cropland (Figure 7.5).

Future revisions to the GHG inventory will switch the LULUCF sector from a net emissions sink to a net source:

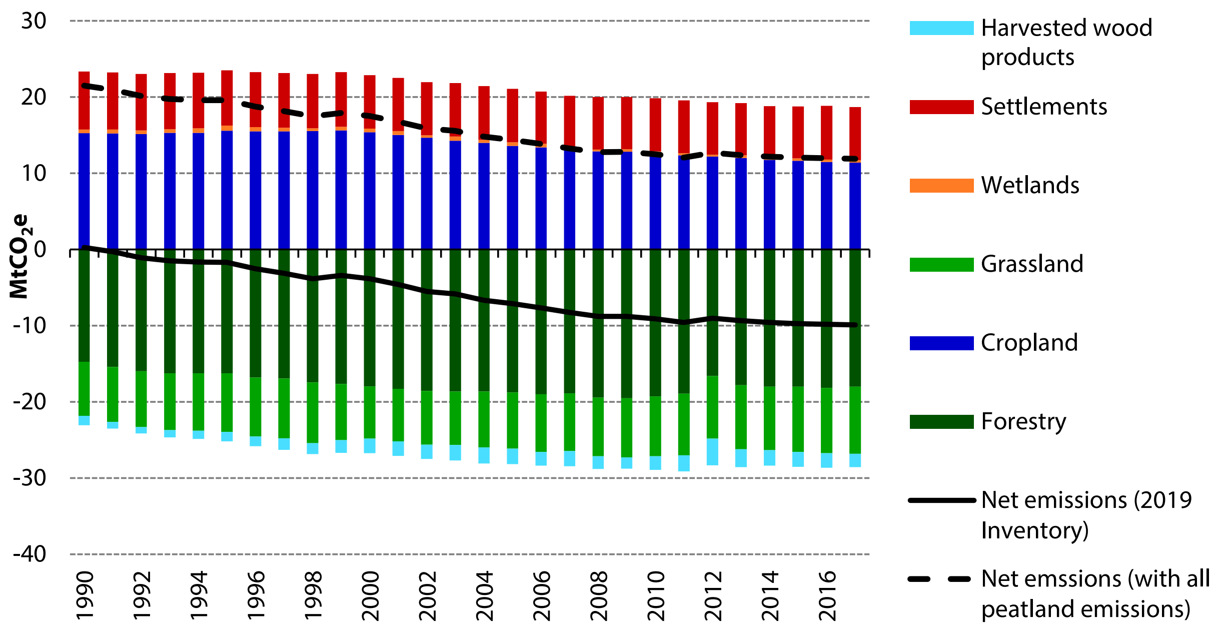
- The current inventory only captures about 1.3 $MtCO_2e$ of emissions from peatlands, but all sources of peatland emissions will be in the inventory from next year. Work by the Centre for Ecology and Hydrology (CEH) for the BEIS Wetland Supplement project,[202] estimate net annual emissions from all peatlands sources of between 18.5 and 23 $MtCO_2e$ in 2017.[203]
- The adoption of the new Global Warming Potential (GWP) values in the inventory in 2024 will increase methane emissions by 36% and leave N_2O emissions unchanged if the GWP values include for feedbacks on the carbon cycle.

Including all peatland emissions would leave the LULUCF sector a net carbon source of around 12 $MtCO_2e$ in 2017, rising to 13.7 $MtCO_2e$ with the new GWP values.

For the remainder of this chapter, our analysis is based on the assumption that peatland emissions are fully reflected in the LULUCF inventory. We adopt the upper end of the range for these emissions (23 $MtCO_2e$) based on the existing GWP values. This leaves the LULUCF sector a net carbon source of around 12 $MtCO_2e$ in 2017.

[202] Chris Evans et al. (2019) *Implementation of an Emissions Inventory for UK Peatlands.*
[203] This variance is due to the different approaches that are used to model forestry peat emissions. A decision on the approach to take will be made later this year by the National Inventory Steering Committee.

Figure 7.5. LULUCF emissions and removals (1990 -2017)



Source: BEIS (2019) *Final UK greenhouse gas emissions national statistics 1990-2017*; Chris Evans et al. (2019) *Implementation of an Emissions Inventory for UK Peatlands.*
Note: Estimates of net emissions (with all peatland emissions) is based on the higher value for forestry peat.

7. Reducing emissions in the LULUCF sector

(a) The current options to reduce emissions

Current efforts to increase carbon sequestration and slow the release of emissions have focused on afforestation and minimising carbon losses from degraded peatland:

- Woodlands currently accounts for 13% of UK land area. In the year to end March 2018, the level of new tree planting reached 9,100 hectares, of which 78% was in Scotland and 15% in England.
- Peatland accounts for around 12% of UK land area. A quarter of peatlands are in a near-natural or re-wetted state and are a small net carbon sink. The remaining peatland area is in various states of degradation and is classified by different land use types comprising upland grassland, lowland agriculture and forestry. Efforts to restore peatland have focused on the uplands and the removal of low-productive trees on forested peat[204] which have contributed to a 2% reduction in peatland emissions since 1990.

(b) Options for reducing emissions further

Under current commitments by Defra and the devolved administrations (DAs), net emissions could fall by 2.6 $MtCO_2e$ by 2030:

[204] Removal of low-productive trees off peatland can increase the overall carbon balance by allowing degraded peat to recover and reduce carbon losses.

- England and the DAs have an ambition to increase woodland creation, which if achieved, would deliver annual planting of 20,000 hectares by 2020, and 27,000 hectares from 2025. This saves 2 $MtCO_2e$ by 2030.
- There are proposals to increase the planting of trees on-farm, albeit by an unspecified amount. Agroforestry take-up has been extremely low to date. Arrangements under CAP have encouraged some planting on grasslands in Scotland, but this has not been the case in England and Wales. We estimate that this saves emissions of 0.6 $MtCO_2$ by 2030.

There are other opportunities to reduce land based emissions further. Deep emissions reduction in the LULUCF sector rely on fundamental changes in how land is used. These entail releasing land from agriculture to other uses such as increasing afforestation, planting energy crops, restoring peatlands and increasing agricultural diversification:

- **Increasing afforestation rates**. Historic UK tree planting rates suggests it is possible to go beyond the ambition set out by England and the DAs. Analysis for the Committee's land use report suggest a high ambition could achieve 50,000 hectares of new woodland per year. This is not far off the planting levels achieved in the early 1970s in England, Scotland and Wales, when including both afforestation and restocking of existing forested areas.
- **Improving forest productivity**. Options include:
  - Forestry management. Around 80% of broadleaf woodlands in England (74% of woodland area) are in an un-managed or under-managed state. Introducing sustainable management into neglected woodlands can enable young and better quality trees to thrive, which can allow for increased carbon sequestration. It can also increase resilience to wind, fire, pests and diseases, which could increase under a warming climate, thereby avoiding carbon losses from dead trees.
  - Improving forestry yields. Improving yields[205] of new woodland increases the amount of CO_2 sequestered and the volume and quality of the harvested wood. This can be achieved by adopting best practice in silviculture (e.g. good soil preparation and ensuring adequate protection for young trees against damage from deer), and the use of breeding and genetics to improve the nursery stock.
- **Planting energy crops.** Planting perennial energy crops (e.g. miscanthus and short-rotation coppice (SRC)) and short-rotation forestry (SRF) can deliver increased soil carbon sequestration, particularly if planted on arable land. In addition, once established, there is little requirement to apply fertiliser thus avoiding N_2O emissions. The current area of energy crops is only around 0.2% of UK arable area, while SRF for bioenergy is non-existent.
- **Diversification on-farm.** Options include:
  - **Hedgerows.** The current area of hedgerows on farms in the UK is around 120,000 hectares. Creating more hedgerows can deliver enhanced carbon sequestration in the biomass and the soils.
  - **Agro-forestry.** There are no official estimates on the amount of land used for agroforestry, but a reasonable proxy would be the use of trees and hedges for buffer strips alongside water courses, fruit production in shrubs and shelter belts. These account for about 1% of UK agricultural land. Agroforestry confers similar carbon sequestration benefits to hedges.

[205] Trees have different growth rates and levels of productivity as measured by their Yield class (YC).

- **Peatland restoration and management.** Options cover:
  - Lowland peat restoration. Lowland peat on cropland and grassland accounts for 14% of peatland area in the UK but is responsible for 56% of peat emissions. Emissions are between 30-39 tCO_2e/hectare compared with around 3 tCO_2e/hectare in the uplands. The savings potential from restoring lowland peatland is therefore more significant.
  - Management of lowland peat. Management practices such as seasonal re-wetting (the water-table is raised in the winter months when there are no crops on the ground) could reduce carbon losses from lowland peatland that remains in agricultural production.
  - Taking less-productive trees off peatland will improve the overall carbon balance by allowing the degraded peat to recover. It is estimated that Scotland accounts for around 80% of the UK peatland area that is forested with low-yielding trees of less than Yield Class 8, which would be good candidates for removal.

We exclude land management practices as a potential option to increase soil carbon on agricultural land on mineral soils. This is in line with existing evidence which finds that management practices have a limited role in increasing soil carbon on cropland,[206] and this is reflected in the current GHG inventory. Emerging evidence[207] for BEIS on grassland indicates that age is the most important factor determining the amount of carbon stored in grassland, but even then the amount of carbon will eventually reach an equilibrium, and may be reversible. Therefore, effort may be better placed on preserving existing stocks of soil carbon.

Options to deploy other greenhouse gas removal technologies on land, such as biochar and enhanced weathering, are considered separately in Chapter 10 of this report.

(c) Challenges in reducing emissions from different parts of the LULUCF sector

There are some sources of emissions in the LULUCF sector that are relatively easier to reduce, and which will have lower costs and fewer barriers. These include planting trees, albeit rates have been low to date and restoring some upland peat:

- Afforestation is an established practice and high levels of over 30,000 hectares/year were achieved in the late 1980s when supported by policy. It is also a cost-effective measure from a societal perspective.
- Active management is a common practice for conifer woodlands as they tend to be planted for productive means. Extending management into under-managed broadleaf woodlands could also provide harvested wood for fuel or timber.
- There are established practices in restoring uplands peat which can deliver multiple benefits:
  - Restoration costs vary widely depending on technique used, ease of access, and the level of damage at the site. In many cases restoration is not cost-effective from a carbon perspective alone (Box 7.6).
  - However, there is a range of other benefits that upland peat in good condition can provide, such as flood alleviation, improved soil and water quality, natural habitats for wildlife and biodiversity. A recent study of the economics of peatland restoration in

[206] CEH (2013) *Capturing cropland and grassland management impacts on soil carbon in the UK LULUCF inventory.*
[207] Ricardo (in preparation) *Development of the impact of grassland management on the UK LULUCF Inventory.*

Scotland found that benefits exceeded costs and supported the economic rationale of climate mitigation through peatland restoration. [208]

- Trees planted on-farm can deliver a range of benefits beyond emissions reductions such as improving soil quality and, if planted near water courses, enhanced water quality and provision of flood defences. There are also co-benefits from reduced fertiliser requirements and improved productivity for some crops. Trees on grassland can also provide shelter for livestock from the wind and heat.

Box 7.6. Upland restoration costs

The capital costs for restoring upland peat is highly variable and site specific. Costs largely depend on the level of degradation encountered and accessibility of the sites, which will determine the level and type of intervention required:

- Raising the water table can include various techniques to damn ditches, gullies and channels in the peat. For example, gully blocking with peat plugs is a cheaper option compared to installing stone damns.
- Bare peat, which represents the most degraded state will require more than one intervention. This could include work to first stabilise for erosion, before revegetation and restoration of the hydrology can take place.
- These costs rise significantly if helicopters are used to airlift equipment to the site.
- Barriers to changing the use of land are less than for lowland peat. In addition, there may be no requirement to pay for income forgone for those upland areas that are already under environmental stewardship schemes, which require the cessation of damaging practices (e.g. heather burning for grouse shooting).

In contrast to the upfront costs, on-going costs are less significant and are mainly associated with site inspection and monitoring by staff. There may be additional costs associated with pre-restoration work including archaeological and bat surveys.

Deep reductions in land based emissions depends on releasing land from agricultural use and using that land for emissions reduction and sequestration:

- **Afforestation.** Achieving consistently high afforestation rates would entail:
  - Scaling up the whole forestry supply chain, from increasing seed production and nursery capacity to grow the saplings, to having a skilled workforce to plant and manage the trees.[209]
  - Identifying appropriate sites for planting, which could include more remote areas requires building access roads and other forest infrastructure such as log yards and mills. The Forestry Commission has identified five million hectares of low risk areas for afforestation in England.[210]

[208] Klaus Glenk and Julia Martin-Ortega (2018) *The economics of peatland restoration*, Journal of Environmental Economics and Policy.
[209] The Confederation of Forest Industries estimate that 800 people would be needed to plant 40,000 hectares annually.
[210] Excludes Best and Most Versatile (BMV) agricultural land (Grades 1, 2 and 3a) and protected landscapes.

- Making tree planting an attractive investment opportunity given the high upfront costs and long pay back periods compared with faster growing crops.
- The approvals processes for planting trees are seen by many stakeholders as bureaucratic, complex and time-consuming.

- **Increasing forest yields.** Future challenges in raising yields include selecting area-appropriate species and species that are resilient to the impact of climate change, which are uncertain and vary geographically. Adoption of best practice in forest management is also needed.
- **Bioenergy crops.** The Committee's 2018 report on Biomass identified a range of regulatory, economic and technical barriers, as well as a lack of support and suitable incentives in home grown biomass sources.[211]
  - High establishment costs and delayed revenues from harvestable biomass can discourage production of both energy crops and forestry.
  - This combines with a lack of long-term policy certainty and low confidence in future market demand so that land managers often view biomass production as a high risk endeavour.
  - There is a lack of relevant agronomic advice on energy crop establishment and a lack of guidance for farmers and landowners on tree planting and management.
- **Lowland peat restoration.** Restoring lowland peat faces a number of economic and technical challenges:
  - High upfront costs of restoration options and variability of the condition of different sites makes it difficult for landowners to accurately estimate costs and impacts.
  - As much of lowland peat is on prime arable land, restoring it to a natural or semi-natural state has a high opportunity cost associated with lost agricultural production.
  - Seasonal re-wetting of the water tables may be constrained by the need to keep land permanently drained for continued flood management, while better understanding of the hydrology of the surrounding area is required to ensure that practices undertaken by one farmer do not impact a neighbouring farmer.
  - Lack of knowledge and skills among farmers and landowners to use and manage land differently (e.g. shifting from conventional crops to 'wet-farming').
  - The nature of the benefits of restoration means they are not obvious and visible to farmers.

Delivering these measures in order to achieve much deeper emissions reduction required for meeting the net-zero target will require the release of a substantial area of land out of agricultural use as set out in the agriculture section.

(d) The strengthened evidence base used in this report

For this report we have drawn on the evidence published in and alongside recent Committee reports: advice on the fifth carbon budget and the 2018 Land Use report.[212]

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[211] CCC (2018) *Biomass in a low-carbon economy.*
[212] CCC (2018) *Land use: Reducing emissions and preparing for climate change.*

Our trajectory for meeting the fifth carbon budget included cost-effective abatement from afforestation and planting trees on farms (agroforestry):

- Increasing the rate of tree-planting to around 15,000 hectares a year could deliver 1.8 $MtCO_2$ savings in 2030 in the UK. As carbon sequestration increases rapidly as trees mature, savings are estimated to more than triple to 7.2 $MtCO_2e$ by 2050.
- Planting trees on 1% of additional agricultural land by 2030 delivers annual savings of 0.9 $MtCO_2e$ by 2050.

The Committee's land use report considered how changes in the way land is used and managed could deliver deeper emissions reductions by 2050. This entailed releasing agricultural land through measures aimed at increasing productivity, shifting diets away from beef, lamb and dairy, reducing food waste and moving horticulture indoors. A key constraint to the modelling was that per capita food production is at least maintained at current levels by 2050. The results showed:

- Measures aimed at releasing land for other uses could result in 25-30% of land being released out of agricultural production. Alternative uses that allow for deeper emissions reduction include afforestation, peatland restoration and the planting of energy crops and trees on farm land (Box 7.7).[213]
- A shift towards healthier diets, improving crop productivity and increasing livestock stocking densities on grassland released the most land. (Figure 7.6).

The non-CO_2 agricultural savings from our land use analysis were covered in Section 2 (d). For the rest of this chapter we consider the reduction in carbon losses and the increase in the net sink arising from the changes to the use and management of land.

[213] The land use report used the lower estimate for peat emissions (18.5 $MtCO_2e$).

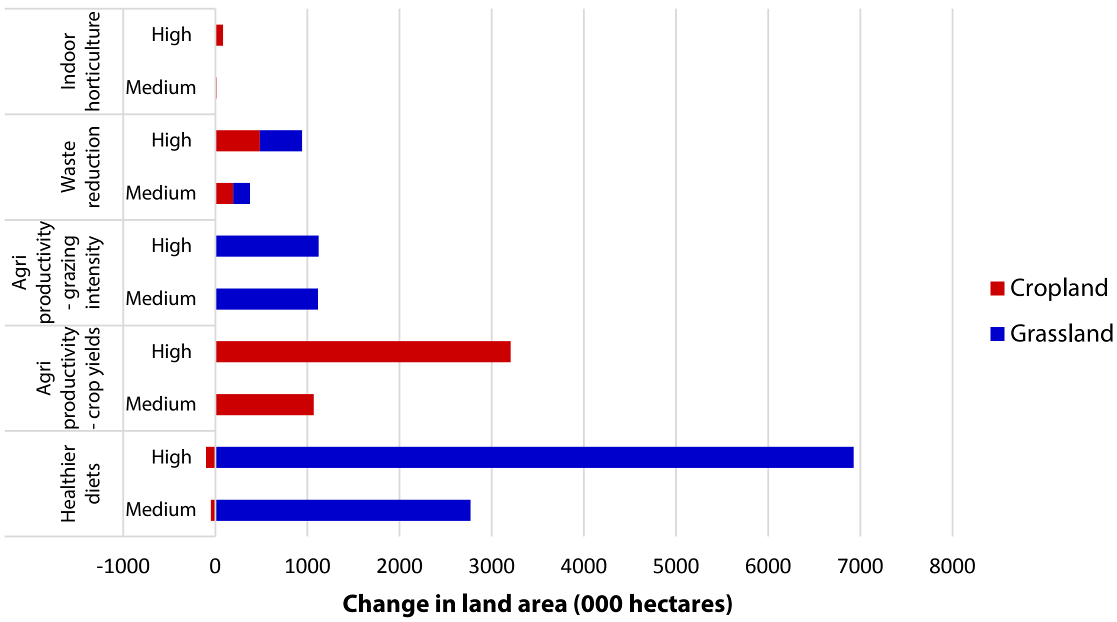
Box 7.7. Range of emissions savings from releasing land from agriculture for alternative uses

The land use report modelled a Business as usual (BAU), medium and high level of ambition for each land use change and land management option. The BAU level reflects current trends, but the medium and high levels go beyond this:

- Annual afforestation rates of between 30,000 and 50,000 hectares would increase woodland cover from 13% of UK land area currently to between 17% and 19%. This would deliver savings ranging 16.2 -27.5 $MtCO_2e$ by 2050.
- The area of restored peatland could increase from the current 25% to around 55-70% by 2050 reducing carbon losses from 18.5 $MtCO_2e$ to 10.7 -14 $MtCO_2e$. By 2050 we assume that peatland continues to remain a net source of emissions.
- The planting of energy crops on 0.7-1.2 m hectares of agricultural land, alongside more trees on 5-10% and hedges on farms, could deliver savings of 4.4 -8.4 $MtCO_2e$ by 2050.
- Additional savings were also quantified from increasing tree yields (by 10-20%), managing neglected broadleaf woodlands (67-80% by 2030) and seasonal management of the water table on lowland peatland that remains in agriculture.

Depending on the level of ambition for each of these options, the net carbon sink increase by between 16 and 36 $MtCO_2e$ by 2050 across the scenarios in the land use report.[214]

Figure 7.6. Agricultural land area released by different options compared with BAU, 2050



Source: CEH and Rothamsted Research (2018) *Quantifying the impact of future land use scenarios to 2050 and beyond*; CCC analysis.

[214] This includes the abatement savings relating to the use and management of land and excludes the non-CO_2 emissions savings in the agriculture sector.

Our findings and assumptions are in line with those of other recent literature:

- The joint report by the Royal Academy of Engineering and Royal Society on delivering net-zero carbon emissions in the UK by 2050 have similar estimates.[215]
  - They assume woodland area rises to 18% of UK land to deliver annual savings of 15 $MtCO_2e$ through afforestation by 2050.
  - The area of peatland restored (1 million hectares) is similar to our study, though net carbon sequestration is assumed to occur before 2050.
- Our planting assumptions for energy crops are broadly consistent with the levels adopted by the Energy Technologies Institute (ETI) based on work by ADAS to identify land for energy crops.[216]
  - Our medium level of ambition (0.7m hectares) is based on the ETI's low estimate, while our high ambition (1.2 m hectares) is lower than the ETI's central estimate of 1.4m hectares as our wider analysis concluded there was not enough land for energy crops and other competing uses.
  - A similar set of measures to free up land are considered including an increase in stocking densities and a 50% reduction in consumer food waste by 2050. The analysis did not consider the role for diet change or improvements in crop yields to release land out of agricultural production.
- A 2016 study modelled the agricultural land requirements and GHG emissions associated with supplying Western Europe with domestically grown food in 2050 under six dietary scenarios.[217] The results found that compared to a projected business as usual the six scenarios (which had varying levels and types of livestock/fish products in the diet from some to none) could release14-86% of agricultural land and reduce GHG emissions by up to 90%. All six scenarios assumed an improvement in crop yields, livestock efficiency improvements and a reduction in food waste, while still maintaining domestic regional production.

We reflect this new evidence along with our existing evidence base in our scenarios in section iii.

8. Scenarios for reducing emissions and increasing the net carbon sink in the LULUCF sector

(a) Opportunities for cutting emissions towards zero

As set out in Chapter 1, we have classified the options for cutting emissions towards zero in three categories:

- **Core option** are those low-cost and low-regret options that make sense under most strategies to meet the current 80% 2050 target. For most the Government has already made commitments or begun to develop policies (although in many cases these need to be strengthened).

[215] The Royal Academy of Engineering and the Royal Society (2018) *Greenhouse gas removals*.
[216] ADAS (2016) *Refining estimates of land for biomass.*
[217] E. Roos, P. Smith et al (2016) *Protein futures for Western Europe: potential land use and climate impacts in 2050.*

- **Further Ambition options** are more challenging and/or more expensive than the Core options, but are all likely to be needed to meet a net-zero target.
- **Speculative options** currently have very low levels of technology readiness, very high costs, or significant barriers to public acceptability. It is very unlikely they would all become available. Some of these options would be required to reach net-zero GHG emissions domestically.

Our baseline assumes that net emissions in the sector increase from around 12 $MtCO_2e$ in 2017 to 20.8 $MtCO_2e$ by 2050.[218] This increase is driven by a weakening of the forestry carbon sink (from -18 $MtCO_2e$ in 2017 to -7.6 $MtCO_2e$) due to the ageing profile of existing woodlands coupled with continuing low rates of afforestation.

Figure 7.7 shows how our options would reduce emissions under the Core and Further Ambition scenarios.

Core options

The Core options reflect current Government proposals and ambition in England and the DAs for afforestation, agro-forestry and forested peatland:

- Increasing woodland cover in the UK annually by 20,000 hectares between now and 2025, and to 27,000 hectares to 2030. If these planting rates are maintained to 2050, we estimate that the area of woodlands would increase to 15% delivering annual savings of around 11 $MtCO_2e$ by 2050. This increases the net forestry sink to 18.7 $MtCO_2e$.
- Our Core scenario adopts the Committee's fifth carbon budget assumption that planting trees on 1% of additional agricultural land by 2030 could deliver annual savings of 0.9 $MtCO_2e$ by 2050.
- Ambition to remove low productive trees (e.g. less than yield class 8) from 68,000 hectares of forested peat area in Scotland by 2029 could deliver savings of 0.7 $MtCO_2e$.

The level of abatement from afforestation in the Core scenario is higher than in our cost-effective path for meeting the fifth carbon budget. The difference reflects the higher ambition for tree planting by Defra and the DAs compared to the 15,000 hectares assumed for the fifth carbon budget.

The Core scenario reduces emissions from this sector by 60% against the baseline, leaving it a net emissions source of 8.2 $MtCO_2e$ by 2050.

Further Ambition options

Options in our 'Further Ambition' Scenario could reduce emissions by an additional 10.7 $MtCO_2e$ by 2050. This moves the sector from being a net emissions source of emissions to a small net sink of 2.5 $MtCO_2e$ in 2050.

The Further Ambition scenario is broadly based on the Multi-functional land use scenario from our land use report. This comprises:

- The medium level of ambition for releasing land from agriculture and options to use land differently (i.e. covering diets, waste reduction, agricultural productivity improvements and

[218] The LULUCF baseline for this report is based on the CEH baseline derived for the land use work, which includes all sources of peatland emissions. For the purposes of this report, the projection to 2050 has been rescaled to reflect outturn emissions for forestry in 2017 based on the latest GHG National Inventory (2019).

afforestation, planting energy crops, peatland restoration, improvements in tree productivity).

- A high level of ambition is assumed for agroforestry, hedge creation and forestry management.

These deliver additional savings compared to the Core scenario:

- For forestry, annual planting rates of 30,000 hectares by 2050 combined with a 10% productivity improvement of new stock could reduce emissions by a further 1 $MtCO_2e$. Actively managing 80% of broadleaf woodlands by 2030 would deliver a further 2.3 $MtCO_2e$ of savings. By 2050, this increases the net forestry sink to 21.9 $MtCO_2e$.
- Planting trees on 10% of farm land and extending hedges by 40% could reduce emissions by a further 5 $MtCO_2e$ by 2050.
- The planting of energy crops increases emissions by 1.5. $MtCO_2e$ by 2050.[219]
- Restoring 55% of peatland area reduces emissions by 4 $MtCO_2e$.
- Additional emissions savings accrue from using the harvested biomass from trees, hedges, and energy crops to displace more carbon intensive options elsewhere in the economy. Under the Further Ambition scenario, we estimate harvested wood products reach 19.8 million oven-dried tonnes, of which 76% is used for fuel and the remainder for longer-lived products, for example in construction. Chapter 5 of the advice report sets out how biomass is used across the economy, while Chapter 10 of this report considers the emissions savings from using these products as wood in construction.

To meet the demands of land for food, housing and the alternative land use options in our Further Ambition scenario requires the release of 3.8m hectares (22%) of agricultural land by 2050. This land release is achieved by:

- A move to healthier diets entailing a 20% shift away from beef, lamb and dairy.
- A medium level of improvement in crop productivity and increase in livestock stocking density.
- A 20% reduction in food waste by 2025.
- Moving 10% of horticulture crop to indoor systems.

The Further Ambition scenario reduces total emissions in the LUUCF sector by 23.3 $MtCO_2e$ by 2050 compared to the baseline, leaving the sector a small net carbon sink of 2.5 $MtCO_2e$.

