The distribution of climate action co-benefits

NZCM Methodology Report

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Climate action often creates additional benefits to society

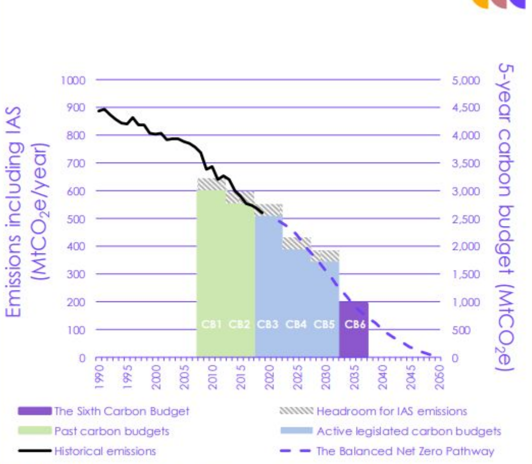
Climate action required by the CCC's Sixth Carbon Budget (6CB) will create a range of co-benefits (and disbenefits) including health, social, environmental and economic impacts that are distributed across the UK population.

There is a broad scope of low carbon actions (LCAs) that individuals can take, such as retrofitting homes with energy-efficient appliances, insulation and heat pumps; shifting from internal combustion engine (ICE) vehicles to electric vehicles (EVs), walking, cycling and public transport; and shifting away from meat and dairy towards plant-based diets. LCAs create outcomes beyond carbon reduction - such as improved air quality or reduced noise pollution - and these are called **co-benefits**. Co-benefits can be positive or negative and lead to health, social, environmental and economic impacts. The kinds of impacts that result from climate actions depends on both the LCAs themselves, as well as the ways in which LCAs are taken. Policy plays a key role in incentivising and targeting the uptake of LCAs by different members of society.

The impacts of climate action co-benefits are large in scale. However, they are frequently unevenly distributed, as they depend on the uptake of LCAs and by individuals (direct impacts), but also by others (indirect impacts). For health impacts, these also depend on an individual's initial health risk factors, based on age and sex. Therefore, assessing co-benefits is key to understanding the ways in which climate action compliments and conflicts with other societal priorities. The distribution of benefits of the net zero transition is an important story to tell, but beyond assessments of the impact on employment, consideration of these wider co-benefits is limited in the current literature.

The CCC's Sixth Carbon Budget (6CB) sets the level of greenhouse gas emissions reduction that is needed to the period 2033-2037 in the UK to limit the rise in global average temperature to well below 2°C and to pursue efforts to limit warming to 1.5°C. Alongside the absolute emissions reduction target, the 6CB sets out different pathways that the UK could take to reach net zero by 2050 through various low carbon actions, as well as a baseline scenario, which estimates the UK's future emissions to 2050, if no further climate action is planned and taken beyond today. A particular focus of the 6CB is the UK's domestic buildings and transport sectors, in