Speculative options

Our modelling of changes in land use relies on options to release land for alternative uses and using that land for GHG mitigation. We matched land used with land released using three discrete pre-determined levels, representing low, medium and high ambition across factors. This construct of the modelling can result in more land being released than is required given

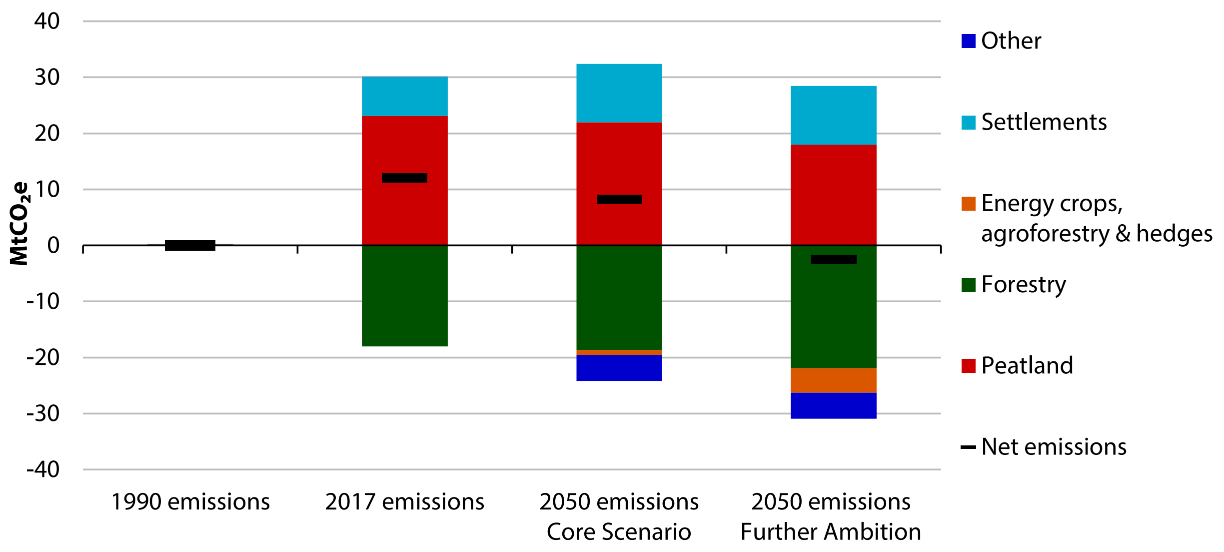
[219] This result reflects modelling that was undertaken by CEH which did not fully account for the carbon sequestration benefits of planting perennial crops on arable land thereby underestimating the emission savings, while overstating the emission losses from planting on grassland. Other studies indicate miscanthus could increase soil carbon stocks by around 50 tCO_2/hectare after 35 years. (e.g. Richards et al (2017) *High-resolution spatial modelling of greenhouse gas emissions from land-use change to energy crops in the United Kingdom*)

planting rates and other factors assumed. This is the case for the further ambition scenario which releases 15% (0.6m hectares) more land than is required to meet our Further Ambition scenario.

Deeper emissions reduction are possible by using this land for other uses and by going further on factors that release land from agriculture:

- If the 0.6m hectares of land released in the Further Ambition scenarios is used to plant more trees, annual planting rates could reach 47,000 hectares, which would lead to 9.6 $MtCO_2e$ of additional emissions savings by 2050.
- Increasing annual afforestation rates to our high level of ambition of 50,000 hectares could reduce emissions by an additional 1.7 $MtCO_2e$ of savings. This would require the release of more land out of agriculture than under the Further Ambition scenario. A 25% shift in diets away from beef, lamb and dairy could deliver the area of land needed.[220]
- Increasing the area of restored peatland in the uplands and lowlands to 75% and 50% respectively delivers an additional 3.5 $MtCO_2e$ of abatement by 2050.
- Seasonal management of the water table on 25% of lowland peat area could deliver a further reduction in peat emissions of 1.4 $MtCO_2e$ by 2050.
- Switching some crop production on lowland peat to paludiculture or 'wet-farming' (e.g. crops that can be grown in water) would allow the water table to be raised permanently and for emissions to fall compared to conventional crop production. There is on-going work by Defra to quantify what the emissions savings could be from this type of agriculture.[221]

Figure 7.7. Scenarios for very deep emissions reductions from the LULUCF Sector



Source: BEIS (2019) *Final UK greenhouse gas emissions national statistics 1990-2017*; CEH and Chris Evans et al. (2019) *Implementation of an Emissions Inventory for UK Peatlands;* CEH and Rothamsted Research (2018) *Quantifying the impact of future land use scenarios to 2050 and beyond*; CCC analysis.
Notes: Other includes net emissions sink/source from cropland and grassland.

[220] Assuming all other land release options are the same as in the Further Ambition scenario.
[221] Defra (on-going) *Managing agricultural systems on lowland peat for reduced GHG emissions whilst maintaining agricultural productivity.*

(b) Timing for cutting emissions towards zero

The fifth carbon budget (covering 2028-2032) already requires significant progress to increase the LULUCF net sink. The cost-effective path that the Committee have identified requires annual afforestation rates to be increased and for additional trees to be planted on farms. If achieved this would deliver:

- Annual afforestation rates rising to 15,000 hectares by 2030 compared with 9,100 hectares, achieved in the year ending March 2018.
- A doubling in the area of trees on farms to 2% by 2030.

Progress achieving the cost-effective path is currently off-track with existing funding streams not delivering on the required tree planting, and there is no policy to encourage trees to be planted on farms across the UK.

With a committed and well-designed policy effort it would be possible to deliver the Core and Further Ambition options set out above in full by 2050:

- In the short term, it will be important to ensure that existing funding schemes such as the Woodland Creation Scheme and the Woodland Carbon Grant encourage further tree planting.
- Development of the post-CAP policy framework to its full roll-out in 2027 represents the largest opportunity to reduce emissions and increase the net sink in the LULUCF sector by encouraging changes in how land is used. These should use public and private money to fund biomass options and peatland restoration:
  - The ELM should provide a strong incentive to deliver increased afforestation and peatland restoration in line with our Further Ambition scenario. These will deliver additional eco-system benefits such as clean air, clean water and avoiding hazards such as flooding.
  - Additional mechanisms and sources of private funding to incentivise land use change. For example, the proposed Forestry investment Zones (FIZ) is aiming to create the conditions that will attract private investment to plant large-scale productive forestry. This includes providing certainty as to where large-scale woodlands can be created and accelerating the approval process.
- Measures need to be put in place in the 2020s to address a range of non-financial barriers which constrain farmers in making the transition to different land uses. These cover inertia in moving away from the status quo; ensuring land owners and managers have the knowledge and training on what and how to plant; and potential disincentives to change practices among tenanted farmers, who account for around 30-40% of famers. Disincentives can arise due to the length of the tenancy (with an average tenancy of less than four years) and the terms of tenancy contracts, which can prohibit changing the use of land.
- Government should put in place measures to enable the release of land from agriculture whilst maintaining a strong agriculture sector. These include:
  - Proactive consumer focussed policies to support a shift in diets and reduce food waste.
  - R&D, testing and demonstration of measures to improve agricultural productivity (Section 3 (b)).

The scenarios we have set out for agriculture and land use imply radical changes to the way land is used in the UK. They rely on many changes being delivered concurrently along a path to 2050. This is challenging but our assessment allows for the various limiting factors on a realistic speed of change:

- Our assumptions on afforestation rates are in line with high planting rates in the 1980s. It may be possible to go further. Planting rates for bioenergy crops are challenging given the limited scale of planting in the UK currently but are deliverable with strong government ambition and policy. Our assessments for both allow for a ramp up over time to enable the supply chain to scale-up but it is critical that early action is taken to maximise emissions reduction and other benefits.
- Restoration of peatlands has mainly occurred in upland areas where there is less competing land use. Further work is needed in the uplands, especially as the remaining area left to restore is expected to include a higher share of the most degraded upland peat. But activity will also need to extend to lowland peat, where restoration could allow for some horticultural products to move into indoor systems. For peatland that remains in agricultural use, the England Peatland Strategy should set out the range of options that farmers could adopt to reduce emissions (e.g. seasonal management of the water table and paludiculture) and how they can be supported.
- The scale of the shift towards healthier diets and waste reduction in our scenarios will take time to achieve given the slow rate of change in recent years. Recent momentum on diets must be maintained through supply side measures and consumer-focussed policies.
- Increasing agricultural productivity and forestry yields relies on R&D and innovation which take time to reach commercialisation. Investment needs to start now for benefits to accrue in time.
- Looking beyond 2050, there is scope for increased contribution towards an economy-wide net-zero target:
  – Continuing with afforestation rates of 30,000 hectares beyond 2050 could deliver 4.8 $MtCO_2e$ more savings by 2060. This is increasing sequestration from trees planted in the 2020s and 2030s as they start to reach maturity.
  – Restoring peatland will continue to reduce emissions beyond 2050, and at some point could transition from a net source of emissions to a growing net sink. Unlike other soil types, well-functioning peatland is able to continuously accumulate carbon at an annual rate of around 1mm.

(c) Summary table of the opportunities to reduce emissions

Table 7.3. Opportunities to reduce emissions from LULUCF

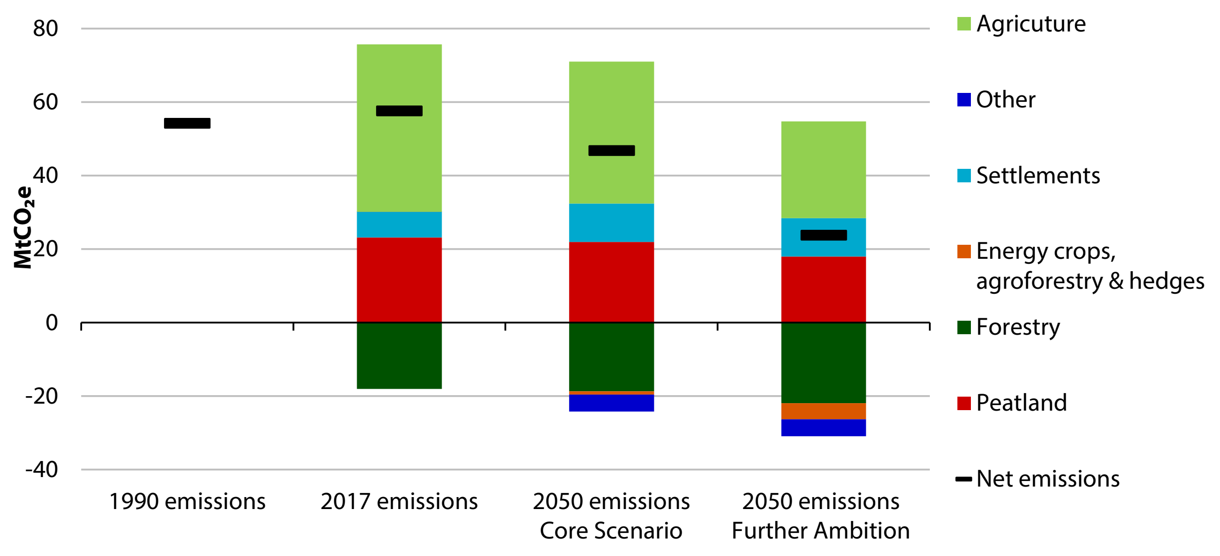
Emissions source/sink	2030 5CB residual emissions/ removals($MtCO_2e$)	Further Ambition residual emissions/removals in 2050 ($MtCO_2e$)	Earliest date for Further Ambition emissions	2050 cost £/tCO_2e
Tree planting*	-3.2	-16.2	2050	£12
Forestry management	-	-5.7	2050	-£52
Agroforestry and hedges	-0.6	-5.9	2050	£81
Energy crops	-	1.5	2050	N/A
Peatland	-	18	2050	£1,000 (£67-£5,883) (covers costs only, but will also deliver a range of benefits)**

Source: CCC (2018) *Land use: reducing emissions and preparing for climate change;* Forest Research (2012) *Marginal abatement cost curves for UK forestry (Table A3);* Okumah, M et al (2019) *How much does peatland restoration cost? Insights from the UK. University of Leeds - SRUC Report*; Artz, R.R.E. et al (2018) *Peatland restoration - a comparative analysis of the costs and merits of different restoration methods.* and CCC calculations.
Notes: Emissions in 2030 and 2050 include all GHGs; £/tCO_2e cost figures represent levelised costs of abatement of the measures in place in 2050, and are averaged across multiple abatement measures applied to the same emission source.. * Includes tree planting and yield improvement. **Upland restoration costs only.

(d) Combined residual GHG emissions in the agriculture and LULUCF sectors

Combined emissions in the agriculture and LULUCF sectors under the Core and Further Ambitions scenarios reach 46.8 $MtCO_2e$ and 23.8 $MtCO_2e$ respectively by 2050 (Figure 7.8).

Figure 7.8. Scenarios for very deep emissions reductions from the agriculture and LULUCF sectors



Source: BEIS (2019) *Final UK greenhouse gas emissions national statistics 1990-2017*; CEH and Chris Evans et al. (2019) *Implementation of an Emissions Inventory for UK Peatlands;* CEH and Rothamsted Research (2018) *Quantifying the impact of future land use scenarios to 2050 and beyond*; CCC analysis.
Notes: Other includes net emissions sink/source from cropland and grassland.

9. Costs and benefits of achieving very deep emissions reductions in the LULUCF sector

Our overall approach to assessing costs and benefits is summarised in Chapter 1 of this report and set out in full in Chapter 7 of the accompanying advice report.

Some of the low-carbon options included in our Further Ambition scenario would avoid costs compared to the high-carbon alternative, whilst others are likely to be more expensive.

- Planting trees is cost-effective from a societal perspective, with estimates ranging between -£50 and 40/tCO_2e.[222] The range does not include non-carbon benefits that trees can deliver such as flood alleviation, air and water quality improvements.
- The capital costs of restoring upland peatland will vary significantly according to the level of degradation, restoration techniques and accessibility of the site:
  – A 2019 study found a median abatement cost of £1,009/tCO_2e with a range of £74 to £5,883/tCO_2e across more than ten different types of restoration.[223] This is slightly higher

[222] Forest Research (2012) *Marginal abatement cost curves for UK forestry (Table A3).*
[223] Okumah, M et al (2019) *How much does peatland restoration cost? Insights from the UK. University of Leeds – SRUC Report.*

than a study of sites in Scotland which had an average cost of £880/tCO_2e (£67-£2,425/tCO_2e).[224]

 – The wide variability in costs reflects a wide range of restoration technique as well as other factors such as site characteristics, location of the intervention, land ownership, restoration time-frames, and costs of pre-restoration interventions.

 – These estimates do not take account of the wide range of other benefits that peat in good condition can deliver, such as improving water filtration and enhancing biodiversity. These are difficult to quantify but would justify current restoration projects. Restoration of damaged upland peat in a case study of Moor House and Upper Teasdale suggests a NPV of £8,400 per hectare.[225] A further study setting out an ex-post evaluation of two different peatland restoration projects of different conditions, resulted in positive cost:benefit ratios using average benefit estimates.[226]

- The upfront costs for planting perennial energy crops, which can be twice that of annual arable crops are due to the cost of propagating the planting material (e.g. rhizomes and woody cuttings). For miscanthus, total establishment costs with rhizomes average £2,300/hectare in the UK, while SRC willow costs can range £1,500-1,700/hectare.[227] For miscanthus, there are opportunities to reduce this by switching from rhizomes to seeded hybrids. Although trials using seeded hybrids reduces the establishment costs slightly, it allows for faster upscaling of the planting rates (e.g. increase current multiplication from 20 with rhizomes to over 2,000). This means, one hectare of seeds can grow 2,000-4,000 hectares annually.
- Best practice in forestry silviculture and crop agronomy could cost-effectively deliver the increase in yields under the Further Ambition Scenario. These practices typically reflect better management, such as soil preparation, selecting the right tree to take account of soil moisture and for crops selecting the optimum planting period.
- The diet change and waste reduction measures in the Further Ambition scenario are cost neutral from a societal perspective (Section 4).

Beyond the reduction of emissions, these measures can deliver additional benefits not included in this chapter (see Chapter 7 of the advice report).

10. Delivering very deep emissions reductions in the LULUCF sector

This section considers how the scenarios can be delivered, including the need to design policy to ensure UK industry is not competitively disadvantaged.

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[224] Artz, R.R.E. et al (2018) *Peatland restoration - a comparative analysis of the costs and merits of different restoration methods.*
[225] CCC (2018) *Land use: Reducing emissions and preparing for climate change*
[226] Klaus Glenk and Julia Martin-Ortega (2018): The economics of peatland restoration, Journal of Environmental Economics and Policy, DOI: 10.1080/21606544.2018.1434562
[227] John Clifton-Brown et al (2018) *Breeding progress and preparedness for mass-scale deployment of perennial lignocellulosic biomass crops, switchgrass, miscanthus, willow and poplar.*

(a) What is needed to deliver the scenarios

Delivering the level of emissions reduction in our Further Ambition scenario requires fundamental changes to the way land is used and managed. This will require strong and effective Government leadership at all levels, supported by actions from people and businesses.

Table 7.4 summarises our assessment of the degree of challenge for the major opportunities to reduce emissions across a number of dimensions, in line with the approach set out in Chapter 1:

- **Addressing the key barriers to transitioning to different patterns of land use and management**. There is a pressing need to address financial and non-financial barriers, given some of the measures such as tree planting and peatland restoration take time to deliver emission savings:
  - **Financial barriers:** The new environmental land management policy should support a move towards alternative land uses and reward land-owners for public goods that deliver emissions reduction. In addition, new mechanisms need to be developed to unlock private sector investment to support the high up-front costs and long-term pay-back of adopting alternative uses of land. The proposed Forestry Investment Zone is one example being developed by Defra and the Forestry Commission, but action is needed to `progress plans; identify suitable catchments for large scale woodland creation, and attract stakeholder investment.
  - **Non-financial barriers:** Land owners and managers will need support to address the lack of knowledge, experience and skills on how land can be used differently. This should cover knowing what and how to plant and on-going management. There could be a role for an advisory service to provide support. Tenants account for a large share of farms, and policy will be required to address their needs. For example, resolving tenancy contracts could allow and encourage tenanted farmers to undertake long-term investment decisions.
- **Role for technology and innovation:** Ensuring adequate investment to improve both crop and forest productivity, and resilience to the impact of climate change through the use of breeding and genetics. There is also a need to consider actions to shorten the time between R&D and commercial deployment to ensure that the benefits can contribute in a timely manner.
- **Behavioural change among consumers and the supply chain**: These have already been set out in Section 5 (a).

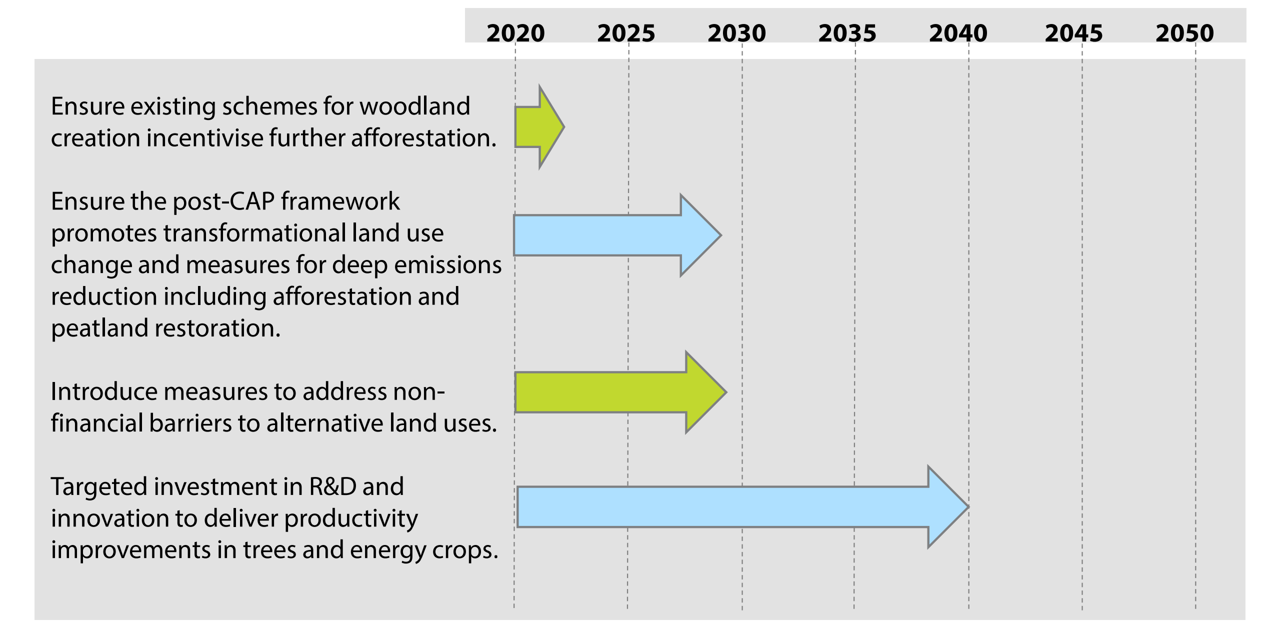
Table 7.4. Assessment of abatement options against dimensions of challenge for the LULUCF sector

Emissions source	Abatement measures	Barriers and delivery risks*	Funding mechanisms	Co-benefits and opportunities
Forestry	Tree planting Yield class improvement Forestry management	Land owner/manager behaviour Skills, knowledge and training R&D investment	Tax-payer funded Businesses	Air, water and soil quality Flood alleviation Recreational amenity
Peatland	Restoration Management practices on lowland peat Paludiculture	Land owner manager behaviour Hydrological challenges	Tax-payer funded Businesses	Water quality Biodiversity Flood alleviation
Agroforestry and hedges	Trees on crop and grassland Extending hedgerow length	Farmer behaviour	Tax-payer funded Businesses	Animal welfare Biodiversity Water and soil quality
Energy crops and SRF	Bioenergy crops Short-rotation forestry	Commercial scale-up of hybrid seeds for miscanthus	Businesses	Harvested products Biodiversity if planted on arable land

Source: CCC analysis.
Notes: The rating of measures in the table is based on the following criteria: 'barriers and delivery risks' are rated as 'red' if there is evidence that a given measure is particularly hard to implement, and 'green' or 'amber' otherwise; 'funding mechanisms' are rated as 'red' if the delivery of a given measure has high costs and these have a negative impact on businesses' competitiveness or are regressive on households, and 'green' or 'amber' otherwise; when there is evidence of positive 'co-benefits and opportunities' these are rated as 'green', otherwise no rating is given.

We set out below the timings for key decisions to deliver the net-zero scenarios in the LULUCF sector (Figure 7.9).

Figure 7.9. Timing of key decisions and changes to deliver the net-zero scenarios for the LULUCF sector



Source: CCC analysis

(b) Key policy implications for driving deep emissions reductions from the LULUCF sector

This report does not aim to identify a full policy package to deliver the scenarios set out above. However, there are important high-level policy implications that should be understood by Government and Parliament when considering the setting of a UK net-zero emissions target:

- Develop a post-CAP framework that promotes transformational change in land use and management that rewards land owners for the public goods required to deliver deep emissions reduction, and facilitates private sector investment.
- Improve incentives to promote best practices in agronomy and silviculture, coupled with R&D investment in breeding and genetics to bring forward crops and forestry yield improvements.
- Pro-active consumer focussed policies to support a shift in diets and reduce waste.
- R&D, testing and demonstration of measures to improve agricultural productivity (Section 3 (b)).

The Committee's annual progress reports to Parliament include our detailed progress assessments. Our June 2018 report identified a number of areas where policy strengthening was required to deliver existing ambition. These are a necessary condition to support the increased effort required to deliver a UK net-zero emissions target. We will report on progress against them in July 2019.

Chapter 8: Waste

Introduction and key messages

This chapter sets out the scenarios for the waste sector that inform the Committee's advice on reviewing long-term emissions targets for the UK, Scotland and Wales. It draws on new research on the potential and costs of reducing landfill and waste water treatment emissions.

The key messages from this chapter are:

- **Background.** Emissions from waste were 20.3 $MtCO_2e$ in 2017, 4% of total UK greenhouse gases (GHGs). Key sources of waste emissions are methane emissions from the decomposition of biodegradable waste in landfill sites; emissions produced from treatment of waste water; and from biological treatment, composting and incineration of waste.
- **'Core' measures.** Five key[228] biodegradable waste streams are diverted from landfill in England, Wales and Northern Ireland by 2030 and in Scotland by 2021 alongside an increase in recycling in line with ambition set out in England and the Devolved Administrations (DAs).
- **'Further Ambition' measures.** Our Further Ambition scenario additionally involves:
  - A 20% reduction in avoidable food waste by 2025, in line with scenarios used in the land use sector.
  - Key bio-degradable waste sent to landfill is eliminated earlier, by 2025 at the latest.
  - An increase in re-cycling rates of all municipal waste across England and the DAs to 70% by 2025 or in line with stated ambition if earlier.
  - Improved efficiency of waste water treatment plant to achieve at least a 20% reduction in waste water handling emissions by 2050.
- **Costs and benefits.** The reduction in avoidable food waste is cost saving to households and firms involved in food production and hospitality. The costs of eliminating bio-degradable waste to landfill and increasing recycling rates are uncertain, but cost-effective at current carbon values. Optimising existing water treatment operations and processes is low-cost. More advanced technological solutions are likely to have higher costs. There are considerable co-benefits of these measures including resource efficiency in land use, manufacturing and hospitality; a reduction in toxins and leachate and improvement in soils and ground water quality; and the production of biogas, compost and digestate for fertiliser use.
- **Delivery.** The following priority actions should be taken as soon as possible to support the transition to zero emissions across waste management:
  - Government and the DAs should legislate a mandatory ban on biodegradable waste from key waste streams going to landfill by 2025 at the latest. In order to achieve this, separate waste collection should be introduced by 2023 and supporting measures to increase municipal recycling rates to 70% by 2030 at the latest.
  - Policies and measures should be introduced to achieve a 20% reduction in avoidable food waste by 2025 including more proactive waste avoidance measures.
  - Government and the DAs should work with waste water companies to develop a strategy to reduce non-CO_2 emissions from waste water handling by at least 20% by 2050.

[228] Food, paper and card, wood, textiles and garden waste.

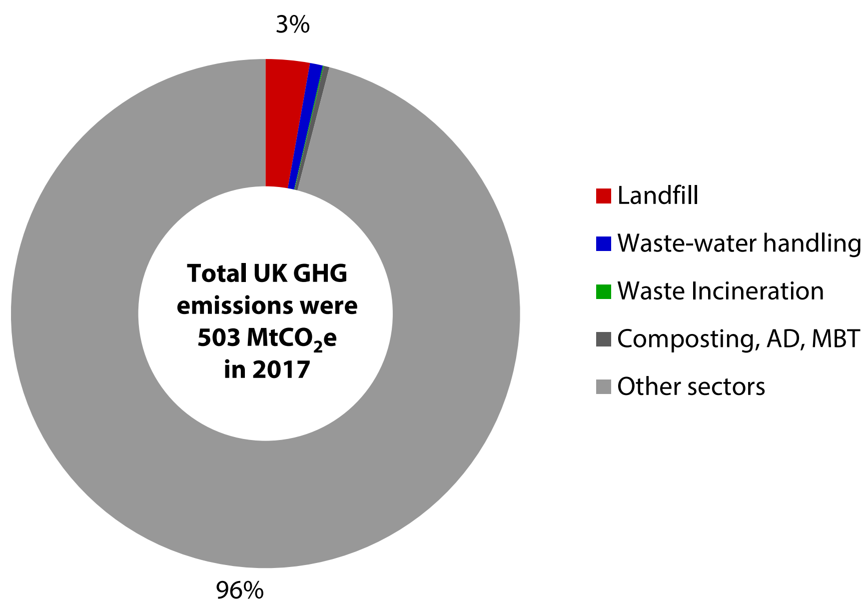
We set out our analysis in five sections:

1. Current and historical emissions from waste.
2. Reducing emissions from waste.
3. Scenarios for minimising waste emissions.
4. Costs and benefits of delivering very deep emissions reductions in the waste sector.
5. Delivering very deep emissions reductions in the waste sector.

1. Current and historical emissions from waste

In 2017 GHG emissions were 20.3 $MtCO_2e$, accounting for 4% of UK GHGs.[229] Waste emissions are predominantly methane (92%) which arise due to the decomposition of biodegradable waste in landfill sites in the absence of oxygen. Emissions also arise from wastewater treatment, biological treatment and incineration of wastes, with a small amount from other waste disposal methods (Figure 8.1).

Figure 8.1. Emissions from waste in 2017

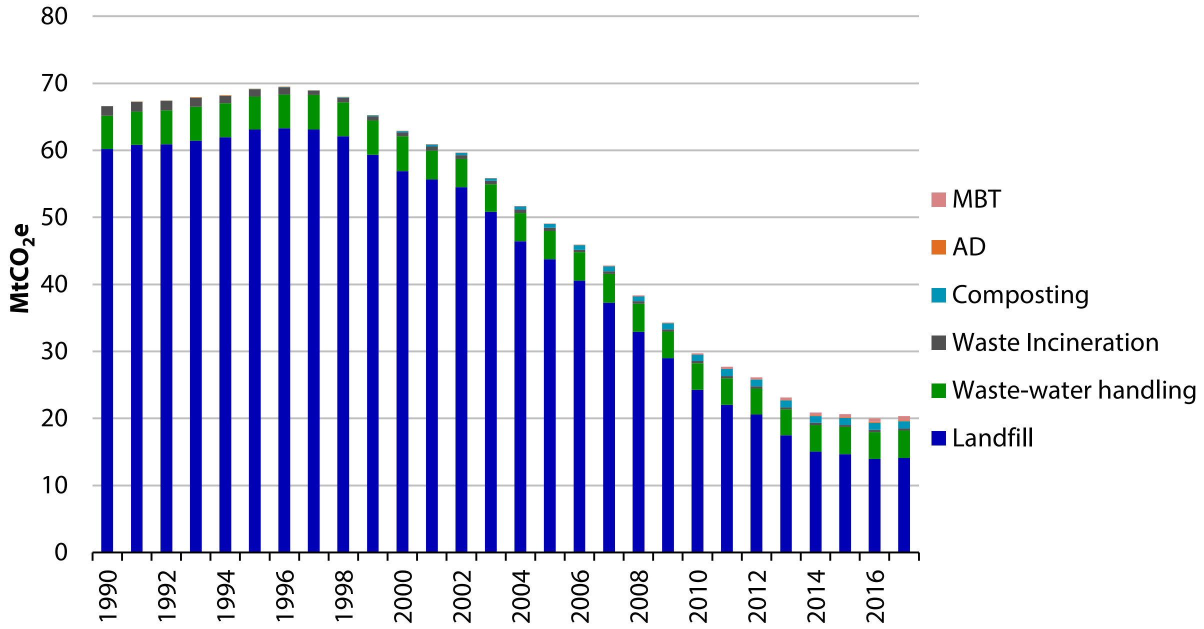


Source: BEIS (2019) *Final UK greenhouse gas emissions national statistics 1990-2017.*

Emissions have decreased by 70% between 1990 and 2017 largely driven by reduced biodegradable waste going to landfill, investment in methane capture technology and improved management at landfill sites. Waste emissions increased by 0.3 $MtCO_2e$ (1.5%) in 2017, due to higher emissions from landfill and waste water treatment. Emissions from composting, mechanical biological treatment (MBT) and Anaerobic Digestion (AD) are a relatively recent source of GHGs, with composting first recorded in the inventory in the mid-1990s, with MBT and AD following in the next two decades (Figure 8.2).

[229] The total includes emissions from International Aviation and Shipping.

Figure 8.2. GHG emissions from waste by source (1990-2017)



Source: BEIS (2019) *Final UK greenhouse gas emissions national statistics 1990-2017.*

Future estimates of agricultural emissions will increase when the IPCC's revised Global Warming Potential (GWP)[230] values for methane and N_2O are adopted in the GHG inventory by the end of 2024:

- Methane GWP will increase from the current 25 to 28 (or 34 if the feedbacks on the carbon cycle are included).
- N_2O GWP will reduce from 298 to 265, but remain unchanged at 298 if feedbacks on the carbon cycle are included.

On the basis that the carbon feedbacks are included for estimating both methane and N_2O emissions, the new GWP values would result in 2017 waste emissions being 20% higher (4 $MtCO_2e$) than estimated under the current methodology.

2. Reducing emissions from waste

Emissions from waste have decreased by 69% since 1990. However, achieving net-zero emissions in landfill is challenging mainly because of the difficulty in further reducing methane emissions from landfill and tackling emissions from waste water treatment.

(a) Options for reducing emissions further

Landfill emissions

Measures aimed at reducing emissions from landfill sites focus on waste prevention, waste diversion and methane capture.

[230] IPCC (2014) *The Fifth Assessment Report (AR5).*

Waste prevention

Waste prevention offers substantial upstream environmental and economic gains associated with resource efficiency, beyond the benefits of reducing methane emissions from landfill. There are benefits to households, businesses and local authorities from preventing waste arising:

- WRAP[231] estimate that around a quarter of food purchased by households and businesses in the UK is wasted, worth around £15 billion per year to households and £5 billion to firms.
- It is estimated around £150 million worth of clothing goes to landfill each year.[232] Clothing has a significant carbon, water and waste product life-cycle.
- The UK uses five million tonnes of plastic each year, nearly half of which is packaging. Plastic waste does not decompose and can last for hundreds of years in landfill, soils and oceans, damaging natural habitats and essential ecosystems.

Defra and the DAs have acknowledged the value of materials through the supply chain and the benefits from resource efficiency and a circular economy which aims to maximise use of resources through re-use, repair, remanufacture, refurbishment and re-selling of goods. There are benefits for producers through becoming more efficient and paying less for resources; the environment through reduced landfill and carbon emissions further up the supply chain; taxpayers and local authorities (LAs) through lower costs of waste disposal; and society in general through protection of natural resources.

Opportunities for waste prevention occur throughout a product life-cycle. Actions include:

- Minimising waste through process design, material efficiency and optimising manufacturing processes.
- Improved design to expand the lifespan of products and to enable materials to be separated, repaired, remanufactured or re-used.
- Use of schemes to encourage resource efficiency, such as producer responsibility and take-back schemes.

Chapter 4 of the technical report sets out estimates of resource efficiency opportunities in industry and the upstream impact on GHG emissions.

Waste diversion

Where waste cannot be prevented, there is potential to reduce emissions through diverting biodegradable waste away from landfill to other treatment options. This would also contribute to a circular economy through recovering and regenerating materials at the end of life:

- **Re-cycling**. Processing different waste streams (e.g. plastics, glass and paper/card) into new products can reduce the use of raw materials as well as emissions from waste processing (e.g. incineration). Diverting biodegradable waste streams such as food, paper and card avoids landfill emissions.
- **Composting.** Composting can be used to treat food and green waste. If properly managed, organic waste in a compost pile will decompose in the presence of oxygen (i.e. aerobically rather than anaerobically) and will produce (biogenic) CO_2 instead of methane. The compost

[231] WRAP(2018) *Food Surplus and Waste in the UK - Key Facts.*
[232] WRAP http://www.wrap.org.uk/content/clothing-waste-prevention

can be applied to land, reducing the need for fertiliser and associated emissions. Composting requires that food and green wastes are collected separately from other wastes.

Defra and the DAs recognise that more can be done to reduce emissions from landfill through diversion away from landfill (Box 8.1). To be successful, these need complementary policies to avoid waste, increase recycling and separate collection and increase investment in alternative treatment facilities for waste.

Box 8.1. Ambition on waste in England and the Devolved Administrations

In its 2019 Waste Strategy Defra set out plans to minimise waste, promote resource efficiency and move towards a circular economy. Its key ambitions on waste are to work towards zero food waste to landfill by 2030, to recycle 65% of municipal waste by 2035 and to explore policies to work towards eliminating all biodegradable waste to landfill by the same date and work towards zero avoidable waste by 2050.

Key themes of the Welsh 2010 waste strategy were to improve resource efficiency, develop a circular economy and promote green growth. In 2017, the targets increased to recycling 70% of waste by 2025 and to reducing landfill waste to 5% within the next decade. More recently, the Welsh government's 2019 strategy to tackle climate change included an ambition of 'zero landfill' by 2025 and zero waste by 2050. A new strategy will be consulted in 2019, including plans to halve food waste by 2025, against a 2007 baseline.

In Scotland, the Waste (Scotland) Regulations 2012 set out a number of provisions to help Scotland move toward the objectives and targets set out in the Scotland's Zero Waste Plan and help transition toward a circular economy. These provisions include a ban on biodegradable municipal waste going to landfill from January 2021. Scotland's Climate Change Plan also has a target for reducing waste by 50% by 2030.

Northern Ireland passed legislation to provide for the separate collection and treatment of food waste in 2015. This makes it compulsory for councils to provide separate household food waste collection and bans the landfilling of separately collected food waste from April 2015.

Source: Defra 2019 *Our waste, our resources: A strategy for England.*
Wales (2010) *Towards Zero Waste 2010.*
Wales (2019) *Prosperity for All: A Low Carbon Wales.*
Scotland (2012) *The Waste (Scotland) Regulations.* Scottish Government (2018) *Climate Change Plan: Third report on proposals and policies 2018-2032.*
Northern Ireland (2015) The Food Waste Regulations.

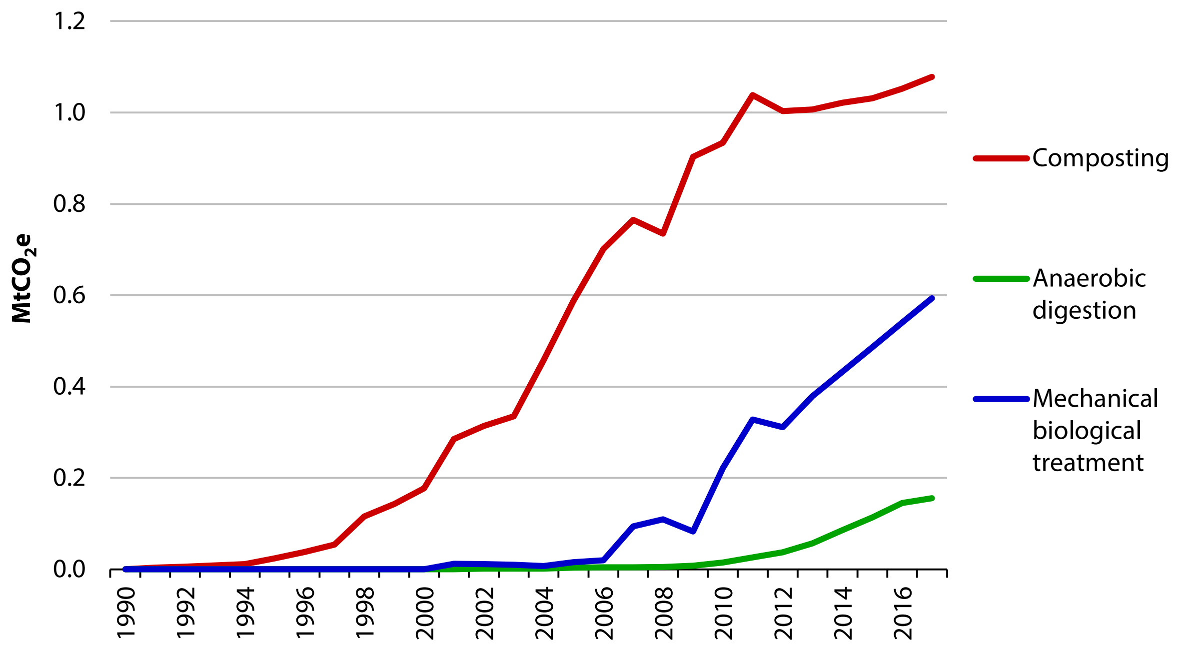
Preventing methane at landfill sites

Even if biodegradable waste sent to landfill could be eliminated completely, there would still be legacy emissions from waste, given the time taken for biodegradable waste to decay. Preventing methane at landfill is therefore important, and can be done through methane capture and biogas combustion technologies, flaring or through natural oxidisation whereby bacteria act on methane and natural oxygen to produce CO_2. The average methane capture rate in the UK was estimated to be 59% in 2017. Methane capture at modern landfill sites is over 80% and can reach as high as 90%. In practice the capture rate is site specific, depending on the age of landfill sites, technology implemented, and its day-to-day operation.

Alternative waste treatment systems

Biodegradable waste that is diverted from landfill can be treated in AD and MBT systems. Emissions from these sources were 1.8 MtCO2e in 2017 (0.4% of waste emissions). Emissions from composting have increased since the mid-1990s and from AD and MBT since the mid-2000s as more waste has been diverted to these facilities (Figure 8.3):

Figure 8.3. GHG emissions from composting, AD and MBT (1990-2017)



Source: BEIS (2019) *Final UK greenhouse gas emissions national statistics 1990-2017.*

- Anaerobic digestion is the process by which organic matter such as animal or food waste is broken down to produce biogas and biofertiliser. This process happens in the absence of oxygen in a sealed tank called an anaerobic digester. AD represents the best environmental outcome for food waste that cannot be prevented or redistributed. The number of AD facilities using food waste or farm waste has increased sharply since the Anaerobic Digestion Strategy in 2016[233] and there are currently about 4200 active AD plants in the UK.
- Mechanical biological treatment (MBT) systems are a type of waste processing facility that combines a sorting facility with a form of biological treatment such as composting or anaerobic digestion. MBT plants are designed to process mixed household waste as well as commercial and industrial wastes. They provide an effective way to stabilise and separate waste which is not suitable for recycling, extract recyclable materials and produce a solid recovered fuel (SRF).
- Waste incineration. Emissions from all municipal solid waste (MSW) incineration plant with energy recovery are reported in the power sector. All incineration of MSW without energy recovery and of chemical wastes, clinical wastes, sewage sludge and animal carcasses are

[233] Oregionni et al. (2017*) Potential for Energy Production from Farm Wastes Using Anaerobic Digestion in the UK: An Economic Comparison of Different Size Plants*. Energies 2017, 10, 1396.

reported in the waste sector. Emissions from this source were 0.3 $MtCO_2e$ in 2017 and are a low and declining source of emissions.

Emissions from waste water handling

Emissions from waste water treatment were 4.1 $MtCO_2e$ in 2017. Wastewater emissions are mainly methane (83%), with the remainder nitrous oxide (N_2O). Emissions rose by 2% in 2017 but the longer term trend has been declining – down 17% since 1990. Measures to reduce emissions in waste-water treatment include:

- Operational measures. These are relatively low cost and can be applied to both methane and N_2O.
  - Methane emissions can be reduced through covering sludge thickening tanks and post-combustion system installed at the exhaust gas outlet of the motor generator to capture and use the bio-gas.
  - Operating biological wastewater treatment plants at high solid retention times (SRT) to maintain low ammonia and nitrite concentrations in the media.
  - Use of large bioreactor volumes to dispose of systems able to buffer loadings and reduce the risk of transient oxygen depletion.
  - Limiting stripping of N_2O by aeration to enable microorganisms more time to consume the gas.
- Measures to capture and treat GHGs including:
  - Using nitrifying and denitrifying bacteria or microalgae, to control NOx gas emissions.
  - Collect the outlet gaseous stream from the top of the nitrifying unit, containing N_2O, and use it as oxidizer to burn the methane produced in the anaerobic sludge digester.
  - Using biological processes to oxidise methane into CO_2.
- Application of new processes to remove organic matter and GHGs:
  - Using microalgae or partial nitritation-Anammox processes to remove ammonia from wastewater, instead of conventional processes, can significantly reduce N_2O and methane emissions. Barriers to implementation include high capital costs, the substantial area required by microalgae systems and the current lack of information about the stability of these processes operating in the plant.

Some water companies are trialling new technologies and have set targets to reduce emissions (Box 8.2).

Box 8.2. Water companies' ambition to reduce emissions

In England, Wales and Scotland, several water companies have set ambitious, long-term, emission reduction targets in their strategic direction statements. For example, Wessex Water and Northumbrian Water aim at being carbon neutral by 2020, Thames Water wants to reduce CO_2e emissions by 34% by 2020 from a 1990 baseline, and United Utilities aims at reducing CO_2e emissions by 50% by 2020 (baseline 2005/06) and by 60% by 2035.

Measures to reduce emissions are mostly focused on energy efficiency, renewable energy using CHP, hydro and wind, and on sewage sludge incineration. Some water companies (e.g. United Utilities, Thames Water, Yorkshire Water, Scottish Water) have invested in the thermal hydrolysis process (THP) to maximise energy generation from sewage sludge. Scottish Water is also trialling biocatalysts to reduce the amount of sludge and consequently the energy requirements to manage bio-solids and the space for the treatment process.

Plans in place by Thames Water to build and test its first pyrolysis plant could deliver higher methane capture rates. The company sees this as a 'world's first' and a step-change for the treatment of sewage sludge, which will be heated up to 800°C in the absence of oxygen to produce a fuel gas that is hydrogen rich. To prove the process, a three-year pilot at Crossness sewage plant, processing sewage sludge from over 450,000 people, is being commissioned.

Source: Ofwat (2010) *Playing our part – reducing greenhouse gas emissions in the water and sewerage sectors.*
Northumbrian water Group's environment, social and economic report, 2017.
http://unitedutilities.annualreport2017.com/governance/directors-report

(b) Challenges in avoiding emissions from different parts of the Waste sector

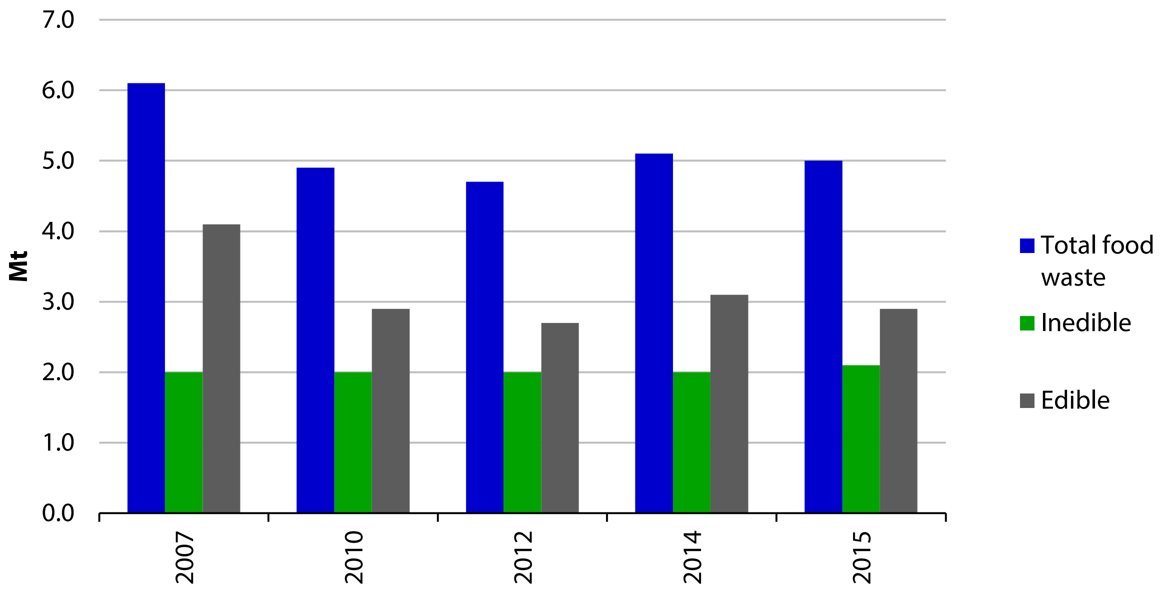
Whilst there are options to further reduce emissions from waste, there are a number of challenges to adoption.

Landfill emissions

Waste prevention. The amount of household food waste that is deemed to be avoidable or 'edible', was 5 million tonnes in 2015[234] (Figure 8.4). Voluntary initiatives to reduce food waste include the 'Love food hate waste' campaign which provides advice and tips to consumers, while the UK Food Waste Reduction Roadman is targeting a 50% reduction in waste arising across the food supply chain from farm to consumer by 2030. However, the scale, targeting and effectiveness of interventions has been limited. Per capita household food waste (HHFW) in the UK has remained unchanged at around 110kg between 2010 and 2015.[235] HHFW in Wales has declined over recent years and is now below the UK average, whilst Scotland is around the same as the UK as a whole.

[234] WRAP(2018) *Food Surplus and Waste in the UK - Key Facts.*
[235] WRAP (2016) *Household Food Waste in the UK, 2015.*

Figure 8.4. Household food waste in the UK (2007-2015)



Source: WRAP (2018) Household food waste: restated data for 2007-2015. This report restates previously published estimates which have been reinterpreted using the most recent international definitions and classifications relating to food waste.

Separate waste collection. There is no legal requirement on English local authorities to introduce separate food waste collections. Food waste collected separately remains a very small proportion of total waste collected, only 1.6% in 2016.

– Around two-thirds[236] of English local authorities (LAs) offer food waste collections, although a third of this is mixed in with garden waste.

– Over 80% of households in Scotland have access to food waste collection. This equates to around 1.95m households, up from just over 0.5m households in 2013.

– All local authorities in Wales are required to provide separate food waste collection.

Defra and the DAs have set out ambition to eliminate food waste to landfill and increase recycling rates. Recycling and diversion of waste from landfill is a cost-effective way to reduce emissions, but achieving Defra and DA targets requires overcoming a number of financial and on-financial barriers:[237]

- There are high upfront costs of providing separate waste collection services and uncertain future savings which depend on assumptions around recycling rates and secondary material prices.
- There is a continuing need to shift societal attitudes towards using resources efficiently and to reducing and separating waste.

[236] WRAP (2015) *Local Authority Scheme Data 2017/18.*
[237] Defra (2019) *Consistent municipal recycling collections in England. Impact Assessment (IA).*

- Diverse collection rules across LAs can cause confusion to householders over the type of materials collected.
- Current waste service arrangements in the commercial sector do not drive economies of scale or incentivise recycling. There is a lack of knowledge among small and microbusinesses about potential cost savings.
- Some specific biodegradable materials, such as disposable coffee cups, are technically recyclable in specialist facilities, but are not widely recyclable in most local authority recycling centres (only three exist in the UK).

Achieving these targets relies not only on LAs to provide separate food and other biodegradable waste collection, but for businesses and households to change current attitudes to reduce and recycle waste.

Preventing emissions at landfill sites. It is important that methane continues to be captured at landfill sites. This can be challenging given the diminishing capacity of sites to produce gas, as biodegradable waste is diverted away from landfill to more efficient capture systems. However, an inexpensive way to reduce methane emissions from existing landfills is to exploit the natural process of microbial methane oxidation through improved landfill cover design. Landfill covers ('biocovers') can improve environmental conditions for bacteria that metabolise methane.

Defra is looking to develop techniques for direct emission measurement from landfill sites to help improve their data set and allow the targetting of efforts at the worst performing sites.

Alternative waste treatment systems. Increased recycling and diversion of waste from landfill requires waste facilities to separate and reprocess waste, and a stable supply of recyclable material. Barriers to investment in these include high upfront costs, market uncertainty and competition from abroad. Defra and the DAs have set out measures to tackle these by:

- Providing a large and stable supply of recyclable waste materials through an extended Producer Responsibility Scheme to ensure produce have a value at end of life.
- Increasing the quality of the waste materials to be recycled by setting targets to increase recycling of a number of waste streams and better design of packaging materials.
- Improving demand for recycled materials and market confidence so that more recycling can be processed in the UK. This includes levelling the playing field for UK reprocessors and minimising illegal waste exports.

Through the Waste Infrastructure Delivery Programme, the Government is committed to spending £3bn by 2042 on developing new waste infrastructure. This programme should help to give the private sector the confidence to invest in waste management projects including AD and MBT.

Waste water treatment

There are relatively low-cost measures to optimise the operational conditions for treating waste although this could still entail disruption and changes to processes and machinery. Barriers to more advanced technologies such as microalgae or partial nitritation-Anammox processes include high upfront costs and large area needed by microalgae systems.

Novel technologies such as thermal hydrolysis process (THP) and biocatalysts are at early stages of testing and trialling and costs and impacts are still uncertain.

(c) The strengthened evidence base used in this report

We have drawn in this report on the evidence published in and alongside recent Committee reports including the Fifth Carbon Budget and 2018 Land use report:

- Our central scenario in the Fifth Carbon Budget assumed that five biodegradable waste streams (food, paper/card, wood, textiles and garden waste) would be prevented from landfill across the UK by 2025.
- Our 2018 land use report presented scenarios for food waste reduction across the supply chain. In the medium level of ambition this led to a 20% reduction in food waste by 2025 in line with the Courtauld Agreement and a higher level of ambition reaching a 50% reduction in food waste by 2050.

We have also undertaken new analysis for this report:

- We have assessed the impact of different options of reducing waste sent to landfill using latest models for England and the DAs (Box 8.3).
- Costs and benefits of providing separate collection of waste streams are estimated based on WRAP and Defra assumptions.[238]
- We have considered literature on how improved techniques applied to waste water handling can lead to efficiency improvements.[239]

We reflect this new evidence along with our existing evidence base in our scenarios in section 3.

Box 8.3. Modelling landfill emissions

The NAEI inventory estimates landfill emissions based on information about the level and type of waste sent to landfill, the characteristics of the waste, and the landfill management regime. Waste materials are categorised by how quickly they degrade and are assigned different decay rates. The model used is called 'MELMod' and is operated by Ricardo Energy and Environment for Defra.

Input data for the landfill model was updated for the 2011 inventory. This was done as part of a research project commissioned by Defra. The main issues investigated were:

- the emissions factors included for different types of waste and rates of decay;
- the assumptions around oxidation through the cap (including oxidation rate if gas escape through cracks and fissures was minimal);
- the different categories of waste types (e.g. food, paper,) included in the model, and how these could be improved to more accurately reflect emissions
- the composition of waste sent to landfill.

A peer review on the revised model has since resulted in the revision of some values used in the model.

Our analysis is based on the 2017 version of MELMod, which estimates landfill methane emissions from 1945 to 2050 for each individual country of the UK. The model enabled us to run different scenarios for eliminating specific waste from landfill at different points in time and to assess their impacts to 2050.

Source: Eunomia (2011) *Landfill Improvement Project UK Landfill Emissions Model*.
Ricardo Energy and Environment (2019) *UK GHG Inventory Report, 1990-2017*.

[238] Defra (2019) *Consistent municpal recyling collections in England Impact Assessment.*
[239] J. L. Campos et al (2016) *Greenhouse gas emissions from wastewater treatment plants: Minimisation, treatment, prevention,* Journal of Chemistry.

3. Scenarios for minimising emissions from the waste sector

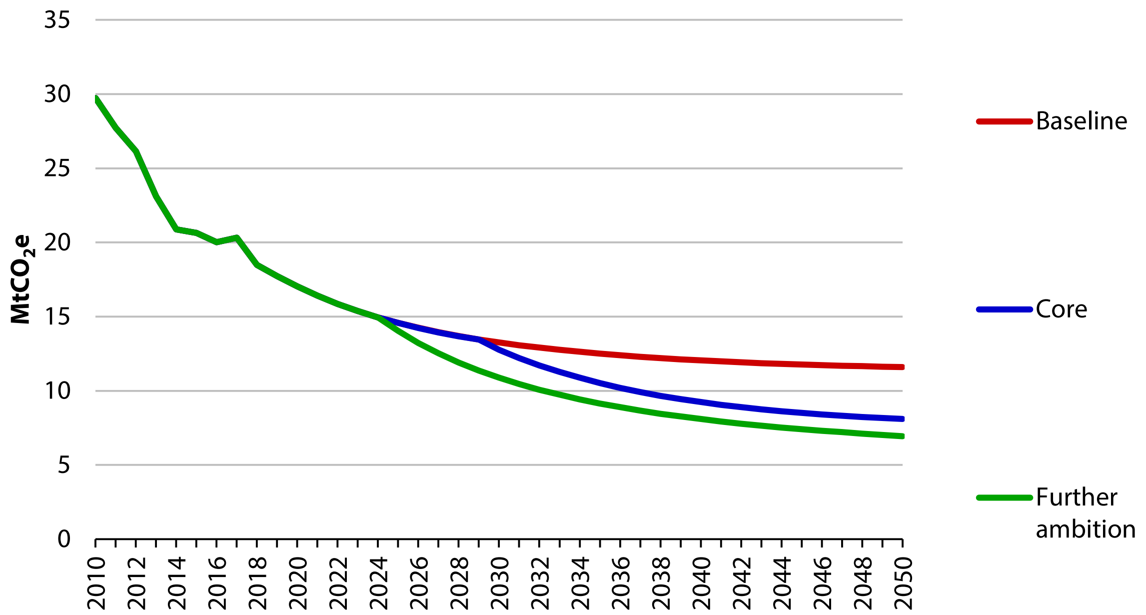
(a) Opportunities for cutting emissions towards zero

As set out in Chapter 1, we have classed the options for cutting emissions towards zero in three categories:

- Core options are those low-cost low-regret options that make sense under most strategies to meet the current 80% 2050 target. For most, the Government has already made commitments or begun to develop policies (although in many cases these need to be strengthened).
- Further Ambition options are more challenging and/or more expensive than the Core options, but are all likely to be needed to meet a net-zero target.
- Speculative options currently have very low levels of technology readiness, very high costs, or significant barriers to public acceptability. It is very unlikely they would all become available. Some of these options would be required to reach net-zero GHG emissions domestically.

Figure 8.5 shows how these options would reduce emissions from the waste sector.

Figure 8.5. Scenarios for minimising emissions from waste management



Source: CCC analysis.

Core options

Many of the Core opportunities in the waste sector are already included in Defra and DA plans, albeit with policy strengthening likely required to deliver them. They would reduce waste emissions to 8.1 $MtCO_2e$ by 2050:

- Our Core scenario assumes the elimination of five biodegradable waste streams to landfill in England, Wales and Northern Ireland by 2030 and in Scotland by 2021.
- It also assumes increased recycling rates in line with ambition in England and the DAs:
  - England: Recycle 65% of municipal waste by 2035.
  - Scotland: Recycle 70% of remaining waste by 2025.
  - Wales: Recycle 70% of waste by 2025.
  - Northern Ireland: No further recycling ambition.

Further ambition options

Our "Further ambition" options would reduce emissions to 6.9 $MtCO_2e$ by 2050 (Figure 8.6). This could be needed to deliver the UK's existing 2050 target and will almost certainly be needed for a net-zero target:

- A 20% reduction in avoidable food waste by 2025, in line with scenarios used in the land use sector.
- Five key bio-degradable waste streams sent to landfill is eliminated by 2025 at the latest.
- Increase re-cycling of municipal waste across all DAs to 70% by 2025 or in line with DA ambition if earlier.
- Waste water treatment plant to achieve a reduction in methane and N_2O emissions of least 20% from waste water handling by 2050. This can be achieved by optimising operational conditions to handle waste and through roll-out of the most efficient treatment technologies.

Alternative options to deliver the Further Ambition scenario

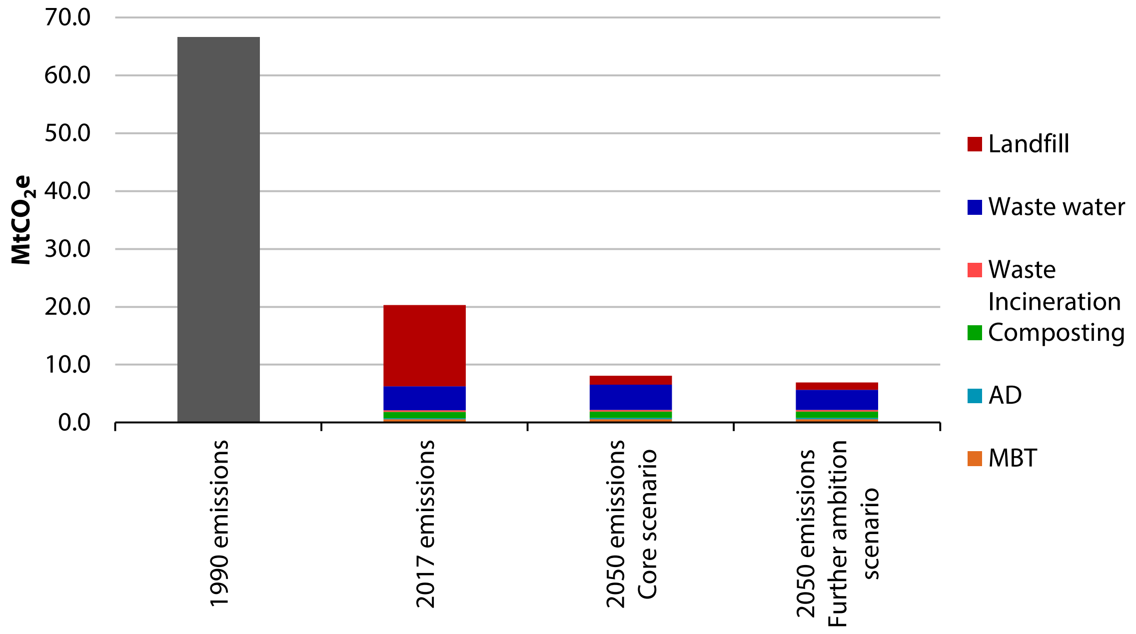
In many cases there would be alternative technical or behavioural approaches that could deliver part or all of the emissions reductions in our Further Ambition scenario. In the waste sector these options include waste prevention measures, e.g. through process design, increasing product lifespan and re-use of materials in line with moving to a circular economy. Better management of legacy landfill sites could reduce emissions further but this requires further data and exploration to fully assess.

'Speculative' options

Our speculative scenario goes further in relation to societal change on food waste:

- A 20% reduction in avoidable food waste by 2025 rising to 50% reduction by 2050 in the UK as a whole.

Figure 8.6. Scenarios for deep emissions reductions from the waste sector



Source: CCC analysis.

(b) Timing for cutting emissions towards zero

The fifth carbon budget (covering 2028-2032) already requires significant progress towards these net-zero scenarios. The cost-effective path that the Committee has identified, and that can be delivered through existing policy with some strengthening, includes the elimination of five biodegradable waste streams to landfill in England, Wales and Northern Ireland by 2030.

With a committed and well-designed policy effort it would be possible to deliver the Further Ambition options set out above in full between 2020 and 2050:

- A 20% reduction in food waste across all countries of the UK by 2025. This is in line with ambition for Wales and Scotland, but would require further policies and measures across the UK to inform and enable producers, firms and consumers to reduce waste. These could include promoting waste avoidance more proactively, increasing availability of reduced portion sizes for smaller households, and communications on avoidance techniques.
- Mandatory separate collection of bio-degradable waste by 2023 to allow consumers time to adjust and alter current waste disposal habits, to achieve a ban on five biodegradable waste streams to landfill by 2025 and achieve 70% re-cycling of municipal waste by 2030 at the latest.
- Incentivisation of low-cost options to improve operational efficiencies in the treatment of waste water in the early 2020s. The demonstration and testing in the early 2020s of more advanced and novel technologies to treat waste water would help to develop options for deeper emissions reduction in the 2030s and 2040s.

This assessment allows for the various limiting factors on a realistic speed of change:

- LAs need time to plan and implement changes to their waste collection facilities and introduce new bins and refuse vehicles. Businesses need to transition to become more resource efficient, increase recycling rates and invest in new waste handling and disposal facilities.
- It builds in time for societal values around waste collection to shift towards greater recycling and waste reduction and moves to a circular economy.
- Water companies need to identify and implement operational efficiencies in water treatment. Testing and trialling of new technologies to reduce non-CO_2 emissions from water treatment will be needed, allowing take-up within companies' natural investment cycles.

Table 8.1 summarises the opportunities to reduce emissions from waste.

Table 8.1. Opportunities to reduce emissions from waste

Source	2030 5CB residual emissions ($MtCO_2e$)	Further Ambition residual emissions in 2050 ($MtCO_2e$)*	Earliest date for Further Ambition emissions	2050 cost £/tCO_2e**
Landfill emissions: - 20% reduction in food waste by 2025. - ban biodegradable waste to landfill no later than 2025 - recycle 70% of residual wase by 2025.	3.6	1.3	2050	Reduction in food waste is cost saving. Landfill ban on biodegradable waste and 70% recycling: £30-£100
Waste water handling	4.5	3.5	2050	Operational options low cost. Technological solutions higher cost.

Source: CCC analysis. Abatement measures based on Defra and Wrap analysis.
Notes: Emissions in 2030 and 2050 include all GHGs; £/tCO_2e cost figures represent levelised costs of abatement of the measures in place in 2050, and are averaged across multiple abatement measures applied to the same emission source.

4. Costs and benefits of achieving deep emissions reductions in the waste sector

Our overall approach to assessing costs and benefits is summarised in Chapter 1 of this technical report and set out in full in Chapter 7 of the accompanying advice report.

We consider several mitigation measures for this sector:

- Elimination of bio-degradable waste from landfill and increasing recycling rates has a range of costs and savings:[240]
  - Additional capex of providing separate waste collection to households and the municipal sector, capex for new vehicles and additional operational spend on new staff.
  - Savings from using only one vehicle to collect both dry recyclables and food waste, savings from reduced sorting at material recycling facilities, increased revenue from selling separately collected dry material, increase in gate fees for sending different waste streams to alternative treatment plants (e.g. AD/MBT) and reduced payments of landfill gate fees.
  - There is considerable uncertainty in cost estimates, which range according to a number of factors e.g. the amount of future waste material and how it is sorted by households; the biodegradable content of waste and how it decays over time; the aftercare of landfill sites; whether estimates take account of a reduction in upstream use of materials; and the impact on costs of other waste facilities such as AD, MBT and Energy from Waste plant.
- Reduction in food waste is cost saving to households, to firms in the manufacturing, wholsesale and retail of food, and in hospitality.
- Optimising existing water treatment operations and processes is low-cost. More advanced technological solutions are likely to have higher costs and currently untested impacts.

Together, these imply a total annual cost compared to a counterfactual without any action of around £110 million[241] in 2050 (in real 2018 prices), for cutting waste sector emissions to around 7 $MtCO_2e$ in line with our Further Ambition scenario.

The next section considers how the scenarios can be delivered, including the need to design policy to ensure changes in behaviour that underpin key measures are delivered.

5. Delivering very deep emissions reductions in the waste sector

(a) What is needed to deliver the scenarios

Delivering the level of emissions in our Further Ambition scenario will require strong and effective Government leadership at all levels, supported by actions from people and businesses. Table 8.2 summarises our assessment of the degree of challenge for the major opportunities to reduce emissions across a number of dimensions, in line with the approach set out in Chapter 1. Figure 8.7 sets out the timing for when key changes need to occur.

- Banning all biodegradable waste to landfill no later than 2025, and increasing recycling rates of other waste streams, requires legislation for mandatory separate waste collection across

[240] Defra (2019) *Consistent municipal recycling collections in England. Impact Assessment (IA)*.
[241] Excluding waste water treatment costs which are not available.

all LAs before this date. The public sector should take a lead in disposal of waste on its estate and in schools, hospitals and other public buildings.

- Additional private sector investment is required in alternative waste disposal facilities – AD, MBT and incineration to deal with waste diverted from landfill. There are risks of offshoring waste if this doesn't happen.
- Societal changes are needed to reduce food waste and increase recycling. To reduce food waste this requires information and advice, enabling measures such as different sizes of food products in supermarkets as well as smaller plate sizes in hospitality and other sectors. For recycling this requires informing people of the value and importance of dealing with waste in this way, and enabling them through separate waste collection bins. Raising consumer awareness of the impacts of waste is critical to the success of these measures, which need to take effect no later than 2025.
- Waste water treatment companies need to assess and implement operational measures to reduce GHGs from water treatment in the 2020s. More advanced technologies and processes need to be demonstrated in the 2020s and 2030s in time for roll-out by 2050 and in line with investment life-spans.

There is a role for further innovation in this sector including:

- Digital recording of waste movements/ data use from sensors that enable LAs to track and monitor activities such as compactor fullness, refuse/recycling collection routes. Collection routes can then be adjusted for bins that are near capacity and need collection, reducing travel time and fuel costs.
- Intelligent packaging, for example to provide the consumer with improved information on the freshness of food, with substances that mop up oxygen from containers so that food lasts longer.[242]
- In the future it has been suggested that robotics could be used to shred waste materials into micro-particles which are then used to recognise different types of material and collect them in a pure form so they can be reused by industry. This will help to reduce the amount of waste that cannot be used and has to be thrown away to almost zero.[243]

These types of innovations could help deliver the scenarios but are not explicitly taken into account.

Key uncertainty and risks include the significant changes in societal behaviour and attitudes to reduce waste and increase recycling that are needed to deliver our scenario. Supporting policies and measures and leadership in the public sector (schools, hospitals and LAs) as well as hospitality sector can help to embed new behaviours.

There are also uncertainties in the extent of operational measures to minimise waste water treatment emissions and the effectiveness and costs of more advanced technologies.

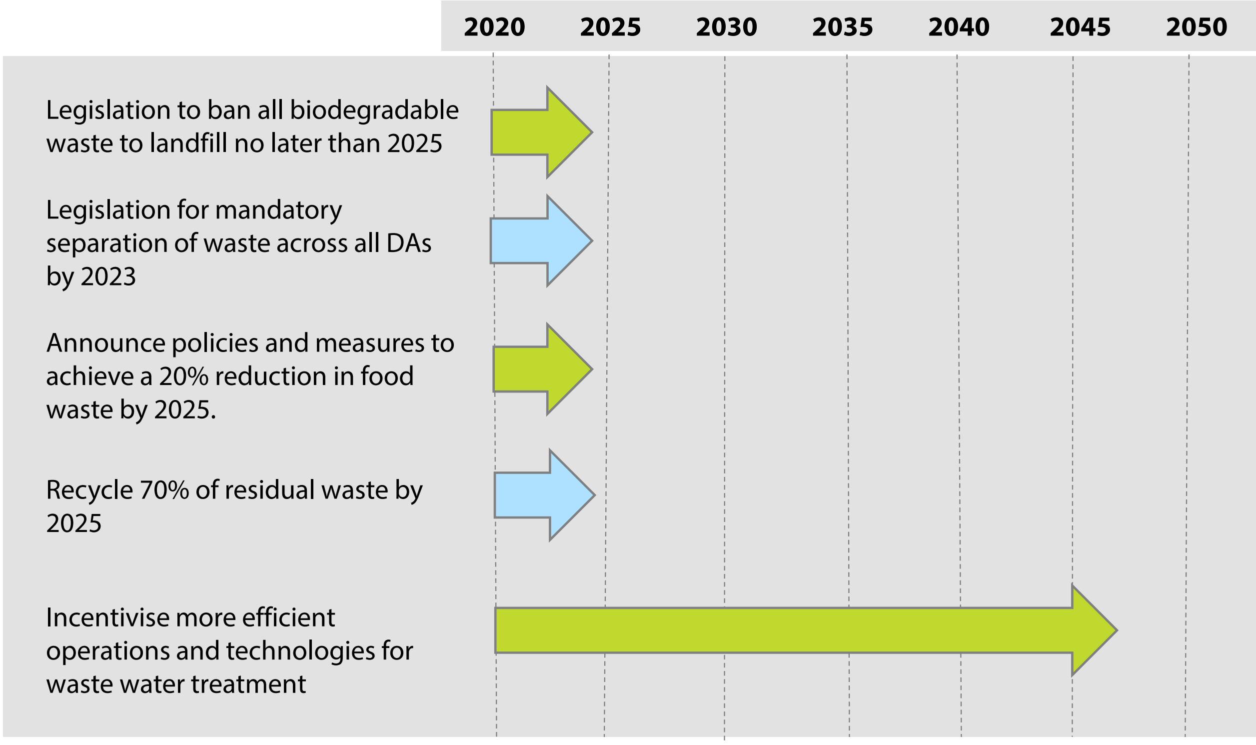
[242] Veolia *Imagine 2050 The future of water wate and energy.*
[243] Veolia *Imagine 2050 The future of water wate and energy.*

Table 8. 2. Assessment of abatement options against dimensions of challenge for the waste sector

Source	Abatement measure	Barriers and delivery risks*	Funding mechanisms	Co-benefits and opportunities	Alternative options
Landfill	Reduce food waste	Consumer awareness and societal change (amber)	Cost saving (green)	Resource efficiency in land use, manufacturing, packaging and processing and hospitality (green)	Ban food waste from landfill
Landfill	Ban biodegradable waste to landfill and increase recycling	LAs to provide separate waste collection and consumer behaviour change (amber)	Tax-payers (amber)	Resource efficiency in manufacturing Biogas production Production of digestate from AD for fertiliser use (green)	Reduce demand and increase re-use of products across the economy.
Waste water treament	Operational and technology measures	Awareness of full range of options (amber)	Firms/ con-sumers (amber)	Biogas capture and use (green)	

Source: CCC analysis.
Notes: The rating of measures in the table is based on the following criteria: 'barriers and delivery risks' are rated as 'red' if there is evidence that a given measure is particularly hard to implement, and 'green' or 'amber' otherwise; 'funding mechanisms' are rated as 'red' if the delivery of a given measure has high costs and these have a negative impact on businesses' competitiveness or are regressive on households, and 'green' or 'amber' otherwise; when there is evidence of positive 'co-benefits and opportunities' these are rated as 'green', otherwise no rating is given.

Figure 8.7. Timing of key decision and changes to deliver the net-zero scenaros for waste



Source: CCC analysis.

(b) Key policy implications for driving deep emissions reductions from the waste sector

This report does not aim to identify a full policy package to deliver the scenarios set out above. However, there are important high-level policy implications that should be understood by Government and Parliament when considering the setting of a UK net-zero emissions target:

- Policies and measures should be introduced to achieve a 20% reduction in avoidable food waste by 2025. These include promoting waste avoidance more proactively, increasing availability of portion sizes for smaller households, and communications on avoidance techniques.
- Government and the DAs should legislate a mandatory ban on biodegradable waste from five waste streams going to landfill by 2025 at the latest. In order to achieve this it needs to introduce separate waste collection by 2023 and supporting measures to increase municipal recycling rates to 70% by 2030 at the latest. This should be supported by campaigns to raise consumer awareness of the importance of re-cycling and by extended producer responsibility schemes.
- Government and the DAs should work with waste water companies to undertake a comprehensive assessment of the scope and costs of measures to reduce emissions from waste water handling, and develop a strategy to implement these to 2050.

The Committee's annual progress reports to Parliament include our detailed progress assessments. Our June 2018 report[244] identified a number of areas where policy strengthening was required to deliver existing ambition. These are a necessary condition to support the increased effort required to deliver a UK net-zero emissions target – we will report on progress against them in July 2019.

[244] CCC (2018) *Reducing UK emissions: Progress Report to Parliament*.

Chapter 9: F-gas emissions

Introduction and key messages

This chapter sets out the scenarios for F-gas emissions that inform the Committee's advice on reviewing long-term emissions targets for the UK, Scotland and Wales. It draws on new evidence of cost-effective abatement measures that go beyond existing EU regulations.

Fluorinated gases (F-gases) are released in very small volumes relative to other greenhouse gases, but can have a global warming potential up to 23,000 times greater than carbon dioxide. They are used across many sectors of the UK economy as refrigerants, aerosols, solvents, insulating gases, or blowing agents for foams, although they can also be emitted as fugitive emissions from other manufacturing processes. Due to their highly damaging impact on the climate, F-gases should be restricted to the very limited uses where there are currently no viable alternatives.

The key messages from this chapter are:

- **Background.** F-gas emissions accounted for 3% of UK greenhouse gas emissions in 2017, and were 14% below 1990 levels. Emissions in 2017 were 40% below the year of highest emissions in 1997, as abatement technologies at halocarbon production plants have cut F-gas leakage by over 99%. The largest source of emissions is now the refrigeration, air-conditioning and heat pump (RACHP) sector, where emissions are released due to refrigerant leakage from appliances.
- **'Core' measures.** There is a strong international framework for reducing F-gas emissions through the 2014 EU F-gas Regulation and 2006 Mobile Air Conditioning (MAC) Directive, and the Kigali Amendment to the UN Montreal Protocol (Box 9.1). It is crucial that the UK maintains a regulatory framework at least as strong as the EU F-Gas Regulation in order to deliver an 80% reduction of F-gas emissions in 2050 compared to 1990 levels.
- **'Further Ambition' scenario.** Our 'Further Ambition' scenario includes additional cost-effective action to reduce emissions in the RACHP sector, and a transition to medical inhalers that have a much lower climate impact. This scenario may require stronger regulation in the RACHP sector and measures to overcome informational and behavioural barriers among clinicians and patients. Combined, the Further Ambition scenario can deliver an additional 1.2 $MtCO_2e$ of abatement, to 86% below 1990 levels.
- **Speculative options.** We have identified Speculative options to reduce emissions. These options are either not considered cost-effective or technology has not yet been demonstrated. The Speculative options could deliver a combined 0.2 $MtCO_2e$ of emissions reductions from the RACHP sector, insulation of high-voltage electricity networks, hydrocarbon production and magnesium works.
- **Costs and benefits.** Actions to reduce F-gas emissions are expected to deliver annual cost savings of around £100 million (in 2017 prices) for cutting emissions from F-gases to close to zero in line with our Further Ambition scenario in 2050. This can be split out by RACHP sector (net savings of around £120 million), and all other sectors (net costs of around £20 million).
- **Delivery.** The main immediate priority for the UK is to continue to participate in the EU F-Gas Regulation or develop and enforce a regulatory regime that is at least as strong. Beyond this, there will be a need to increase training, certification and monitoring of non-compliance in the RACHP sector, introduce alternatives to Metered Dose Inhalers, and consider regulatory approaches to deliver further reductions in the RACHP sector.

We set out our analysis in five sections:

1. Current and historical F-gas emissions
2. Reducing F-gas emissions
3. Scenarios for minimising F-gas emissions
4. Costs and benefits of achieving very deep F-gas emissions reductions
5. Delivering very deep F-gas emissions reductions

1. Current and historical F-gas emissions

F-gas emission levels were 15 $MtCO_2e$ in 2017, accounting for 3% of total UK GHG emissions (Figure 9.1). Emissions were 14% below 1990 levels and 40% below the peak in 1997.

F-gases are released in small volumes. However, they are very effective at trapping heat and some of them will remain in the air for many centuries after their release. As a result, they have a high climate impact per molecule, which is reflected in the high Global Warming Potentials (GWP) used in international emissions accounting.

The climate impacts of all greenhouse gases are compared to CO_2, which has a GWP defined as 1. As our scientific understanding of the climate impact of F-gases develops, methodological changes to how F-gases are accounted for could lead to a significant change in the UK greenhouse gas inventory. Switching from the current generation of GWPs to the next is expected to have a low overall impact (around 1 $MtCO_2e$ in 2017) on F-gas emissions in the latest UK inventory and in 2050 (Net Zero advice report, Box 5.1).

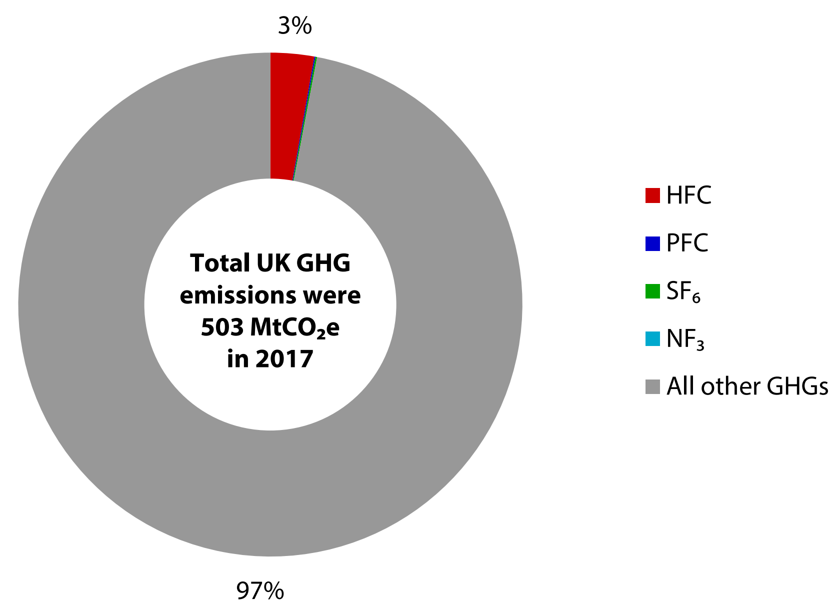
The four F-gases included in the UK emissions inventory are hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulphur hexafluoride (SF_6) and nitrogen trifluoride (NF_3):

- HFCs (94% of total F-gas emissions in 2017) are used in refrigeration, air-conditioning appliances, aerosols and foams, metered-dose inhalers and fire equipment. They are emitted during the manufacture, lifetime and disposal of these products and can stay in the atmosphere for up to 270 years.
- SF_6 (4%) is mainly used in insulation for electricity networks, magnesium casting and military applications. It stays in the atmosphere for around 3,000 years.
- PFC emissions (2%) result mainly from the manufacture of electronics and sporting goods. They are also a by-product of aluminium and halocarbon production. Their lifetime in the atmosphere ranges from 2,600 to 50,000 years.
- NF_3 emissions are currently very low and result from semi-conductor manufacturing. NF_3 stays in the atmosphere for around 700 years.

The largest source of emissions in 2017 was leakage from refrigeration and air-conditioning systems (78%), which have mainly used HFCs since ozone-depleting chlorofluorocarbons (CFCs) were phased out. Other F-gas emissions came from technical aerosols and metered-dose inhalers (11%), and other sources (11%) including fire-fighting equipment and foams.

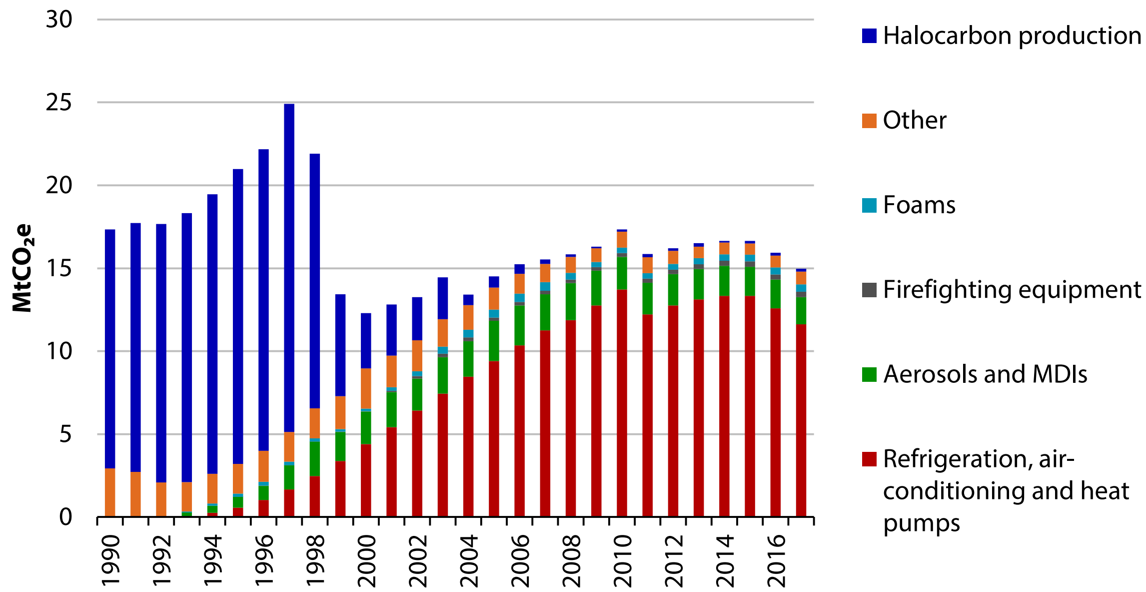
Total F-gas emissions peaked in 1997, reaching 25 $MtCO_2e$, around 80% of which was due to F-gas production. Between 1997 and 2000, F-gas emissions dropped significantly as a result of mitigation measures to reduce leakage during the production process. From 2001 to 2015, F-gas emissions rose slowly, mainly due increasing demand for refrigerants used in air-conditioning and refrigeration (Figure 9.2). F-gas emissions fell by around 10% from 2015 to 2017.

Figure 9.1. Current emissions from F-gases



Source: BEIS (2019) *Final UK greenhouse gas emissions national statistics: 1990-2017.*

Figure 9.2. F-gas emissions since 1990 by sector



Source: BEIS (2019) *Final UK greenhouse gas emissions national statistics: 1990-2017.*

2. Reducing F-gas emissions

(a) The current role of low-GWP alternatives to F-gases

In 1990, **F-gas production** was the largest source of F-gas emissions in the UK. Emissions fell substantially between 1997 and 2001, as a result of fitting abatement technologies at halocarbon production sites (Figure 9.2). There is now little potential to further reduce emissions from this source.

The UK has signed up to a strong international legal framework for reducing F-gas emissions through the F-Gas Regulation (EU) 517/2014, the Mobile Air Conditioning (MAC) Directive, and the Kigali Amendment to the UN Montreal Protocol (Box 9.1). This legislation has been the key driver of a transition to low-GWP alternatives in recent years.

Box 9.1. International policy to deliver F-gas emissions

There are three main policies to drive reduction in F-gas emissions. These are the 2014 EU F-Gas Regulation, the Mobile Air Conditioning (MAC) Directive and the Kigali Amendment to the Montreal Protocol:

- The 2014 EU F-Gas Regulation came into force in the UK in January 2015. It introduced a number of new measures and strengthened the measures in 2006 EU F-Gas Regulation:
  - The regulation sets an EU-wide cap on the amount of HFCs that producers and importers are allowed to place on the EU market.[245] The cap will be cut every three years until reaching a 79% cut by 2030 from 2015 levels.
  - Some uses of HFCs are exempt from the regulation, including medical use, military equipment and manufacturing of semiconductors. Emissions from SF6 and PFC are not included in the cap.[246]
  - The regulation bans the use of F-gases in many new types of equipment where less harmful alternatives are widely available, such as fridges in homes or supermarkets, air-conditioning and foams and aerosols;
  - The regulation strengthens existing obligations in terms of mandatory 'management measures' including regular leak checks and repair, gas recovery at end-of-life, record keeping, training and certification of technicians and product labelling.
- The 2006 MAC Directive focuses on emissions from air-conditioning in new cars and vans. From 2017, all new cars and vans are required to use substances with a GWP less than 150.
- The Kigali Amendment to the UN Montreal Protocol sets out pathways for developed and developing countries for controlling the production and consumption of HFCs, similar to the EU F-Gas Regulation. Under the amendment HFCs in developed countries will be reduced through incremental targets up to a cut of 86% by 2036. These plans are less stringent than the EU F-Gas Regulation up to 2034, after which the Kigali Amendment targets are currently more ambitious. This may not remain the case as the EU plans to consider an extension of the ambition of the F-Gas Regulation beyond 2030 in 2022. The UK ratified the Kigali Amendment in November 2017 and the amendment took effect in January 2019.
- Emissions of PFCs from aluminium production are priced under the EU Emissions Trading System.

[245] The regulations do not place a cap on the level of F-gas emissions.
[246] Emissions from these sources are included in the UK emissions inventory.

Refrigeration, air-conditioning and heat pumps accounted for 78% of F-gas emissions in 2017. HFCs have been widely adopted as they are well-suited to many RACHP applications.

The use of HFCs in new RACHP systems is significantly restricted by the 2014 EU F-Gas Regulation. Analysis for the Committee has identified over twenty lower-GWP refrigerants that are either in use or recently commercialised, eight of which have an ultra-low GWP of below 10.[247]

Some sections of the RACHP market have been using non-HFC refrigerants for many years. Domestic refrigerators have been using hydrocarbons (such as iso-butane) on a large scale in the UK since the early 2000s and many large industrial refrigeration systems use ammonia.

Other areas of the RACHP market are already making 'very good' progress, where ultra-low GWP alternative refrigerants are already commercially available for new equipment: small sealed and multi-compressor commercial refrigeration; water chiller air-conditioning; mobile air-conditioning units in cars and vans.

Metered dose inhalers (MDIs) typically use F-gases (HFA 134a and HFA 227) as propellants, and account for around 1 $MtCO_2e$ of annual emissions in the UK. There are viable alternatives to MDIs in the form of dry-powder inhalers (DPIs). Around 25% of all inhalers prescribed in the UK are currently DPIs, which is a much lower share than many European countries.[248]

Technical aerosols using HFC gases with GWP of greater than 150 have been banned in the UK since January 2018. Technical aerosols are exempt from this ban if HFCs are required to meet national safety standards, usually due to flammability concerns, but low-GWP alternatives are available in the vast majority of cases.

(b) Options for reducing emissions further

Existing policy is expected to deliver F-gas emissions reductions of 65% from 2017 to 2030. The majority of this abatement can be achieved in the RACHP sector, whilst emissions from other sectors can be reduced to near-zero.

Projections of F-gas emissions indicate that the EU F-Gas Regulation will deliver significant abatement across several sectors:

- **RACHP:** emissions fall by 75%, from 12 $MtCO_2e$ in 2017 to around 3 $MtCO_2e$ in 2030.
- **Technical aerosols:** emissions fall by 94% between 2017 and 2022 to less than 0.05 $MtCO_2e$ following the ban of high-GWP F-gases.
- **Fire Protection Systems (FPS):** emissions to fall by around two-thirds by 2030 and to zero emissions by 2038.
- **Manufacture of new foams:** emissions fall to zero in 2023, following a ban on the use of high-GWP F-gases as blowing agents in 2022.
- **Gas Insulated Switchgear (GIS):** emissions from GIS in electricity networks are expected to fall slowly (35% from 2017 to 2030), as older SF_6 equipment is replaced with modern equipment with much smaller SF_6 charges and lower levels of leakage.

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[247] Ricardo and Gluckman Consulting (2018) *Assessment of the potential to reduce UK F-gas emissions beyond the ambition of the F-gas Regulation and Kigali Amendment*. Table 3-2.
[248] House of Commons Environmental Audit Committee (2018) *UK Progress on reducing F-gas Emissions.*

Reducing emissions further towards net-zero will require replacing MDIs with less harmful alternatives, and further progress in reducing emissions from the RACHP sector:

- It is feasible and cost-effective to switch MDIs to DPIs and low-GWP alternatives by 2027, delivering a reduction of more than 90% to near-zero emissions (below 0.2 $MtCO_2e$).
- Additional, cost-effective measures that can be deployed in the RACHP sector could deliver further reductions of 0.2 $MtCO_2e$ by 2030

Existing and future F-gas regulations will only deliver the expected abatement if appropriate compliance measures are in place. The Environmental Audit Committee has raised concerns about suspected non-compliance in the F-gas sector, and has recommended increasing the number of inspections, expanding training for workers who handle refrigerants, and regularly reviewing the effectiveness of the compliance regime, including the impact of new civil penalties for F-gas breaches.[249]

(c) Challenges in avoiding emissions from different parts of the F-gas sector

Many sources of F-gas emissions should be relatively easy to reduce, with low costs and barriers. However, there are sources that are more challenging, typically due to long product lifetimes or a lack of viable alternative technologies to replace F-gases:

- **RACHP emissions where no low-GWP alternatives currently exist.** The EU F-Gas Regulation is already driving a shift from very high-GWP gases to lower-GWP options such as HFC-32, which is expected to be the dominant HFC refrigerant in 2040. There is, however, little current progress towards an alternative. For small systems, hydrocarbon refrigerants such as propane are a good option, but high flammability limits the proportion of the market that can safely use hydrocarbon refrigerants. It is unlikely that more than 25% of the small sized air-conditioning market and 50% of the residential heat pump market could use hydrocarbons. There is little likelihood of an ultra-low-GWP refrigerant with similar properties to HFC-32 becoming available.[250]
- **Lifetime and disposal emissions from foams.** It is extremely challenging to recover F-gas blowing agents for foams, typically used in building insulation, because of the difficulties in separating the foam from the associated building material.
- **Emissions from current GIS.** The long lifetime (up to 40 years) of high voltage switchgear equipment and the lack of market-ready non-SF_6 alternatives means that accelerating the replacement of existing GIS equipment would be difficult and very expensive.
- **Other sources of F-gas emissions.** Emissions from other small sources, including aluminium fugitives, semiconductors, solvents, military use, and laboratory use are difficult to reduce, reflecting a lack of alternatives. It is possible that there may be some scope to reduce emissions from halocarbon production and magnesium casting.

[249] House of Commons Environmental Audit Committee (2018) *UK Progress on reducing F-gas Emissions.*
[250] Ricardo and Gluckman Consulting (2018) *Assessment of the potential to reduce UK F-gas emissions beyond the ambition of the F-gas Regulation and Kigali Amendment*.

(d) The strengthened evidence base used in this report

In this report, we have drawn on evidence from our fifth carbon budget advice. This laid out how F-gas emissions could be reduced to around 4.3 $MtCO_2e$ by 2050, based on DECC projections of non-CO_2 greenhouse gases out to 2035.

We have also made use of new analysis. In February 2018 we commissioned Ricardo and Gluckman Consulting to investigate the potential to reduce F-gas emissions further and faster than the existing F-Gas Regulation. The work has considered the cost of abatement measures, non-financial barriers and potential rates of uptake. The results from this work show that there is cost-effective potential to go further:

- There is modest potential to reduce RACHP emissions further and faster than the EU F-Gas Regulation. This potential lies in deploying equipment that can use lower-GWP refrigerants (e.g. hydrocarbons or CO_2), replacing the high-GWP refrigerants in some existing equipment with lower-GWP refrigerants, and reducing leakage rates further.
- In the small-medium building air-conditioning market, ultra-low-GWP non-flammable replacement refrigerants are not available at present and industry has not started to develop these refrigerants. However, recent developments in the car air-conditioning market suggest that there could be some potential to develop not-in-kind systems that use alternative low-GWP refrigerants.
- There are cost-effective alternatives to high-GWP metered-dose inhalers (MDIs) that maintain the clinical effectiveness of existing inhalers. The potential alternatives include dry-powder inhalers and MDIs with a low-GWP propellant. DPIs are already used more than MDIs in most European countries. Whilst DPIs could replace MDIs used in the UK quite quickly (over a 3 to 5 year period), the introduction of low-GWP MDIs is likely to take up to ten years as alternative low-GWP MDIs are in advanced stages of development but not yet market-ready.
- The cost of accelerating emissions abatement from the insulation of electricity networks (GIS) is not cost effective with current technology. Emissions are expected to fall slowly between now and 2050 as equipment is replaced.

3. Scenarios for minimising F-gas emissions

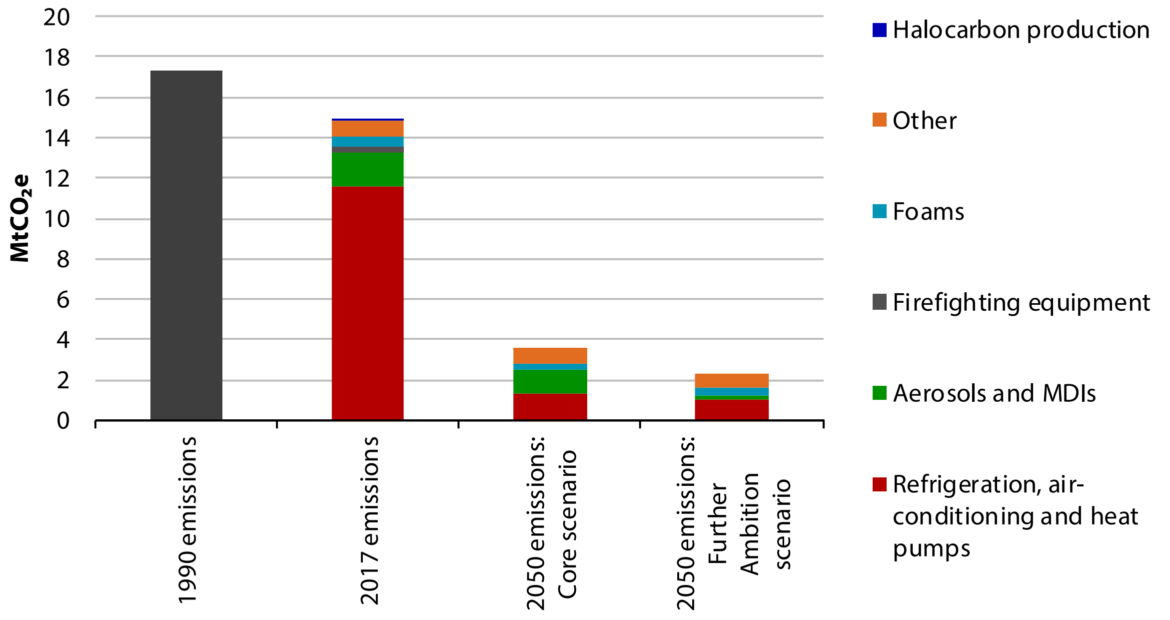
(a) Opportunities for cutting emissions towards zero

As set out in Chapter 1, we have classed the options for cutting emissions towards zero in three categories:

- **Core options** are those low-cost low-regret options that make sense under most strategies to meet the current 80% 2050 target. For most, the Government has already made commitments or begun to develop policies (although in many cases these need to be strengthened).
- **Further Ambition options** are more challenging and/or more expensive than the Core options, but are all likely to be needed to meet a net-zero target.
- **Speculative options** currently have very low levels of technology readiness, very high costs, or significant barriers to public acceptability. It is very unlikely they would all become available. Some of these options would be required to reach net-zero GHG emissions domestically.

Combined, these measures are expected to reduce emissions from F-gases to very low levels by 2050 (Figure 9.3).

Figure 9.3. Scenarios for deep F-gas emissions reductions



Source: BEIS (2019) *Final UK greenhouse gas emissions national statistics: 1990-2017*, CCC analysis.

Core options

The Core opportunities in this sector are already covered by the existing EU F-Gas Regulation and Kigali Amendment, although policy will need to be backed up with training, certification and an effective enforcement regime to ensure these emissions reductions are delivered.

If the UK were to stop participating in the EU F-Gas Regulation, it must develop and enforce a regulatory regime that is at least as strong. This would include:

- A market cap on HFCs that is 79% below 2015 levels by 2030.
- Bans on the use of F-gases in many new types of equipment where less harmful alternatives are widely available.
- 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.

Combined, the Core options could achieve annual abatement of 12 $MtCO_2e$ of F-gas emissions against a no-policy baseline by 2050.

Further Ambition options

Our 'Further Ambition' options would reduce F-gas emissions further, to very limited uses where there are currently no viable alternatives. These measures may be required to deliver the UK's existing 2050 target, and will almost certainly be needed for a net-zero target:

- A transition from MDIs to dry-powder inhalers (DPIs) and low-GWP alternatives before 2027, which would reduce emissions by around 90%. In this scenario we assume that salbutamol MDIs are replaced with low-GWP alternatives due to their lower costs compared to DPIs.
- Additional regulations to deliver further reductions in the RACHP sector, including:
  - Reduced use of R-410A (GWP of 2088) in medium sized air-conditioning, replaced with variable refrigerant flow (VRF) systems using lower-GWP HFC-32 (GWP 675).
  - Wider use of propane split air-conditioning.
  - Reduced use of HFO/HFC blends in small commercial, industrial and marine refrigeration.
  - Retrofitting of existing equipment that uses HFCs (R-134a systems and small R-404A systems).
  - Leak reductions through improved design, maintenance and end-of-life recovery.

Combined, the Further Ambition options could achieve an additional annual abatement of 1.2 $MtCO_2e$ of F-gas emissions abatement by 2050.

Speculative options

In addition, the Committee have identified further Speculative options to reduce F-gas emissions. These options are either not considered cost-effective or technology has not yet been demonstrated:

- Low GWP alternatives to HFC-32 in RACHP equipment (0.2 $MtCO_2e$).
- Accelerated turnover of Gas Insulated Switchgear (GIS) equipment (<0.1 $MtCO_2e$)
- Emissions from halocarbon (PFC) production could be targeted by the Environment Agency under the Industrial Emissions Directive (< 0.1 $MtCO_2e$).
- Stricter controls on SF6 in magnesium production (< 0.1 $MtCO_2e$).

In combination, the Speculative options could deliver an additional 0.4 $MtCO_2e$ of emissions reductions.

(b) Timing for cutting emissions towards zero

The cost-effective path that the Committee has identified for achieving the fifth carbon budget requires policy that is at least as strong as the EU F-Gas Regulation and MAC Directive. If properly enforced, our latest analysis suggests this would deliver at least a 65% fall in F-gas emissions between 2017 and 2030, to around 5 $MtCO_2e$ in 2030:

- Emissions from stationary refrigeration to fall by 75% from 2017 to 2030.
- Emissions from stationary air-conditioning to fall by 67%.
- Emissions from mobile refrigeration and air-conditioning to fall by 82%.
- Emissions from aerosols eliminated by 2030.

The EU F-Gas Regulation and Kigali Amendment will have a continued, but diminishing, effect on F-gas emissions from 2030 to 2050, ultimately delivering a 76% reduction in F-gas emissions between 2017 and 2050.

With a committed and well-designed policy effort it would be possible to deliver the Further Ambition options set out above in full between 2020 and 2050:

- MDIs using high-GWP propellants can replaced with DPIs and low-GWP alternatives before the start of the fifth carbon budget in 2028.
- Further reductions in the RACHP sector can be delivered between 2020 and 2050 as old equipment is replaced with new, low-GWP alternatives.

This assessment allows for the various limiting factors on a realistic rate of emissions abatement, without requiring significant levels of early capital scrapping. For example:

- Prescriptions for MDIs tend to be renewed on timescales much shorter than one year,[251] so equipment turnover is not a limiting factor in replacing all high-GWP MDIs before 2030.
- In the car air-conditioning sector, there was a ban on the use of refrigerant R-134a for all new cars from January 2017. The typical lifecycle of a car is around fourteen years,[252] so by 2030 the vast majority of the car fleet will have switched to a new low-GWP alternative refrigerants.
- In the industrial refrigeration sector, equipment has a typical lifecycle of over thirty years. By 2040 only a small proportion will still be in use.
- Other equipment, such as Gas Insulated Switchgear (GIS) in electricity networks can have lifetimes of up to forty years.[253] Emissions may continue to fall after 2050 as switchgear is replaced.

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[251] NHS Nene CCG (2012) *Inhaler Repeat Prescriptions.*
[252] SMMT (2018) *Automotive sustainability report.*
[253] Ricardo and Gluckman Consulting (2018) *Assessment of the potential to reduce UK F-gas emissions beyond the ambition of the F-gas Regulation and Kigali Amendment*.

(c) Summary table of the opportunities to reduce emissions from F-gases

Table 9.1. Opportunities to reduce emissions from transport towards zero

Source	2030 5CB residual emissions ($MtCO_2e$)	Further Ambition residual emissions in 2050 ($MtCO_2e$)	Earliest date to reach zero or minimum Further Ambition emissions	2050 cost £/tCO_2e
RACHP	3.0	1.1	2040	-11
MDIs	1.2	0.2	2028	3
Technical aerosols	0.0	0.0	2020	10
Firefighting equipment	0.2	0.0	2038	10
Foams (manufacture)	0.0	0.0	2023	0
Foams (lifetime)	0.2	0.3	2050	0
Other	0.8	0.8	2050	24

Source: CCC analysis.
Notes: Emissions in 2030 and 2050 include all GHGs; £/tCO_2e cost figures represent levelised costs of abatement of the measures in place in 2050, and are averaged across multiple abatement measures applied to the same emission source. We assume low-GWP inhalers replace existing salbutamol MDIs. If DPIs replaced salbutamol MDIs this would lead to higher costs (up to £100/tCO_2e).

4. Costs and benefits of achieving very deep F-gas emissions reductions

Our overall approach to assessing costs and benefits is summarised in Chapter 1 of this report and set out in full in Chapter 7 of the accompanying advice report.

Some of the options included in our net-zero scenario for F-gases would avoid costs compared to the high-GWP alternatives, especially in the RACHP sector, whilst others are likely to be more expensive (Table 9.1):

- Cost savings in the RACHP sector are typically due to efficiency improvements derived from lower energy requirements or reduced leakage. These savings are significant enough to offset the marginal additional capital costs of equipment designed for low-GWP refrigerants and any increased cost of refrigerant.
- Together, these costs imply a total annual cost saving compared to a theoretical counterfactual without any action on emissions of around £50 million (in 2017 prices) for cutting emissions from F-gases to close to zero in line with our Further Ambition scenario in 2050. This can be split out by RACHP sector (net savings of around £150 million), and other sectors (net costs of around £100 million).
- These costs and savings are expected to be broadly consistent between now and 2050, as equipment is replaced at a constant turnover rate.

The next section considers how the scenarios can be delivered, including the need to design policy to ensure that users of F-gases are informed.

5. Delivering very deep F-gas emissions reductions

(a) What is needed to deliver the scenarios

Delivering the level of emissions in our Further Ambition scenario will require strong and effective Government leadership at all levels, supported by actions from people and businesses.

We summarise our assessment of the challenges to reduce emissions across a number of dimensions, in line with the approach set out in Chapter 1, in Table 9.2 and Figure 9.4.

Table 9.2. Assessment of key abatement options against dimensions of challenge for F-gas emissions

Source	Abatement measure	Barriers and delivery risks*	Funding mechanisms	Co-benefits and opportunities	Alternative options
RACHP	Low-GWP refrigerants and minimising leakage	Market-led development of low-GWP systems, in line with equipment turnover rate Training and certification, non-compliance	Net cost saving to consumers, with higher upfront costs Consumers, UK environment agencies	Energy efficiency	Demand reduction
MDIs	DPIs and low-GWP MDIs	Lack of knowledge in clinicians and patients Development and clinical testing of low-GWP MDIs	NHS and (global) MDI users	Lower error rate for DPI users	Wider roll-out of DPIs if low-GWP MDIs are not developed.
Firefighting equipment, technical aerosols, foams	Existing low-GWP alternatives	Training and certification, non-compliance	Consumers		

Source: CCC analysis.
Notes: The rating of measures in the table is based on the following criteria: 'barriers and delivery risks' are rated as 'red' if there is evidence that a given measure is particularly hard to implement, and 'green' or 'amber' otherwise; 'funding mechanisms' are rated as 'red' if the delivery of a given measure has high costs and these have a negative impact on businesses' competitiveness or are regressive on households, and 'green' or 'amber' otherwise; when there is evidence of positive 'co-benefits and opportunities' these are rated as 'green', otherwise no rating is given.

Market-led innovation in the RACHP sector. There are low-GWP systems already on the market in many sub-sectors, but others are currently less developed. These are typically medium-sized systems located in public access areas, which are too large to safely use flammable refrigerants, but not large enough to be located in restricted access areas. As the EU-wide cap restricts the supply of HFC and increases demand for low-GWP alternatives, industry is expected to develop new equipment that can use existing low-GWP refrigerants.[254]

Capital costs of RACHP equipment. A shift to RACHP systems that use lower-GWP refrigerants as the cap on HFCs tightens may also require a shift in investment patterns:

- Low-GWP systems are typically more expensive up front (by an additional £50 - £100 for switching small air conditioning units to propane, up to £4000 for marine refrigeration units), but deliver net cost savings due to improved efficiency over the product lifetime.
- Any increases to capital costs for domestic equipment are likely to be small, and changes to larger commercial and industrial RACHP equipment are not likely to be prohibitive to businesses with access to capital and longer payback periods.

Development of low-GWP MDIs: The NHS Sustainable Development Unit has stated that DPIs have a lower clinical error rate than MDIs but are not suitable for all patients, especially young children and elderly users. Alternative low-GWP aerosols for MDIs are not yet market-ready, but there are three alternatives in development:

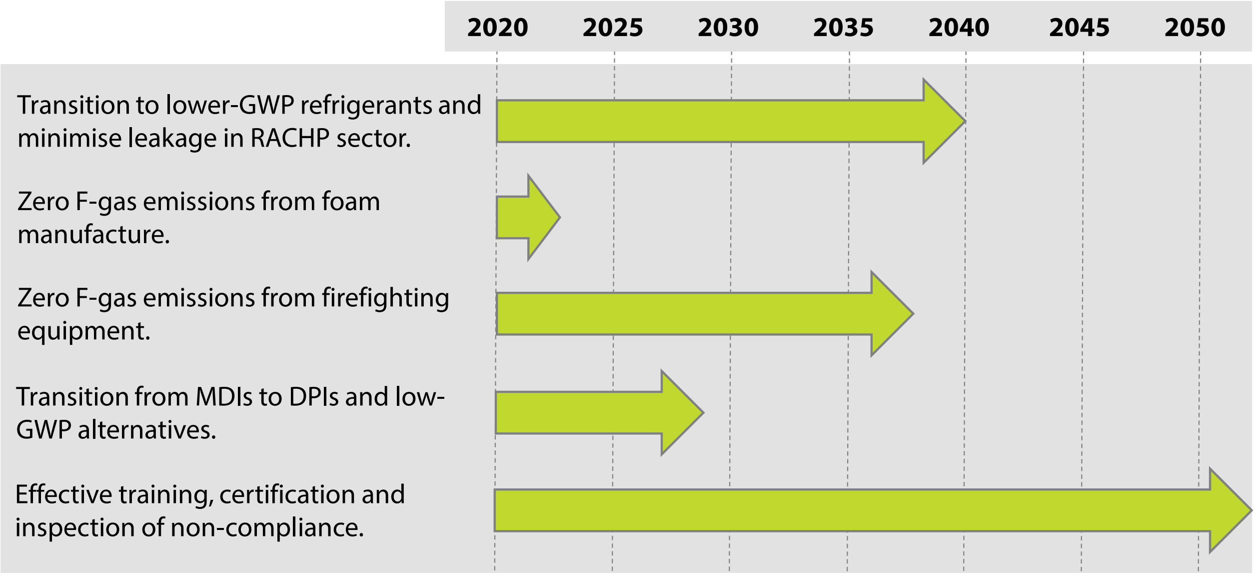
- The development costs to fund clinical testing of low-GWP MDIs are expected to be up to £200 million, but these costs will be spread across the international inhaler market. As a large consumer of MDIs, the UK could expect to contribute between 5% and 10% of these development costs in the early 2020s.
- Once alternatives have been developed that meet clinical standards, production costs are expected to be comparable to those of current MDIs and can be delivered at no additional cost to the NHS. At a conservative estimate, low-GWP MDIs can deliver abatement at less than £20/tCO_2e in the UK.

Overcoming knowledge and behavioural barriers. Overcoming these barriers through education, training and certification is particularly important for workers in the RACHP sector who handle F-gas refrigerants and for clinicians and patients who prescribe and use MDIs:

- As the EU-wide cap leads to increasing demand for lower-GWP alternatives, it will be important to have trained and qualified technicians who are familiar with their use.
- New analysis for the Committee has found a lack of awareness of the high global warming impact of MDIs, the fact that the UK prescribes fewer DPIs than most other EU countries, and the fact that DPIs can be more effective for a large proportion of patients. This lack of knowledge is a behavioural barrier to a transition away from MDIs. The Environmental Audit Committee corroborated this finding, reporting that low take-up of DPIs in the UK is, in part, due to low awareness of DPIs as an alternative among patients and GPs.
- In addition, there may be behavioural barriers to the uptake of alternative inhalers as patients are reluctant to switch. Clinicians and patients must be informed of the equivalent (or better) performance of DPIs and low-GWP MDIs as well as the environmental benefits.

[254] Ricardo and Gluckman Consulting (2018) *Assessment of the potential to reduce UK F-gas emissions beyond the ambition of the F-gas Regulation and Kigali Amendment*. Table 3-4.

Figure 9.4. Timing of key decisions and changes to deliver net-zero scenarios for F-gases



Source: CCC analysis.

(b) Key policy implications for driving deep F-gas emissions reductions

This report does not aim to identify a full policy package to deliver the scenarios set out above. However, there are important high-level policy implications that should be understood by Government and Parliament when considering the setting of a UK net-zero emissions target:

- **Maintain a regulatory framework at least as strong as EU F-Gas Regulation.** Legislation has been passed that enables the UK to set a quota system that is independent from the EU quota.[255] Defra has committed to maintaining the same percentage reductions as the EU F-Gas Regulation.[256]
- **Minimise non-compliance, especially in the RACHP sector.** The Environment Audit Committee has reported evidence of suspected non-compliance, especially as EU F-Gas Regulation increase demand for lower-GWP refrigerants, and a lack of resources for the Environment Agency to carry out adequate inspections.
- **Increased training and certification for F-gas users.** The current F-Gas Regulation and MAC Directive do not require retrospective training for workers trained under previous regulations, and allows untrained members of the public to top-up their own car air-conditioning units with high GWP refrigerants. The Government should consult with industry and bring forward proposals to ensure that all those who handle refrigerants have up-to-date training.
- **Promote the use of DPIs.** This is likely to require engagement across organisations such as the Royal College of GPs, the British Thoracic Society and the National Institute for Health and Care Excellence (NICE) and the NHS Sustainable Development Unit.

[255] The Ozone-Depleting Substances and Fluorinated Greenhouse Gases (Amendment etc.) (EU Exit) Regulations 2019.
[256] Defra (2019) *Using and trading fluorinated gas and ozone-depleting substances: rules and processes if the UK leaves the EU with no deal.*

The Committee's annual progress reports to Parliament include our detailed assessments of policy progress. Our June 2018 report[257] identified a number of areas where policy strengthening could deliver cost-effective abatement. These are a necessary condition to support the increased effort required to deliver a UK net-zero emissions target, and we will report on progress against them in July 2019.

[257] CCC (2018) *Reducing UK emissions, 2018 Progress Report to Parliament.*

Chapter 10: Greenhouse gas removals

Introduction and key messages

This chapter considers the extent to which removals of greenhouse gases from the atmosphere could compensate for residual emissions from across the UK economy, beyond those 'natural' removals solutions considered in the Land Use sector (e.g. afforestation - see Chapter 7).

We draw on evidence from the Committee's recent work on *Biomass in a low-carbon economy* and dedicated evidence reviews commissioned for this report to assess options for removing greenhouse gases, their potential scale, and the possible speed of deployment.

Our key messages are:

- **Potential.** There is potential for greenhouse gas removal (GGR) in the UK, but this cannot be relied upon as a substitute for emissions reduction in other sectors.
- **Sustainability.** It is essential that any GGR is undertaken sustainably. This requires strong and comprehensive standards. Done in the right way, increasing the domestic supply of timber and biomass fuel can promote biodiversity and resilience to climate change in UK landscapes whilst avoiding conflicts with food production. Strong governance capabilities will be needed to ensure that any biomass imports are genuinely low-carbon and sustainable. The UK should be at forefront of developing and strengthening these rules. Risks of negative impacts from additional land-based removals, such as enhanced weathering and biochar should be addressed before large-scale deployment is considered.
- Some removal options should be considered as '**Core**' measures that would be efficient contributors to achieving the current 80% reduction target. This includes the use of wood in construction and some deployment (20 $MtCO_2$/yr) of biomass with CCS (BECCS).
- Achieving net-zero emissions in the UK will require some level of GGR. **Further Ambition** measures that are likely to be needed to meet this goal include additional BECCS deployment (up to a total removal of 51 $MtCO_2e$/yr) and increases in the use of timber in construction. It would also be sensible to aim for at least a demonstration level of direct air capture of CO_2 with storage (DACCS) of 1 $MtCO_2$/yr. In total this scenario contains 53 $MtCO_2$/yr of removals in addition to the 31 $MtCO_2e$ from natural sequestration (see Chapter 7), accounting for an overlap between wood in construction and our land-use scenarios.
- Additional **Speculative** options exist to remove more carbon dioxide from the atmosphere, including direct air capture of CO_2 well beyond demonstration scale (e.g. 25 $MtCO_2$/yr), additional use of BECCS based on imported biomass feedstocks and other removal technologies including enhanced weathering and biochar. The scales of deployment, costs, and in some cases the possible side-effects, of these more speculative options remain uncertain today.
- **Costs.** The costs of achieving the 53 $MtCO_2$/year of removals under the Further Ambition scenario reach around £8.6 billion /year in 2050, largely from the costs of BECCS.
- **Policy.** It is essential that policies are put in place today to ensure that an at-scale removal industry can develop with appropriate environmental safeguards and relatively low costs. This means development of CO_2 transportation and storage infrastructure, also required for decarbonisation of industry and energy generation, as well as putting in place means of incentivising removals and support for innovation.

We set out the analysis that underpins our key messages in the following four sections:

1. The need for greenhouse gas removal
2. Potential for greenhouse gas removal in the UK
3. Scenarios for greenhouse gas removal deployment in the UK
4. Innovation, near-term action and uncertainty

1. The need for greenhouse gas removal

(a) Residual emissions from across the economy

The scenarios presented in this report seek to minimise emissions of greenhouse gases to the atmosphere from all sectors of the economy. Chapter 5 of the Net Zero advice report summarises the extent to which this is possible.

Two scenarios representing levels of emission reduction effort approximately equivalent across sectors are considered:

- **Core:**
  - Core is defined as low-cost and low-regret options that make sense under most strategies to meet the current 80% target by 2050.
  - Measures consistent with the 'Core' scenario give residual emissions across sectors of 214 $MtCO_2e$/yr in 2050 before removals, a 75% reduction on emissions in 1990.[258]
- **Further Ambition:**
  - Further Ambition is defined as measures that will definitely be needed for a net-zero emissions target and may be needed for the current 80% reduction target. They are likely to be more challenging to deploy and/or more expensive than the 'core' measures.
  - Measures consistent with the 'Further Ambition' scenario give residual emissions across sectors of 89 $MtCO_2e$/yr in 2050 before removals, a 89% reduction on emissions in 1990.

Additional more '**Speculative**' options to further reduce emissions were also identified in each sector. Some of these additional measures will be needed to reach net-zero greenhouse gas (GHG) emissions, but they cannot all be relied upon at the present time.

(b) Removals in previous Committee scenarios

Previous Committee scenarios have included methods that could achieve net-removal of greenhouse gases from the atmosphere by 2050.

Beyond land-based removals (e.g. afforestation), which are covered in Chapter 7, our scenarios for the advice on the fifth carbon budget contained two greenhouse gas removal options:

- **Wood in construction:** Harvested wood can be used as a construction material, creating an additional store of carbon in the built environment. As forests regrow following harvest, they resequester from the atmosphere the carbon content of the harvested wood.

[258] Removals in the land-use sector are already included in these reductions.

- **Bioenergy with carbon capture and storage (BECCS):** The use of biomass in energy applications where the combusted biogenic carbon is prevented from entering the atmosphere and is stored in long-term geological storage sites.

Our recent reports on *Land Use: Reducing emissions and preparing for climate change* and *Biomass in a low-carbon economy* updated the Committee's assessment of the potential for these methods to remove carbon from the atmosphere:

- Large increases in the percentage of houses and flats constructed with timber could enable up to 3 $MtCO_2$/yr to be stored long-term in the built environment through wood used in construction. A similar level of contribution is possible through use of engineered wood products (e.g. cross laminated timber and glulam) in non-residential buildings.
- Depending on the availability of low-carbon sustainable harvested biomass, 20-65 $MtCO_2$ could be sequestered annually through BECCS by 2050 if CCS has been developed. BECCS used to produce hydrogen, power, or aviation biofuels, or used in industry, could all be efficient uses of a limited biomass resource.
- We also considered a scenario in which the UK imported more harvested biomass than its 'fair share' of the global resource as part of a wider international effort to sequester and store carbon dioxide (a 'UK BECCS Hub').
  - The total biomass resource in this scenario could be used to produce up to 180 $MtCO_2$/yr of removals if done with BECCS.
  - Article 6 of the Paris Agreement allows for bilateral collaboration on mitigation actions between countries. Large-scale use of biomass from abroad may be suitable for collaboration under Article 6. This may mean that not all the removals from imported biomass would be accounted for under the UK's international commitments, with some of the emissions removals allocated to the exporting country. It is likely that these arrangements will emerge on a case-by-case basis, so it is very difficult to predict exactly how they might develop in the long-term.

These previous scenarios, combined with the new work the Committee has undertaken and commissioned, have informed the GGR scenarios used in this report. Whilst we refer to GGR throughout this chapter, we only consider methods capable of removing CO_2 from the atmosphere as other gases have much lower concentrations in the atmosphere and hence are even more difficult to remove.

(c) New evidence on greenhouse gas removals

Since the Committee's 2016 report on *UK Climate Action Following the Paris Agreement*, further UK and international research and assessment has been undertaken into the potential for CO_2 removals to contribute to climate mitigation:

- Comprehensive assessments of GGR solutions and deployment potentials have been undertaken by the National Academy of Sciences, the European Academies Science Advisory Council and the Royal Society/Royal Academy of Engineering (RS and RAE). GGR has also been considered in the recent IPCC Special Report on a Global Warming of 1.5°C, building on the IPCC 5th Assessment Report.[259]

[259] The IPCC will also soon be publishing a Special Report on Climate Change and Land, which will provide an additional assessment on the potential for, and consequences of, land-based removals including BECCS.

- The RS and RAE found that up to 130 $MtCO_2e$/yr of removals could potentially be deployed within by UK by 2050.[260] This included additional contributions from biochar, enhanced weathering (EW), and direct air capture of CO_2 with storage (DACCS) beyond the methods present in previous Committee scenarios. These additional options together totalled 45 Mt CO_2/yr (Box 10.1).
- The Government has also funded a set of research projects on GGR through the Natural Environment Research Council's Greenhouse Gas Removal research programme, covering topics related to a wide range of GGR technologies.

The Committee has reviewed this new information to assess the potential deployment of GGR in the UK. In support of this work, the UK Energy Research Centre's Technology and Policy Assessment team has further undertaken a review of the requirements, potentials and costs of BECCS and DACCS (Box 10.2).

This chapter considers the potential for wood in construction and BECCS-based removals to be deployed in the UK by 2050, along with the potential from additional GGR technologies of DACCS, biochar and enhanced weathering:[261]

- **Direct Air Capture of CO_2 with Storage (DACCS)** is the separation of CO_2 from the ambient air using chemical reagents. The captured CO_2 is then permanently stored in geological formations.
- **Biochar** is the thermal decomposition of biomass in low-oxygen conditions to form a charcoal. This can be added to soils as a stable long-term store of carbon which also helps to improve soil fertility.
- **Enhanced weathering** spreads silicate rocks over the land surface, which naturally fix carbon out of the air over geological timescales. This natural process is speeded up by grinding up rocks to maximise their reactive surface area.

These methods are assessed as being at a level of development such that they might feasibly contribute to net removals of GHGs in the UK around 2050 or soon after. There are other proposed GGR methods that we have not assessed in detail in this report. Several possible barriers to including other GGR technologies within UK emissions reduction scenarios have been identified. These include:

- Technologies at a very early stage such that it is very difficult to estimate deployment potentials, costs and possible side-effects with any confidence.
- Technologies that are not applicable for use at scale in the UK.
- Methods with substantial 'non-local' impacts. Some GGR technologies (for example methods directly affecting the ocean environment) are best considered in an international framework to ensure appropriate governance.

As research and development continues the barriers identified above may be removed for particular GGR technologies. If so, other technologies could be included within scenarios for GGR in the UK in the future.

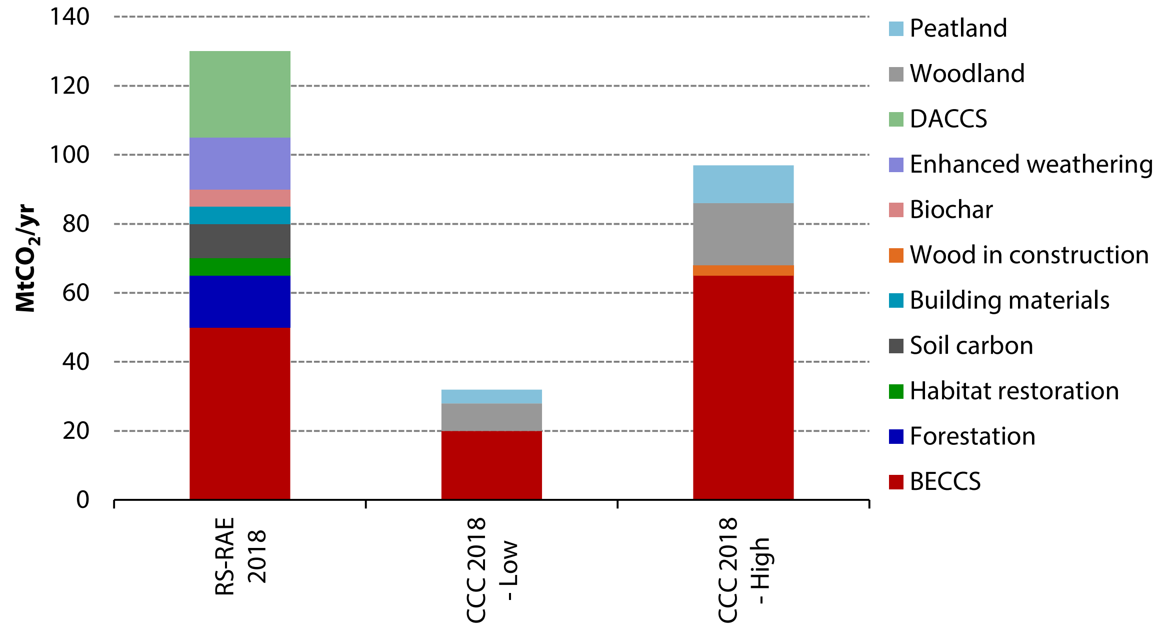
[260] This includes the land-based removals covered in Chapter 7 in addition to the 'engineered' removal methods considered in this chapter.
[261] Scenarios for removals from the land-use sector (including afforestation) are considered in Chapter 7.

Box 10.1. The Royal Society/Royal Academy of Engineering report on greenhouse gas removal

The Royal Society and Royal Academy of Engineering (RS and RAE) published an assessment of the potential scale of GGR in both the UK and globally in September 2018.

- They considered it was technically feasible to remove up to 130 $MtCO_2e$/yr in the UK by 2050 (Figure B10.1) but that this would be very challenging. The RS and RAE report did not look in detail at a broader range of feasibility constraints, including sustainability and institutional feasibility required to bring about a very large scale of removals deployment.
- This scale of removal would require GGR methods ready to deploy today (such as tree planting) at a very large scale, as well as the development of a number of new GGR options including BECCS and DACCS, all of which would have to be deployed at large-scale.

Figure B10.1. Removals in the RS and RAE report and CCC biomass and land-use reports



Source: CCC (2018) *Biomass in a low-carbon economy*; CCC (2018) *Land use: reducing emissions and preparing for climate change*; Royal Society and Royal Academy of Engineering (2018) *Greenhouse gas removal*.
Notes: The middle and right hand columns show the low and high end of the removals in the CCC's 2018 reports. All columns are for the year 2050. There is some, but not complete, overlap between some RS/RAE categories (e.g. forestation) and CCC categories (e.g. woodland).

The RS and RAE report suggested a number of key actions for developing at-scale removals in the UK:

- Pursue rapid ramp-up of forestation, habitat restoration, and soil carbon sequestration, across large UK land-areas.
- Establish an incentive or subsidy system to encourage changes of land practice, particularly for soil carbon sequestration.
- Encourage changes in building practice to use wood and concrete manufactured with carbonated waste.

Box 10.1. The Royal Society/Royal Academy of Engineering report on greenhouse gas removal

- Develop monitoring and verification procedures and programmes to track the effectiveness of GGR.
- Grow and import sustainable biomass at large scale to meet the need for both energy and GGR demands.
- Pursue research into the GGR potential of enhanced weathering and biochar in UK agricultural soils, and into BECCS and DACCS for longer term deployment.
- Capitalise on UK access to suitable reservoirs for CCS, and relevant engineering and industry expertise, to establish substantial infrastructure for transport and storage of CO_2.

While the Committee does not consider it appropriate to include all of the GGR options identified in this work, it considers the recommendations broadly appropriate.

Source: Royal Society and Royal Academy of Engineering (2018) *Greenhouse gas removal*.

Box 10.2. UKERC rapid evidence review of BECCS and DACCS

The Technology and Policy Assessment function of the UK Energy Research Centre (UKERC) has conducted a rapid evidence review of the literature on the costs and potential of BECCS and DACCS, alongside the Committee's work.

The UKERC review addressed two overarching questions, for both bioenergy with carbon capture and storage (BECCS) and direct air capture (DAC):

1. What is the potential contribution that these technologies could make to CO_2 removal and potentially CO_2 emissions reductions to achieve net zero emissions in the UK?

2. What are the current and projected costs, globally and in the UK, of these technologies and how plausible are projected cost reductions (including evidence for the benefits to be derived from economies of scale/technology learning)?

Over the course of the systematic literature review, 170 documents were selected as directly and potentially relevant. Whilst the review covered articles published since 2005, over 70% of the literature was published in the last three years, which shows a clear acceleration of the research activity on CO_2 removal.

Most of the documents fall into five main categories: review-type studies (15%), bottom-up assessments of BECCS potential (20%), techno-economic studies (30%), top-down and integrated assessment studies (12%) and inter-disciplinary studies investigating the political environment, market opportunities, value creation and social considerations of deploying BECCS (11%).

Source: UKERC (2019) *Bioenergy with carbon capture and storage, and direct air carbon capture and storage: Examining the evidence on deployment potential and costs in the UK.*

2. Potential for greenhouse gas removal in the UK

This section sets out our analysis for the extent to which different removal methods could remove emissions from the atmosphere. We address several technologies in turn:

(a) Land-based removals

(b) Wood in construction (WiC)

(c) Bioenergy with carbon capture and storage (BECCS)

(d) Direct air capture of CO_2 with storage (DACCS)

(e) Biochar

(f) Enhanced weathering

(a) Land-based removals

Land-based removals are covered in detail as part of our land-use scenarios in Chapter 7. Further Ambition options considered there for removing carbon from the atmosphere include:

- **Forestry.** Afforestation of around 30,000 ha/year (increasing woodland cover from the current 13% of UK land area to 17%), combined with an increase in active woodland management, increases the net forestry sink to 22 $MtCO_2e$/yr by 2050 compared to 18 $MtCO_2e$/yr in 2017 (under a business-as-usual scenario it would be expected to decline to less than 8 $MtCO_2e$/yr by 2050).
- **Peatland** restoration reduces losses of carbon to the atmosphere, but peatland overall remains a source of emissions in 2050.

Combined together, all land-based removals provide a total removal of 30.9 $MtCO_2e$/yr in 2050.

The remainder of this chapter focuses on other types of GGRs, which we collectively refer to as 'engineered removals'.

(b) Wood in construction (WiC)

Using WiC provides a long-term store for carbon in the built environment. The potential contribution of WiC to removals of carbon from the atmosphere depends on both the level of future house building and the extent to which timber is used as part of the construction process. Avoided emissions from the production of cement and bricks are an additional advantage of using WiC. These savings are reported in our Industry scenarios (Chapter 4).

Our scenarios for GGR from WiC are derived from work the Committee commissioned from the Bangor Biocomposites Centre as part of our report on *Biomass in a low-carbon economy*.[262] This work concluded that wood-based construction methods are approximately equal cost to alternative construction methods and therefore removal of CO_2 from WiC is assumed to have no cost in our scenarios.

Our scenarios are based on the number of housing starts rising to over 320,000 each year by 2050, consistent with the Government's house building ambition, but span a range of levels of uptake of WiC:

[262] Bangor Bio-Composites Centre (2019) *Wood in Construction in the UK: An Analysis of Carbon Abatement Potential, Extended Summary*, published as supporting evidence for CCC (2018) *Biomass in a low-carbon economy*.

- **Core:** The proportion of timber-framed houses and engineered wood systems makes up the same proportion of new build as they do today (15-28%).[263] This leads to a removal of 2.0 $MtCO_2e$/yr in 2050, growing from a sequestration of about 1 $MtCO_2$/yr today.
- **Further Ambition:** The proportion of timber-framed new build houses rises to over 40% by 2050. Engineered wood systems remain a minor contributor, reaching 5% by 2050. This leads to a removal of 2.3 $MtCO_2e$/yr in 2050.
- **Speculative:** The proportion of timber-framed houses rises to 80%. Engineered wood systems increase at 10% per year to 2027 then 20% year from 2027 to 2050. This leads to a removal of 3.2 $MtCO_2e$/yr in 2050.

Additional scope from non-residential buildings has not been reflected here as the evidence base is weaker, implying that these are conservative estimates overall.

Several other key assumptions underpin these scenarios:

- **Domestic timber.** Only WiC arising from domestic supplies of wood would appear within the UK emissions inventory. Although only about half of wood used in construction currently is domestically-sourced, we assume that all demand is met with domestic sources in the longer-term, consistent with the upscaling of tree planting for wood and timber in our land-use scenarios.
- **End-of-life considerations.** We assume that WiC represents a long-term sink of carbon equivalent to geological storage. As houses have a finite lifetime, this means that the wood would have to be recycled into the energy system and used in BECCS when the buildings are demolished.

Some of the removal from WiC is included in the land-use scenarios which consider the amount of carbon in harvested wood products as part of the forest carbon stock. Our economy-wide scenarios account for any overlap to avoid double-counting of any removals across the economy.

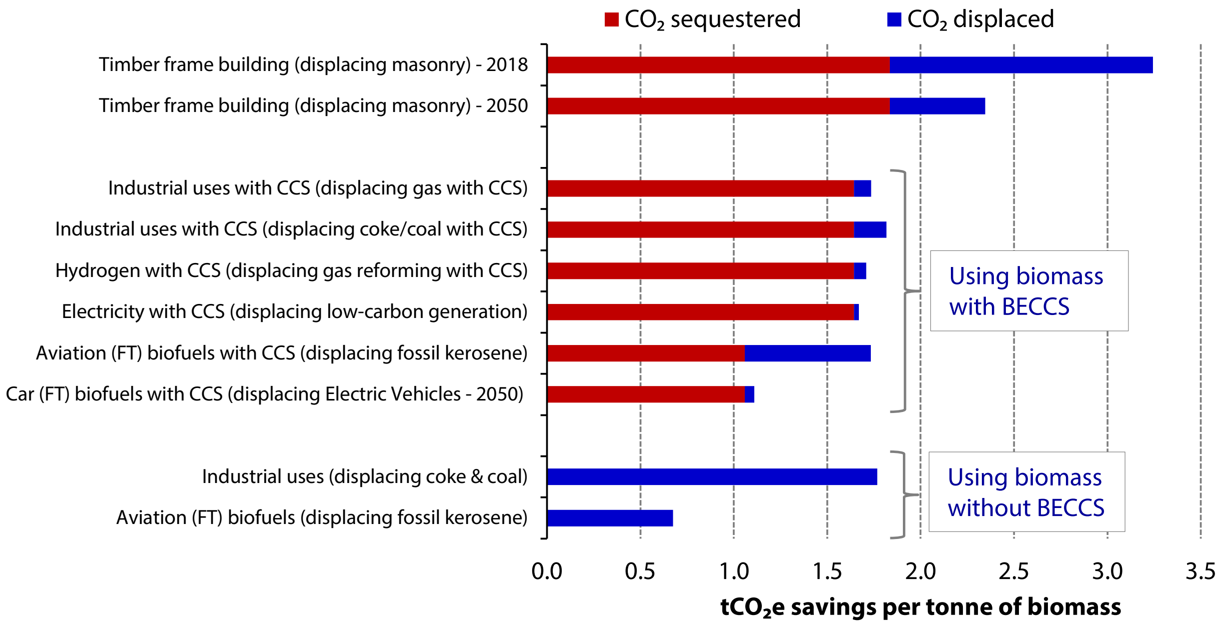
(c) Bioenergy with carbon capture and storage (BECCS)

Our scenarios for use of bioenergy are based on an assumption that harvested biomass is used where it can minimise overall greenhouse gas emissions. This is critical as there is likely to be a finite supply of harvested biomass available to the UK that is truly low-carbon and does not compromise other aspects of sustainability (e.g. food production and biodiversity). The size of this resource was assessed in detail as part of our 2018 report *Biomass in a low-carbon economy.*

In that report we updated our assessment of the relative carbon-efficiency of different options. Within the energy system we concluded that biomass should be used with CCS wherever possible. A range of BECCS applications (e.g. electricity generation, hydrogen production, production of aviation biofuels) can provide similar overall net emissions reductions when considering the combination of CO_2 sequestration and displaced fossil CO_2e emissions (Figure 10.1).[264]

[263] A high value of 28% is assumed for use in the scenarios.
[264] For production of biofuels, achieving a similar level of net reduction in CO_2 emissions depends on the biofuel displacing fossil fuels that cannot otherwise be displaced (e.g. in aviation). Use in other applications (e.g. cars), where fossil fuel combustion can be eliminated, provides significantly lesser net reductions in emissions.

Figure 10.1. Estimated GHG abatement across different biomass applications



Source: CCC (2018) *Biomass in a Low-Carbon Economy*.
Notes: This chart shows estimates of GHG abatement provided by an oven dried tonne of biomass used in various sectors, considering the most appropriate counterfactual (i.e. what we would expect it to be displacing, long-term).

In developing our BECCS scenarios for this report we follow a principle of using biomass where it is most carbon-efficient, but staying within our overall estimate of sustainable low-carbon harvested biomass:

- For overall biomass supply we consider an average of our 'Poor global governance; Low UK supply' and 'Global governance and innovation' scenarios from our report on *Biomass in a low-carbon economy* (Scenarios 1 and 4). The total available harvested biomass resource is assumed to be almost 200 TWh in 2050, equivalent to around 10% of projected UK primary energy use in 2050. Chapter 1 of this report provides a more detailed background to the biomass supply scenarios assumed in this report.
- Subtracting wet waste biomass that is not appropriate for use in BECCS from the total leaves up to around 173 TWh for potential BECCS use in the economy.

Within our **Further Ambition** scenario, this resource is deployed with CCS across end-uses in industry, production of biofuels to displace residual fossil fuels in aviation and off-gas grid buildings, and in energy generation:[265]

- Our **industry** scenarios identified cost-effective options to deploy around 3.8 $MtCO_2e/yr$ removal through BECCS using around 13 TWh of resource.

[265] As indicated in Figure 10.1, allocating the full suitable resource for BECCS to energy generation (i.e. power generation and/or hydrogen production) would lead to a very similar overall emissions saving as we have assumed through a mix of BECCS routes. This would imply a higher level of CO_2 sequestration and a lower level of displacement of fossil fuel emissions in the energy system compared to the assumed mix of BECCS applications we have assumed.

- Within **aviation** we meet up to 10% of fuel demand with sustainable biofuels with CCS, consistent with the recommendations of our *Biomass in a low-carbon economy* report. This is produced with CCS to ensure that it leads to similar emissions reductions as other uses of harvested biomass. Total sequestration with BECCS in this sector is around 6.6 $MtCO_2e$/yr, in addition to 3.3 $MtCO_2$/yr saving from use of the biofuels in aviation, from a total of primary energy resource of 32 TWh that supplies 14 TWh of bio-kerosene.
- In **buildings off the gas grid**, we assume a small amount of residual bio-LPG that is used in hybrid heating systems to supplement heat pumps. The final energy consumption of 7 TWh is produced from 15 TWh of primary energy resource, providing 1.3 $MtCO_2e$ saving from displacing fossil heating fuels and 3.4 $MtCO_2e$ sequestration via BECCS on production of the bio-LPG.
- The remainder of the harvested biomass resource is assumed to be used with CCS in the **power** sector, displacing gas-fired generation with CCS. This provides 35.4 $MtCO_2e$/yr of removals, from 112 TWh of resource. This resource could equally be used for hydrogen production from BECCS with very similar emissions savings, instead displacing hydrogen production from gas with CCS.
- Our analysis suggests that used in the power sector, BECCS would cost £158/tCO_2e removed in 2050, based on a mix of primarily domestic feedstocks with a smaller (20%) contribution from biomass imports. We have costed all of the BECCS in our Further Ambition scenario at this cost, due to the less developed evidence base for the costs of BECCS in industry and for production of biofuels.

Overall, this use of 173 TWh of bio resource is assumed to provide 51 $MtCO_2$ sequestration, in addition to displacement of fossil combustion emissions of 4.6 $MtCO_2$ and contributing 6% of power generation. As the carbon efficiency of all of these BECCS applications is broadly similar, different partitions of biomass resource between BECCS applications would be possible with very similar total removals.

Our **Core** scenario considers total BECCS deployment at less than half that in our Further Ambition scenario, removing a total of 20 $MtCO_2e$/yr across the economy. This is the low end of the range of estimated feasible BECCS deployment set out in our report on *Biomass in a low-carbon economy*. This level of emissions saving is also similar to what would be provided by the use of the Further Ambition quantity of biomass resource used without CCS to produce aviation biofuels (which save only around 40% the emissions of BECCS - see Figure 10.1).

Additional deployment of BECCS under large increases of imported biomass to the UK is possible and is considered as an option in our **Speculative** removals scenarios. As low-carbon sustainable biomass is an important and finite resource for the global decarbonisation effort, it is likely that such a scenario would only be plausible as a contribution to an international negative emissions effort as discussed in Chapter 4 of the advice report.

(d) Direct air capture of CO_2 with storage (DACCS)

Direct air capture of CO_2 (DAC) uses chemical processes to remove CO_2 from the atmosphere. This CO_2 can then be stored permanently in geological reservoirs. Presently there are only a small number of pilot-scale DAC test facilities in operation around the world (Box 10.3), with much technology development still required to be able to deploy at scale. However, several aspects will be common to all DACCS designs:

- **Large energy requirements**. Capturing carbon from the atmosphere is a very energy intensive process requiring a net energy input (heat and/or power) of around 2,000-3,000 kWh per tCO_2 separated, as well as materials and separation chemicals. This input energy needs to be low-carbon to maximise the net removal of CO_2 from the atmosphere.
- **CO_2 transport and storage infrastructure.** Similar to conventional CCS, infrastructure to compress, transport and store CO_2 will be required to ensure DAC provides permanent removals.
- **Small land footprint.** Unlike BECCS, which requires large amounts of land to grow the biomass feedstock, DACCS would have a relatively small land footprint, limited to the physical extent of the plant. In theory DACCS could be located anywhere, so could be sited to take advantage of available low-cost energy and/or access to CO_2 storage capacity.

The scale of DACCS deployment possible in the UK by 2050 is highly uncertain. Unlike most other GGR methods which are limited by the availability of key resources (such as biomass or land), DACCS has the potential to be used at large scales without significant resource constraints:

- DACCS technology could be rapidly developed and deployed as it is could be relatively modular. Similar technologies such as commercial air cooling systems which also process large air volumes have demonstrated a rapid ability to scale-up production with double digit growth seen in some regions.[266]
- As deployment grows capital costs could substantially reduce, similar to that seen for other mass-manufactured energy technologies.

Bringing about large-scale deployment in DACCS and cost reductions will require supply chain development and cost discovery. A sufficiently large-scale deployment such that the technology becomes standardised and the supply of component parts is expanded from workshop to factory scale production will be needed.

Our assessment is that at least a 1 $MtCO_2$/yr removal would be needed to achieve this, which could be delivered by the late 2030s. This would:

- Build up a commercial scale component manufacture supply chain. 1 $MtCO_2$/yr removal would require the production of multiple thousands of modular adsorption units, or a large commercial-scale plant for a hydroxide-based approach.
- Develop operational and regulatory experience and require the creation of frameworks to assess any environmental impacts associated with deployment.
- Have capital costs of a similar order to other strategic investments in energy technologies such as large-scale early-stage CCS deployment. These costs could potentially be shared with other countries, in deploying DAC at a scale to drive cost reductions.

We include DACCS in our **Further Ambition** scenario at 1 $MtCO_2$/yr in 2050, consistent with this minimum scale to develop the necessary supply chains and development to better understand further deployment potentials.

If costs do fall due to initial deployment, DACCS could potentially remove much more by 2050, although this is highly uncertain. The RS and RAE 2050 report included DACCS removal of 25 $MtCO_2$/year in the UK by 2050. This scale of deployment by 2050 would require:

[266] IEA (2018) *The future of cooling,* https://www.iea.org/futureofcooling/

- Around 50 TWh energy input in 2050 (equivalent to approximately 15% of the UK's 2016 total electricity generation). Although some of this could be provided from waste heat, this would require a significant increase in UK electricity generation, implying additional build of up to 10 GW of offshore wind.
- An increase of around 14% in use of CCS compared to our Further Ambition scenario. This additional CO_2 transport and storage capacity would be relatively inexpensive if co-located with large-scale CCS uses (e.g. BECCS) to ensure economies of scale.
- Investment in DAC facilities of around £38 billion with a land footprint of the order of 50 km^2.

If these facilities were delivered in the period from 2040 to 2050, this would require annual installation of a 2.5 $MtCO_2$ DAC facility, potentially consisting of several tens of thousands of separation units, with an investment cost of around £3.8 billion, on a site of around 5 km^2, with the additional energy coming from an extra 1 GW offshore wind farm. Over the 2040s two extra CO_2 pipelines would likely be needed and at least one extra storage site would need to be developed.

We consider a removal of 25 $MtCO_2$/yr by 2050 as the extent of **Speculative** ambition for DACCS removals by 2050, consistent with the RS and RAE report.

Box 10.3. Current DACCS designs

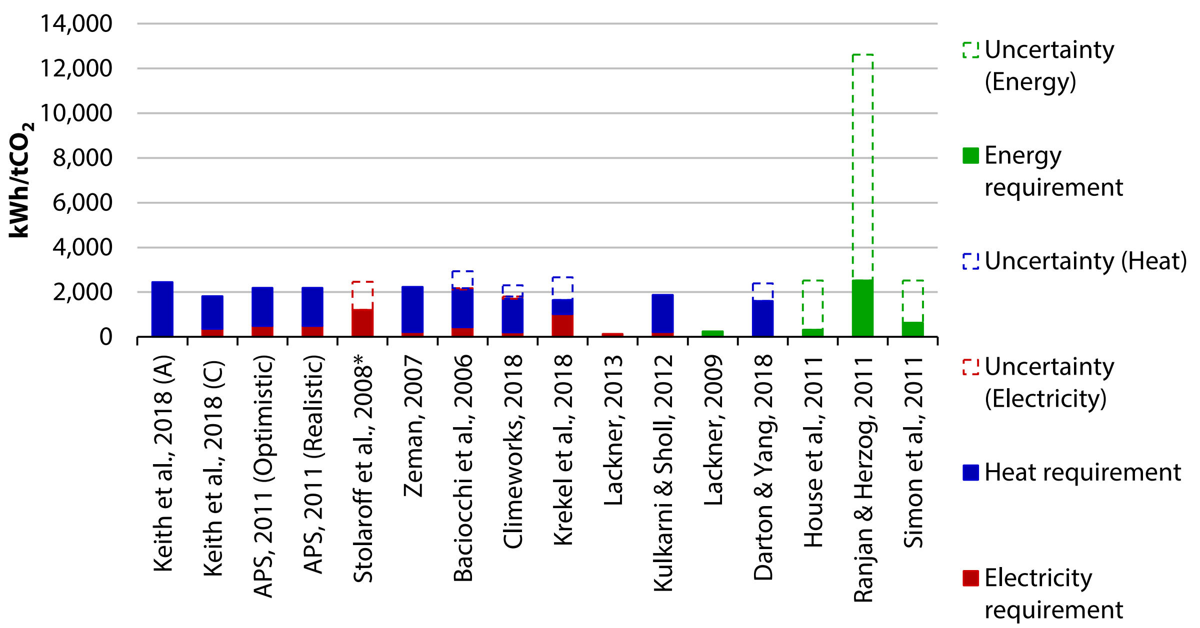
All DACCS designs require a large flow of air (either natural or with fans) to remove significant amounts of carbon. They also all need to regenerate the chemical reagent used to fix the CO_2 out of the air to collect the CO_2 for storage and to allow the reagent to be reused. There are two leading direct air capture approaches around the world today, both with operating pilot demonstration facilities:

- Canada-based Carbon Engineering use a lime-soda process based on well-established industrial chemical processes to facilitate up-scaling, commercial provision of component units and prediction of costs. Air is drawn into contact with sodium hydroxide which absorbs CO_2 to create sodium carbonate and water. Lime is added to the sodium carbonate resulting in regenerated sodium hydroxide and calcium carbonate. High-temperature heat (~900°C) is then applied to regenerate the lime and release the CO_2 enabling the process to continue.
- Switzerland-based Climeworks drive air across a filter where chemicals called amines bind to the CO_2. The filter is then heated (~100°C), potentially by using waste heat from other facilities, releasing the CO_2 and the regenerated filter re-used. The fans and filters are combined into small stand-alone units to enable modular sizing and potentially facilitate rapid scaling through mass manufacture.

Both approaches require similar energy input (around 2,000-2,500 kWh/tCO_2 separated), but differ in the proportions of heat and electricity and the grade (temperature) of heat required. This is consistent with other estimates in the scientific literature (Figure B10.3).

Box 10.3. Current DACCS designs

Figure B10.3. Energy requirements of DACCS processes in the scientific literature



Source: UKERC (2019) *Bioenergy with carbon capture and storage, and direct air carbon capture and storage: Examining the evidence on deployment potential and costs in the UK.*

Source: CCC analysis; UKERC (2019) *Bioenergy with carbon capture and storage, and direct air carbon capture and storage: Examining the evidence on deployment potential and costs in the UK.*

Cost estimates

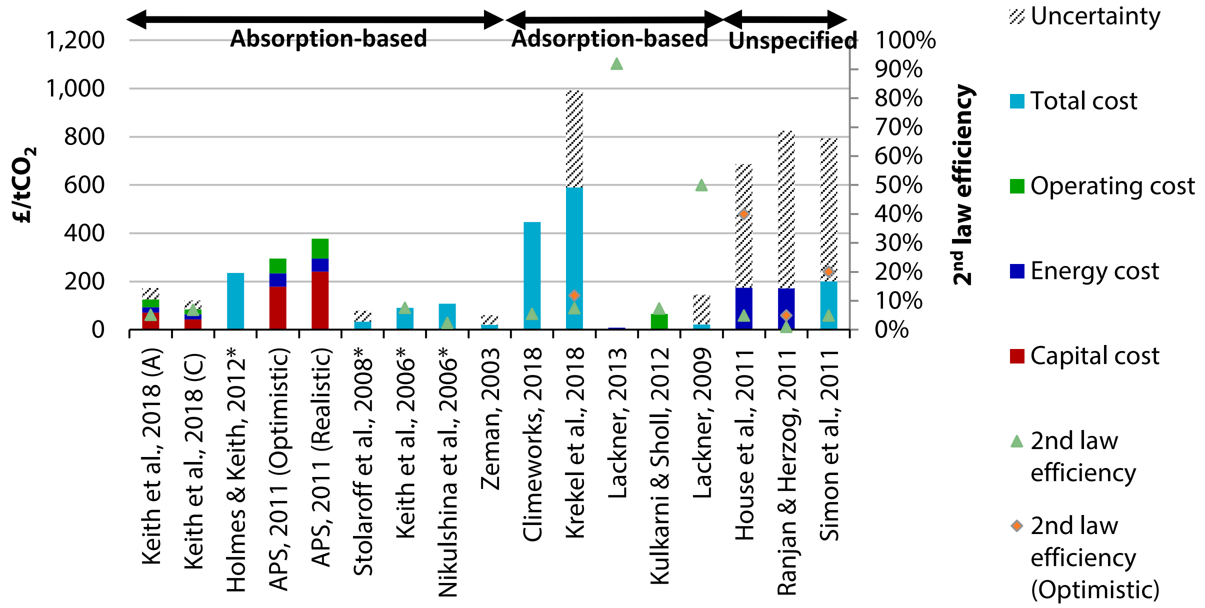
Cost estimates for DACCS, encompassing capital, operational and energy costs, remain uncertain and depend on assumptions on energy sourcing (carbon intensity and availability of low-cost surplus power and waste heat), future power prices, and scaled production of facilities:

- Literature assessments suggest present costs of around £450/tCO_2 (within a range of £150-£600) at large-scale deployment, with some suggesting that technology improvement and scaling savings could potentially bring costs to below £200/tCO_2 (Figure 10.2).
- There is limited data from comprehensive bottom-up DACCS cost assessments. Studies assessing potential to deliver large scale CO_2 removal in the context of system-wide decarbonisation often use future cost projections provided by the developers of the technology. The proprietary protection of underlying technologies make it difficult to verify these cost estimates of current or future deployment independently at the present time.

These costs are in general only for the separation of CO_2, such that compression, transportation and geological storage would be additional. We assume these to be £10/tCO_2 given that DAC can be co-located with other forms of CCS and share CO_2 infrastructure.

The 1 MtCO_2 of DACCS in our Further Ambition scenario, and the potential for a further 24 MtCO_2 as a Speculative option, have been assumed to cost £300/tCO_2.

Figure 10.2. Cost of capture via DACCS processes in the scientific literature



Source: UKERC (2019) *Bioenergy with carbon capture and storage, and direct air carbon capture and storage: Examining the evidence on deployment potential and costs in the UK.*

(e) Biochar

Biochar, a charcoal-like substance, stores biomass carbon in soils in a stable form that is resistant to decomposition, remaining there for an extended period (Box 10.4). It requires a supply of biomass feedstock, facilities to produce the biochar, an ability to distribute large amounts of it to managed land, and regulatory permission and support. However, unlike the use of harvested biomass in BECCS, or direct air capture, it does not depend on the development of a CO_2 transport and storage infrastructure.

Potential for biochar deployment in the UK

The potential for biochar deployment depends largely on the amount of harvested biomass resource available for use:

- The RS and RAE report suggests biochar could contribute removal of 5 $MtCO_2e$/yr through application to 1.5 Mha UK arable land (25% of total), with feedstock supplied half from purpose-grown crops (requiring 0.1 Mha) and half from biomass residues.
- A comprehensive study of UK biochar potential estimated a possible removal of 3.5 - 21 $MtCO_2e$/yr (2-10 $MtCO_2e$/yr directly from biochar emplacement with the remainder from improved crop productivity and displacement of carbon intensive energy production).[267] Costs are estimated at -£140 to £200 per tCO_2e (negative values come from savings from avoided waste disposal fees and revenue from energy production).

[267] Shackley, S., Hammond, J., Gaunt, J. and Ibarrola, R. (2011) The feasibility and costs of biochar deployment in the UK. *Carbon Management*, 2 (3), 335-356.

- A study on Scotland estimates a removal potential of 0.84 - 5.5 $MtCO_2e$/yr (application to 0.2 Mha).[268]

As large-scale biochar deployment requires the use of a finite low-carbon sustainable harvested biomass resource, it competes with other uses of biomass, such as BECCS. Based on current evidence, our analysis indicates that BECCS applications are likely to be a more efficient use of this finite harvested biomass resource:

- Pyrolysis converts approximately half of the carbon content of the biomass to biochar, while BECCS could capture in excess of 90%. In principle, CCS could be applied to the pyrolysis process to capture the released CO_2 so that the process provides removal potentially similar to BECCS, but this will generally not be feasible for smaller-scale biochar production.
- Although biochar is expected to reside in the soil for a long duration, there remains some uncertainty about the duration of some kinds of biochar storage, and is likely to be a less certain long-term store of CO_2 than geological storage.
- As highlighted in our *Biomass in a low-carbon economy* report, the potential for energy services from biomass to avoid emissions elsewhere in the economy is generally likely to be relatively limited by 2050, given the background of a rapidly decarbonising UK economy. The overall carbon efficiency of biomass use is therefore likely to be dominated by the amount of carbon sequestered per tonne of harvested biomass (see Figure 10.1).

Possible environmental consequences

Small-scale production of biochar (e.g. when sold as soil improver) is a mature technology and is in use around the world today. However, using biochar for CO_2 removal requires high rates of application to soils. While this has been widely discussed and researched, including in small field trials, it has not yet become established.

Some possible side-effects and co-benefits of large-scale biochar applications have been identified in the scientific literature:

- Biochar application can improve soil quality, fertility and productivity.
- It may darken soils and reduce their reflectivity, creating a warming influence on the climate partially offsetting the benefits from greenhouse gas removal.
- It may cause increases in the emissions of non-CO_2 greenhouse gases from the soil, but uncertainties about any effect are very large.
- Biochar application can be conducted alongside existing land uses, such as agriculture, so does not require dedicated land for spreading biochar. However, it may require dedicated land for producing the necessary harvested biomass feedstock.

Summary

Throughout our scenarios we take an approach of using harvested biomass where it is likely to produce the most benefit for the climate. Therefore, due to the greater potential for sequestered carbon, we preferentially choose to use harvested biomass in BECCS applications over biochar production.

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[268] Alcalde, J., Smith, P., Haszeldine, R.S. and Bond, C.E. (2018) The potential for implementation of Negative Emission Technologies in Scotland. *International journal of greenhouse gas control*, 76, 85-91.

As application of biochar to soils for CO_2 removal would be effectively irreversible, and the technology is only in the early stages of testing of deployment, we do not judge it to be prudent to pursue large-scale biochar deployment while the potential for undesired side effects is unclear. However, we support further research and testing to help further develop this option and better understand the potential for any long-lasting side effects.

Box 10.4. Biochar

Biochar is produced from either waste or purpose-grown biomass feedstock material through heating in a low-oxygen environment (pyrolysis), then added to managed soils. The pyrolysis process produces more energy (in the form of heat) than it requires and also produces combustible liquids and gases which could be used elsewhere in the economy. The properties of biochar including its longevity in the soil, influence on soil fertility, and overall life cycle CO_2 removal, depend on the choice of feedstock, the pyrolysis conditions and what the output energy is used for, as well as the soil conditions and the rate of application. In general higher-temperature pyrolysis produces less char and more combustibles so the process can be optimised to different demands and different aims.

Biochar has the potential to be developed for small-scale local application to soil, through to large-scale operations with regionally integrated feedstock collection, biochar production and widespread distribution. It can be applied to arable soils in large amount (up to 30 - 60 t/ha) without changing the primary purpose of land use. It could also be applied to other managed soils, for example during forestry planting.

Provided the longevity of CO_2 storage is established, biochar could be included in carbon accounting methodologies on the basis of the amount of material added to the soil.

Source: CCC analysis.

(f) Enhanced weathering

Enhanced weathering requires the crushing and fine milling of rocks, which are then spread onto managed land to remove CO_2 from the air (Box 10.5).

Potential for enhanced weathering in the UK

Achieving a substantial amount of removal would require a relatively large amount of rock material. In the UK, the rock material could come from several possible sources:

- **By-products of industrial processes**. The UK produces industrial mineral waste material (around 86 Mt/yr) potentially suited to use for enhanced weathering of which 90% comes from construction and demolition. In theory much of this construction and demolition waste could be used for enhanced weathering, but would need to be assessed as free from contamination.[269] UK steel production produces around 2.5 Mt/yr of slag which has theoretical potential to remove around 1 $MtCO_2$/yr. There are also legacy industrial mineral waste deposits from past industrial activity. These are widely distributed, although specific properties and access are uncertain.

[269] Construction and demolition waste, provided this is assessed to be uncontaminated, is presently encouraged to be recycled and re-used.

- **Natural deposits** in the UK are a mixture of a large amount of 'basic' minerals that remove carbon from the atmosphere and a small amount of 'ultra-basic' rocks (that more readily remove CO_2 from the atmosphere). Most of these natural deposits are located in potentially environmentally sensitive (e.g. upland) or protected areas such as National Parks, often relatively remote from the UK's largest regions of arable production where they might be spread over land at a large scale.

As crushing and milling of rocks is very energy-intensive, enhanced weathering is a large consumer of energy.[270] Estimates of energy input have a wide range (650-3,500 kWh for basic minerals, 225 - 750 kWh for ultra-basic minerals) per tCO_2 removal, resulting in a correspondingly wide range of cost estimates (£45 - 360 and £15 - 80/tCO_2 respectively). [271]

The RS and RAE report suggested enhanced weathering could remove up to 15 $MtCO_2$/yr by 2050. This would require 20 tonnes of rock per hectare spread over 5.4 million hectares of UK arable land, with two-thirds from industrial waste and one-third from dedicated mining. A previous detailed study[14] estimated a potential of 11.8 $MtCO_2$/yr in the UK, and a recent study[272] estimates a potential in Scotland for 5.1 - 8 $MtCO_2$/yr using natural mineral resources. This would require a large expansion in the relatively small mineral extraction in the UK today.

A small resource of existing unutilised UK mining spoil waste could provide opportunity for initial demonstration with up to 4 Mt/yr of material potentially enabling removal of up to 1 - 1.5 $MtCO_2$/yr, if environmental concerns could be overcome.

Possible environmental consequences

Enhanced weathering is at a very early stage development and there is a lack of large-scale experience and understanding regarding possible environmental consequences of large-scale deployment. Although some milled minerals are currently applied to land to improve soil quality, several potential environmental hazards have been identified with large-scale enhanced weathering:

- Weathering minerals can contain hazardous trace metals which could contaminate soils, water and crops. Similar concerns relate to industrial by-products. Contaminants run off the soil into rivers and other water bodies with potential environmental consequences for river ecosystems.
- Applying finely ground rock to large amounts of agricultural land would create a substantial amount of rock dust in the air. Inhalation of fine rock dust presents a potential health hazard (silicosis), which would require management during production and application.

Large-scale application would require regulatory permission and support, and high confidence in managing possible environmental impact. Using mineral dust from industrial waste on agricultural land would also require an amendment of UK waste spreading regulation.

The Committee considers that it is not appropriate at this stage to include enhanced weathering in its scenarios, due to the irreversibility of its application, the early stage of research, the risk of potentially severe environmental side-effects and the lack of large-scale testing and regulatory

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[270] For UK application, the crushing and fine milling of minerals (up to around 60%), and transport (up to around 30%), are the largest energy input requirements.
[271] Renforth, P. (2012) The potential of enhanced weathering in the UK. *International Journal of Greenhouse Gas Control*, 10, 229-243.
[272] Alcalde, J., Smith, P., Haszeldine, R.S. and Bond, C.E. (2018) The potential for implementation of Negative Emission Technologies in Scotland. *International Journal of Greenhouse Gas Control*, 76, 85-91.

experience, but supports undertaking further research to develop this option and gain a better understanding of the potential environmental consequences.

Box 10.5. Enhanced weathering: mechanisms, scale-up and accounting

Enhanced weathering accelerates naturally-occurring reactions of silicate rocks with CO_2. For it to contribute substantially to greenhouse gas removal in the UK would require massive increases in the natural reaction rate, through crushing and milling rocks to expand the reactive surface area.

Minerals commonly considered for CO_2 removal by weathering can remove around 0.3 - 1.2 tCO_2 per tonne of mineral. This creates metal ions, most of which run-off into rivers and ultimately the sea, resulting in the long term (thousands of years) removal of CO_2. Weathering reaction rates are temperature- and moisture-sensitive, such that many global-scale analyses concentrate on application to tropical regions where maximum reaction rates (up to around five times faster than in temperate climates) might be achieved.

The technology and equipment required to implement terrestrial enhanced weathering (mining, material processing distribution and land application) are either presently available or likely straightforward to adapt:

- Enhanced weathering could be rapidly scaled, subject to regulatory support and confidence in the lack of any negative environmental side-effects. It would require provision of the additional energy and transit capacity (train, truck, ship) to move material from source to dispersion.
- Distribution on agricultural crop-land would not create land competition, and might be integrated with other CO_2 removal activities (e.g. biomass production).
- Mining for mineral supply, most likely open pit, would have a locally significant but overall small surface footprint.

High-level carbon accounting for enhanced weathering is theoretically straightforward, but detailed accounting and monitoring, verification and reporting has not yet been developed. It is likely to be complex and case-specific to the mineral properties, production and transit processes and application environment, and require soil and water sampling.

Source: CCC analysis.

3. Scenarios for greenhouse gas removal deployment in the UK

Further Ambition scenario

Our Further Ambition scenario considers a total of 54.2 $MtCO_2e$/yr engineered removals in 2050 (Table 10.1). Accounting for the overlap between land-based removals and wood in construction this would be reduced to an additional 53.0 $MtCO_2e$/yr removal that is not accounted for in any other sectors considered in this report.

Table 10.1. Opportunities for GGR in the UK in the Further Ambition scenario

Removal option	2030 5CB emissions ($MtCO_2e$)	Further Ambition removals in 2050 ($MtCO_2e$)*	Earliest date for Further Ambition emissions	2050 cost £/tCO_2e**
Wood in Construction	0	2.3	2050	0
BECCS	0	51.0	2045	158
DACCS	0	1.0	2040	300

Source: CCC analysis.
Notes: * All GHGs **Annualised costs, include all removal options contributing in 2050. Savings from wood in construction are defined to be over and above 'business as usual' levels. For the fifth carbon budget analysis, no inclusion was made of wood in construction beyond this 'business as usual' level. A small fraction of the BECCS removal comes from biomethane use in gas-fired CCS power stations.

Speculative removal options

It may be possible to go beyond the level of greenhouse gas removal in the Further Ambition scenario, though further deployment of wood in construction, BECCS and DACCS:

- **Wood in construction.** It may be possible to increase the proportion of timber-framed houses beyond the 40% of new homes assumed in our Further Ambition scenario, to 80%. This would provide an additional 0.7 $MtCO_2e$ of greenhouse gas removal, after accounting for overlaps with assumed sequestration counted in the land use sector.
- **BECCS.** The level of sustainable biomass resource assumed in the Further Ambition scenario was around 200 TWh, which is the mid-point of the range of estimates presented as scenarios in our report on *Biomass in a low-carbon economy*. Assuming the upper end of this range for sustainable resource (i.e. our 'Global governance and innovation' scenario) would increase the availability to around 300 TWh, increasing potential for BECCS by 32 $MtCO_2e$ to 83 $MtCO_2e$ in 2050.
- **DACCS.** Deploying DACCS at a large scale is potentially feasible logistically and could contribute to a cost-effective mix of solution if costs turn out to be towards the low end of current estimates. As a Speculative option, we consider that DACCS could be deployed for the removal of 25 $MtCO_2$ per year by 2050, as against 1 Mt per year in the Further Ambition scenario.

Allocation to Scotland and Wales

Spatial modelling for our 2018 Land Use report enabled allocation of the natural land-based removals (e.g. via afforestation) to different parts of the UK. Removals from WiC are also allocated based on the fraction of timber harvested in each part of the UK consistent with emissions inventory methodologies.

Our 2018 Land Use report also provided the basis for allocating some of the engineered removals, when considered alongside access to CO_2 storage capacity:

- Scotland has excellent potential for biomass production. This suggests Scotland is capable of supporting up to 33% of solid bioenergy and 50% of solid timber for use in construction. Scotland also has good storage sites for CCS, so this is not a constraint. In our Further Ambition scenario, Scotland is allocated 12 $MtCO_2e$ (22%) of all UK removals, which includes 33% of all UK BECCS from domestic sources.
- Conversely, Wales is expected to deliver low proportions of UK solid biomass (8%) and has limited access to carbon storage sites. We have allocated Wales 1.3 $MtCO_2e$ (2%) of all UK removals based on the use of wood in construction and potential CCS storage sites in the Irish sea that could facilitate BECCS in North Wales.

4. Innovation, near-term action and uncertainty

As large-scale GGR outside of the land use sector has not been deployed to date, innovation and uncertainty are more important to our assessment of potential than in other sectors.

Near-term actions and innovation support will be important in a number of different areas for removals to be a plausible contributor at scale to a UK net-zero target and reduce the substantial uncertainties that remain over UK removal potential:

- **Carbon, capture and storage (CCS).** Chapter 6 of the advice report highlights that the development of CCS capability is on the 'critical path' of achieving a net-zero target. For removals to play a significant role in offsetting residual emissions, CCS will be required to provide long-term secure geological storage for both BECCS and DACCS. CO_2 infrastructure deployment should start as soon as possible, through a regional cluster-based approach. A stable long-term policy environment is required to support this deployment pathway.
- **Biomass supply.** Near-term actions are required to ensure that the supply of sustainable low-carbon biomass can be scaled up to provide the necessary resource by 2050. In our 2018 report on *Biomass in a low-carbon economy* we recommended that the Government undertake efforts to increase the supply of sustainable harvested biomass from UK sources. This involves meeting and exceeding current tree-planting targets and overcoming the incentive barriers to the planting of second generation bioenergy crops on lower-grade agricultural land. Similarly, we recommend that the UK take an active role in further developing and improving UK and international biomass governance and sustainability criteria (see Chapter 5 of the advice report). This will be vital for imported biomass to play a significant role in a net-zero UK economy.
- **Policy framework.** Without financial rewards for greenhouse gas removal, BECCS and DACCS will not be deployed. At present, greenhouse gas removals are not valued within policy instruments (e.g. the EU emissions trading system). It will be important to correct this, although it should be recognised that in the nearer term carbon prices are unlikely to rise to a level that would drive deployment of BECCS or DACCS. In Chapter 6 of the advice report we

highlight the potential for sectors with significant residual emissions (e.g. aviation) to fund GGR solutions.

- **Innovation support**
  - For BECCS applications outside the power sector technologies to produce an ultra-clean synthetic fuel are required to turn biomass into energy carriers such as hydrogen or produce biofuels (e.g. from Fischer-Tropsh methods). Current support schemes have failed to bring forward gasification plants capable of producing genuinely ultra-clean synthetic gas. In our Biomass report, we recommended that the Government re-examine its gasification incentive scheme and shift away from a focus on the power sector to a focus on the transport and heating sectors.
  - For DACCS, as the technologies are at an early stage of testing further research and development, support is important. To date, DACCS development has had only very limited public investment. Given the potentially large future contribution from DACCS we recommend Government consider further strategic investment to support its development towards large-scale demonstration, enabling cost discovery and supply-chain establishment. In parallel, Government should consider how current emissions regulation and CCS support policies might be adapted to facilitate DACCS application.
  - For biochar and enhanced weathering, the UK is presently supporting research, including small field experiments and trialling, principally through the UK Greenhouse Gas Removal programme. The Leverhulme Trust funded LC3M centre is also undertaking a major international research programme on enhanced weathering. Subject to the results of this research further support is suggested to develop up-scaling potential and assess corresponding environmental impacts and risk.
  - A stable long-term policy environment for developing and deploying removals, alongside appropriate governance arrangements to ensure sustainability, will be crucial to ensure that a net-zero emissions target can be achieved in the UK.

At a global level, removals of CO_2 from the atmosphere will be a critical strand of the global effort to achieve the long-term temperature goal of the Paris Agreement. Chapters 4 and 6 of our advice report highlights several ways that the UK could support the development of market-based mechanisms to support removals around the globe:

- **Governance.** Without effective safeguards, the large-scale harvesting of biomass can both be high-carbon and have substantial impacts on the provision of food, biodiversity and other sustainability concerns. Strengthened governance is needed to manage the risks to sustainable low-carbon production as the global biomass market scales up, and for any new public subsidies. The long-term role of imported biomass feedstock into the UK should depend on these efforts. This requires a broader approach than existing focuses on sustainability standards to fully consider the impact of biomass production on land-carbon stocks and to drive up standards globally. Biomass sourced from high-carbon content land or with detrimental impacts on other aspects of sustainability should be ruled out by sustainability criteria, with a ratchetting-up of standards over time to incentivise best practice.
- **International accounting of biomass-based removals.** Application of the IPCC Guidelines for National Greenhouse Gas Inventories generally suggests that BECCS removals from imported biomass are reported in the jurisdiction where the capture and storage of CO_2 occurs with no removals reported in the jurisdiction exporting the biomass. However, Article

6 of the Paris Agreement supports collaboration between countries to support higher mitigation ambition around the world. The UK can lead developing international effort sharing frameworks on biomass-based GGRs, to help provide incentives to ensure that the world's sustainable low-carbon biomass resource is used as efficiently as possible.

- **National and international removals markets.** Market-based mechanisms will be important in providing at-scale GGR in the UK and abroad. The UK can support the creation of removals markets by developing rules which would enable removals to be integrated into existing carbon markets such as the EU-ETS and by working through international forums to ensure that removals can be included within the Paris Agreement's successor to the Kyoto Protocols Clean Development Mechanism and the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) with strong environmental safeguards (see Chapter 6 of the advice report).

Uncertainty and risks of non-delivery

Uncertainty is a crucial issue to the scale of GGR that can be delivered in the UK. Important uncertainties include unforeseen costs and technical issues, wider impacts and public attitudes:

- **Unforeseen costs and technical issues.** Due to being early stage technologies, the deliverability and costs of GGR are challenging to predict. For example, DACCS holds the risk of proving difficult to construct or operate at large scale and the corresponding forecast degree of cost reduction not being realised. Similarly, the large energy input needed for DACCS might prove complex to deliver, for instance if sufficient low-cost surplus energy such as waste heat proves to be unavailable. Whilst risks of leakage of CO_2 from geological storage can never be reduced to zero, they are very small compared to in-situ storage of carbon in the biosphere.
- **Scale-up rates.** The analysis in this chapter has considered both the potential for different types of removal options and the rates at which they could be scaled up. However, many of these are not established solutions that are deployed at scale and there is inherent uncertainty about the extent and pace of future potential roll-out.
- **Wider impacts.** Undertaking GGR has implications for the local and wider environment and resources which will likely increase with scale-up. Biomass based methods need to meet sustainability criteria with respect to their effect on food production, water use and biodiversity which could become more challenging at large scales. General principles for producing biomass sustainably involve avoiding sourcing from land with high carbon stocks and/or rich in biodiversity, whilst also minimising conflicts with other land uses such as food production. Some perennial crops (e.g. willow and poplar) have large water demands and are therefore likely to be less suited to planting in areas which are water-stressed.[273] Other land-based GGR methods could also bring both benefits and unwanted side effects. The identified risks from enhanced weathering to air quality and the potential for toxic contamination of soils and ecosystems are very serious barriers and would need to have been clearly addressed before large-scale deployment is considered. Continued testing at a range of scales is suggested to improve understanding and inform support for further development and future practice.
- **Public attitudes**. Developing and deploying GGR technologies that need large amounts of land (such as BECCS, enhanced weathering or biochar) requires acceptance and buy-in from

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

land-owners and land users. This may not be forthcoming where real or perceived conflicts exist with other uses of land (e.g. food production) or where side-effects exist. More broadly, positive public attitudes will be important for developing and deploying engineered removals, particularly regarding perceptions of the safety of CO_2 transport and storage infrastructure and the extent to which removals are viewed as a way of avoiding emissions reductions instead of a necessary addition. Early and sequential small-scale deployment can help build a social license for GGR technologies and test their longer term sustainability, building public acceptance for large-scale deployment of GGR.

Within an interlinked global GGR market (if one develops) the UK may have some comparative advantage for deploying CCS-based GGR technologies due to its access to a large geological store of CO_2. This could lead to the UK being host to more GGR than needed to achieve a domestic net-zero GHG target:

- The UK is well placed to host more BECCS projects given its good CO_2 storage potential and access to a market that values the energy. It is conceivable that the UK might end up deploying more BECCS than we have allowed for based on imported feedstocks and use of Article 6 mechanisms to share credit. Such a scenario was considered in our *Biomass in a low-carbon economy* report. It would require a very large, but potentially manageable, scaling up of UK biomass supply infrastructure, with port and rail transportation the biggest constraints. Sequestering up to 133 $MtCO_2$/yr in 2050 would require on the order of a ten-fold increase over today's level of biomass imports to the UK.
- Similar arguments also apply to the potential for DACCS in the UK. However, other locations with access to CO_2 storage and lower energy costs (e.g. Iceland) may be even better placed to host a large number of DACCS projects.

Wood in Construction

Specific barriers to increases in wood in construction will need to be overcome to maximise carbon stored within the built environment. A number of these were highlighted by our *Biomass in a low-carbon economy* and *UK Housing: Fit for the future?* reports. They include:

- A lack of skills around using timber within the construction industry.
- Business models and procurement processes that inhibit timber-based designs.
- Building life-cycle assessment methodologies that generally do not consider sequestered carbon from wood in construction.

Delivering significant removals from using wood in construction will require a very large increase in UK's timber construction industry, with around 27,000 - 50,000 new homes (15-28%) built in the UK each year using timber frames today. Developing supply chains for timber-based construction will require forward-looking planning and ambitious target-setting by the Government to provide a stable business environment and provide support to establish and expand UK manufacturing capacity of timber products, including engineered wood products such as cross-laminated timber and glulam.

The availability of large amounts of domestic timber for construction depends on efforts to increase substantially the amount of tree planting across the UK in a sustainable manner. Due to the inherent lag between planting and appropriate harvest dates, it is essential that such action commences immediately for large-scale domestic timber use to be possible by 2050. The barriers and risks of non-delivery for achieving this planting ambition are considered in Chapter 7.

Afforestation to provide large increases in wood available for timber and fuel could provide a range of additional benefits, including increased biodiversity if undertaken in the right way. For example, bringing degraded UK forests back under management has both GHG and biodiversity benefits and can improve resilience to a changing climate, pests and diseases. Following best-practice will be essential for avoiding detrimental impacts of large-scale forestation on the environment. These include managing forests for multiple objectives, limiting conflicts with other end-uses (e.g. food production, wood products) consistent with Sustainable Forestry Management principles. Best practice for avoiding sustainability conflicts is considered in more detail in our report on *Biomass in a low-carbon economy*.

Technical appendix: Changes from previous scenarios for the UK, Scotland and Wales

This appendix sets out how our assessment for the UK, Scotland and Wales differs from our previous assessments.

The Committee considered pathways for UK emissions out to 2050 for our advice on the UK fifth carbon budget (covering 2028-2032) in late 2015.[274] This contained a Central Scenario for the path to reach a reduction of 80% by 2050, and a Max Scenario that went further. We updated the Max Scenario in October 2016 in our report on *UK climate action following the Paris Agreement*, at which point it achieved a 92% reduction on 1990 emissions at a UK level.

Following on from this advice, we developed scenarios for Scottish (High Ambition)[275] and Welsh (Max)[276] emissions in 2050. The Scottish and Welsh scenarios were adjusted for the latest available evidence at the time, but were largely based on our Max scenarios for the UK.

Our Further Ambition scenario goes beyond these scenarios to varying degrees for the UK, Scotland and Wales (Table A.1).

Table A.1. Changes from previous scenarios to the Further Ambition scenario

	2050 emissions in previous scenarios		**2050 emissions in Further Ambition scenario**	
	$MtCO_2e$	**Reduction on 1990 in year advice was given**	**$MtCO_2e$**	**Reduction on 1990 baseline (incl. peat)**
UK	64	92%	33 to 45	95% - 96%
Scotland	7	90%	-8 to -4	104% - 110%
Wales	9	85%	2 to 3	95% - 97%

Source: CCC analysis.
Notes: Range presented for Further Ambition includes uncertainty around methodologies selected for global warming potentials and inclusion of peatland emissions (see Chapter 5 of the Net Zero advice report).

The key pieces of evidence that have contributed to our reassessment of the level of emissions abatement that is achievable and appropriate in the UK, Scotland, and Wales by 2050 include:

- The Intergovernmental Panel on Climate Change Special Report on Global Warming of 1.5°C (IPCC-SR1.5).[277] This report summarised the climate risks at a global average warming of 1.5°C and compared them to higher levels of warming, and highlighted the need for active (i.e. human-induced) CO_2 removal in nearly all 1.5°C scenarios.
- Other external publications (for example by the European Commission and Energy Transitions Commission) published following the Paris Agreement, which contain scenarios that go beyond our previous Max assessment. These have focused on decarbonising harder-

[274] CCC (2015) *The fifth carbon budget - The next step towards a low-carbon economy.*
[275] CCC (2017) *Advice on the new Scottish Climate Change Bill.*
[276] CCC (2017) *Building a low-carbon economy in Wales - Setting Welsh carbon targets.*
[277] IPCC (2019) *Special Report - Global warming of 1.5 °C.*

to-treat sectors and the use of new low-carbon technologies (Net Zero advice report, Box 5.6).

- The Committee's 2018 report on *Land Use: Reducing emissions and preparing for climate change* updated our baseline projections for emissions from land use and highlighted the impact of emissions from peatland and the potential for large-scale afforestation to sequester carbon and increase the production of solid biofuels. This analysis was done on a geographical basis, allowing land use emissions to be broken down for Scotland and Wales.
- The 2018 report on *Hydrogen in a low-carbon economy* provided further evidence on how near-full decarbonisation of the energy system can be achieved, and highlighted further potential to reduce emissions in the industry sector beyond the levels we had previously assessed.
- The further assessment of potential to reduce industrial emissions that we have conducted for this report.

Other new evidence set out in this report (e.g. new work on hard-to-decarbonise buildings, HGV infrastructure and rapid electrification) give us more confidence that the deep emissions reductions in our Max scenario are achievable.

In addition, the inventory of emissions in the UK and devolved administrations has been updated in line with the latest scientific evidence. This has been particularly important in the land use sector, where there have been changes to the estimated size of the forestry carbon sink, and new evidence on emissions from degraded peatland that will be included in future inventories beyond 2021.

This technical appendix analyses in which sectors of the economy there have been the biggest changes since our previous scenarios for the UK, Scotland and Wales.

1. Changes in the Further Ambition scenario for the UK

Our previous assessment was that achieving all of the options in the 2016 Max scenario would result in net economy-wide emissions of 64 $MtCO_2e$ in 2050 (92% below 1990 levels), including the UK share of international aviation and shipping.

In our new Further Ambition scenario, the UK could get to 34 $MtCO_2e$ of net emissions[278] (96% below 1990 levels), with scope to go further with a range of speculative options that mean the UK can credibly achieve net-zero emissions by 2050.

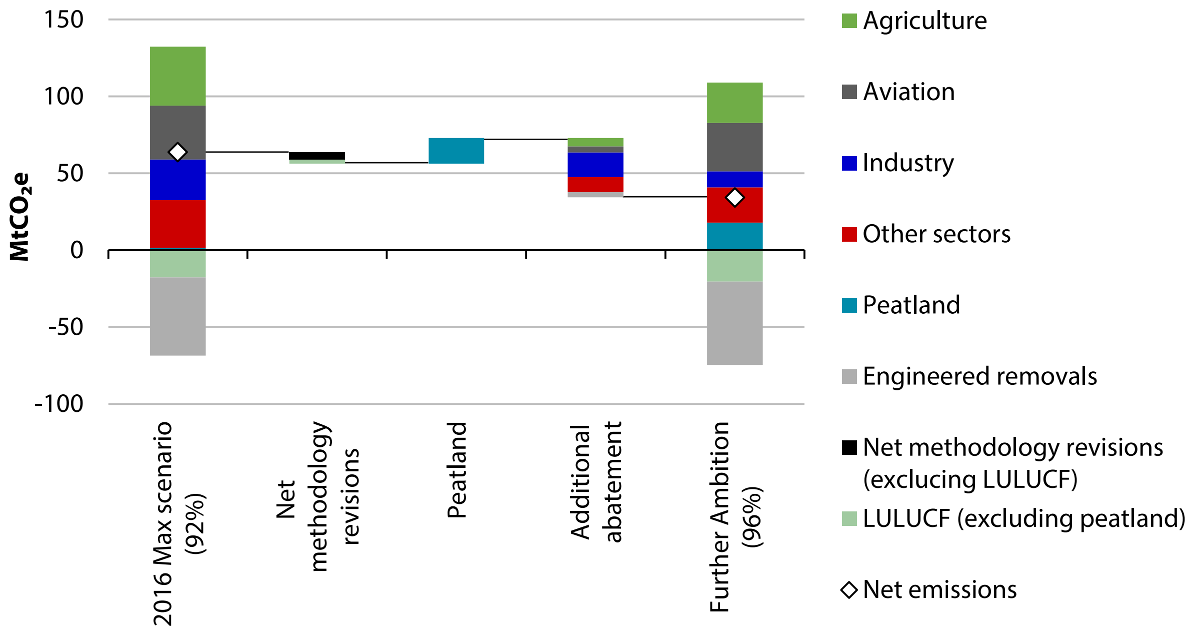
This change is driven by improvements in understanding of the current level of emissions and what can be done to reduce them across the economy:

- **Methodology changes.** Since our previous advice, new inventory changes are reflected in our land use baseline that increase the estimated size of the forestry sink in the UK by around 4 $MtCO_2e$. Other methodology changes have an additional downwards impact of 5 $MtCO_2e$ on our assessment of emissions in 2050.
- **Peatland.** Inclusion of a wider scope of emissions from degraded peatland is expected to add a maximum of 23 $MtCO_2e$ to the inventory in 2050, if actions to restore peatland are not taken.[279] With abatement measures in place under the Further Ambition scenario, this could be reduced to 18 $MtCO_2e$ for the UK as a whole.
- Emissions from **industry** are lower by an additional 16 $MtCO_2e$, particularly due to further abatement potential in stationary combustion, fossil fuel production and industrial process emissions (see Chapter 4). These can be delivered through a combination of resource and energy efficiency, electrification, use of low-carbon hydrogen and application of CCS.
- Emissions from **agriculture** are lower by 5 $MtCO_2e$ as changes in the way we farm and use our **land** put much more emphasis on carbon sequestration and biomass production. Enabled by healthier diets and reductions in food waste, our scenarios involve a fifth of UK agricultural land shifting to tree planting, energy crops and peatland restoration.
- **Other sectors.** Additional potential in other sectors could deliver a further 10 $MtCO_2e$ across the economy.
- **Engineered removals.** Our previous scenario contained 47 $MtCO_2e$ of engineered removals (BECCS and wood in construction), which has increased to 53 $MtCO_2e$ in our Further Ambition scenario (see Chapter 10).

Combined, these changes deliver additional abatement of 29 $MtCO_2e$ in 2050 (Figure A.1).

[278] All numbers presented in this section are based on the higher estimate of peatland emissions and global warming potentials from the IPCC fourth assessment report.
[279] Evans et al. (2019) *Implementation of an Emissions Inventory for UK Peatlands*.

Figure A.1. Drivers of changes to 2050 emissions from 2016 Max scenario to Further Ambition scenario for the UK



Source: CCC analysis.
Notes: Figure shows peatland emissions separated from the rest of the LULUCF sector. The current UK inventory captures around 1.3 $MtCO_2e$ of emissions from peatlands in the UK, but all sources of peatland emissions will be included from 2020. There has been a net downwards methodology revision across all other sectors (which includes changes to shipping, waste and the Smart Inventory for agriculture) since the 2013 inventory originally used for our fifth carbon budget analysis.

On a percentage point basis, our assessment for the level of credible emissions reduction by 2050 has changed more for Wales and for Scotland than for the UK as a whole:

- For **Scotland**, this reflects significant changes in our assessment of the opportunities presented by the land sector in terms of carbon sequestration and our greater ability to disaggregate these opportunities across the UK.
- For **Wales**, this reflects a large change in our assessment of potential decarbonisation of industry across the UK, based on new evidence of opportunities for decarbonisation (e.g. on the potential for use of hydrogen in industry).

2. Changes in the Further Ambition scenario for Scotland

In Scotland, methodology changes to the forestry sink and the inclusion of peatland emissions in future inventories are largely offset by an increase in the amount of engineered removals (Figure A.2). There is further action across all other sectors:

- **Methodology changes.** Since our previous advice, new scientific evidence has been published that increases the estimated size of the existing forestry sink in Scotland by around 5 $MtCO_2e$. Scotland has the largest forestry sink relative to total emissions, so revisions have had a more significant effect.
- **Peatland.** The inclusion of peatland in future inventories is expected to add up to 7 $MtCO_2e$ to emissions in Scotland in 2050, even if the ambitious peatland restoration measures in our Further Ambition scenario are carried out.
- **Industry.** Emissions from industry are lower by an additional 3 $MtCO_2e$.
- **Agriculture.** Emissions are lower by an additional 2 $MtCO_2e$.
- **Other sectors.** Additional potential in other sectors could deliver a further 2 $MtCO_2e$
- **Engineered removals.** Our previous scenario allocated 4.4 $MtCO_2e$ of engineered removals (BECCS) to Scotland, as a per-capita share of the UK total. New analysis for the Committee's 2018 Land Use report shows that Scotland has excellent additional opportunities to remove CO_2 from the atmosphere through BECCS and can deliver a higher share (22%) of all UK removals (Box A.1).

Combined, these changes have resulted in a 13 $MtCO_2e$ shift between the previous High Ambition and the Further Ambition scenario in Scotland (Figure A.2).

Box A.1. Distribution and impact of engineered removals in our scenarios

Before the inclusion of engineered removals, the UK, Scotland, and Wales and Northern Ireland all get to very low levels of emissions in our Further Ambition scenario (Table A.2).

Table A.2. Emissions without and with engineered removals in 2050

	UK	Scotland	Wales
Domestic emissions without engineered removals ($MtCO_2e$)	89	6	3
Engineered removals ($MtCO_2e$)	-54	-12	-1
Domestic emissions including engineered removals ($MtCO_2e$)	35	-6	2

In addition to this abatement effort, there is potential for 54 $MtCO_2e$ of engineered removals across the UK, the majority (49 $MtCO_2e$) of which are based on solid biomass. This is used for bioenergy with

Box A.1. Distribution and impact of engineered removals in our scenarios

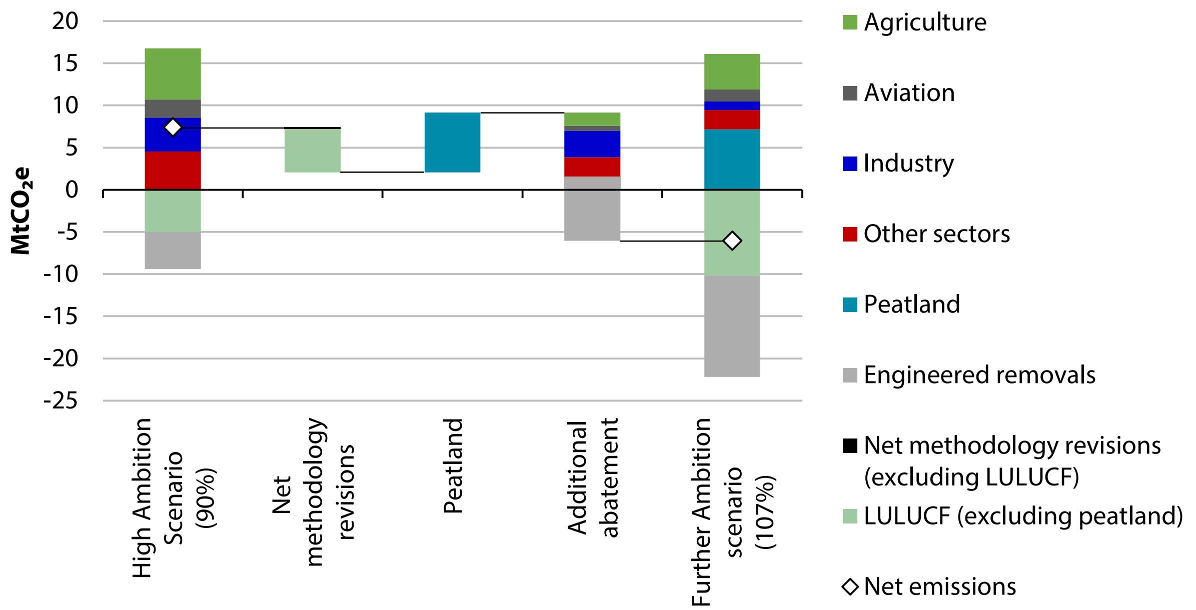
carbon capture and storage (BECCS) in industry and the power sector, and in the production processes of sustainable biofuels with CCS.

The total volume of engineered removals in the UK scenario has not changed significantly since our previous advice (Figure A.1). However, spatial modelling for our 2018 Land Use report demonstrated how each devolved administration has different opportunities to benefit from these removals:

- Scotland has excellent potential for biomass production. This suggests Scotland is capable of supporting up to one-third (33%) of solid bioenergy and 50% of solid timber for use in construction. Scotland also has good storage sites for CCS, so this is not a constraint. In our Further Ambition scenario, Scotland is allocated 12 $MtCO_2e$ (22%) of all UK removals, which includes 33% of all UK BECCS from domestic sources.
- Conversely, Wales is expected to deliver low proportions of UK solid biomass (8%) and has limited access to carbon storage sites. We have allocated Wales 1.3 $MtCO_2e$ (2%) of all UK removals based on the use of wood in construction and potential CCS storage sites in the Irish sea that could facilitate BECCS in North Wales.

Source: CCC analysis.

Figure A.2. Drivers of changes to 2050 emissions from the High Ambition scenario to Further Ambition for Scotland



Source: CCC analysis.
Notes: Figure shows peatland emissions separated from the rest of the LULUCF sector. The latest Scotland inventory captures less than 0.1 $MtCO_2e$ of emissions from peatlands, but all sources of peatland emissions will be included from 2020. There has been a net downwards methodology revision across all other sectors (which includes changes to shipping, waste and the Smart Inventory for agriculture) since the 2014 inventory used for our advice on the Scottish Climate Change Bill.

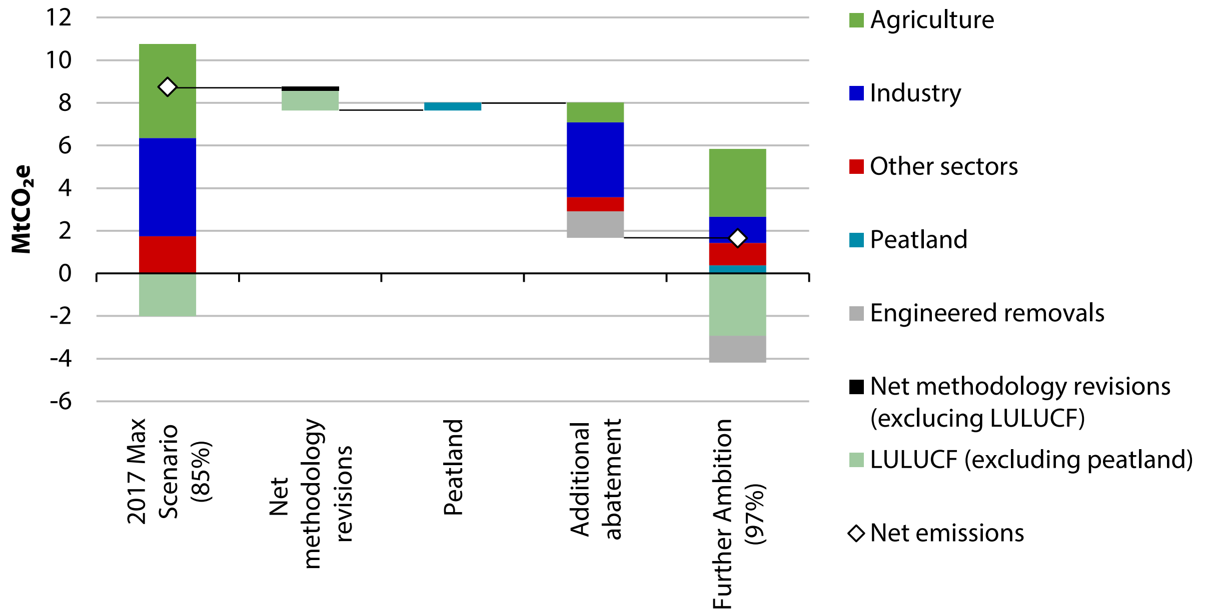
3. Changes in the Further Ambition scenario for Wales

In **Wales**, the most significant driver of change is additional abatement in industry, with more stretching action across all other sectors (Figure A.3):

- **Methodology changes.** Since our previous advice, new scientific evidence has been published that increases the estimated size of the existing forestry sink in Wales by around 1 $MtCO_2e$, plus further methodology changes of around 0.2 $MtCO_2e$.
- **Peatland.** Evidence for our Land Use report shows that Wales can be expected to have a very low share (0.4 $MtCO_2e$) of total UK emissions from peatland in 2050.
- **Industry.** We have identified an additional abatement potential of 4 $MtCO_2e$ in Wales compared to our previous Max scenario. As a high proportion of heavy industry, particularly iron and steel, is located in South Wales, the new evidence for removals from industry has a proportionally bigger impact on the emissions reductions that Wales can achieve by 2050. Residual emissions in industry are mainly in 'other manufacturing' where activity is distributed more evenly across the UK.
- **Agriculture.** Emissions are lower by an additional 1 $MtCO_2e$.
- **Other sectors.** Additional potential in other sectors could deliver a further 1 $MtCO_2e$.
- **Engineered removals.** Our previous scenario did not allocate any engineered removals (BECCS) to Wales due to the lack of carbon storage sites in South Wales. In our Further Ambition scenario, we have allocated Wales 1 $MtCO_2e$ of engineered removals, based on Wales's ability to provide timber for construction, around 8% of UK biomass and the existence of storage sites in the Irish Sea accessible from North Wales.

Combined, these changes have resulted in a 7 $MtCO_2e$ shift between the previous Max scenario and the Further Ambition scenario in Wales (Figure A.3).

Figure A.3. Drivers of changes to 2050 emissions from Max scenario to Further Ambition scenario for Wales



Source: CCC analysis.
Notes: Figure shows peatland emissions separated from the rest of the LULUCF sector. The latest Welsh inventory captures less than 0.1 $MtCO_2e$ of emissions from peatlands, but all sources of peatland emissions will be included from 2020. There has been a net downwards methodology revision across all other sectors (which includes changes to shipping, waste and the Smart Inventory for agriculture) since the 2015 inventory used for our advice on Welsh climate targets.

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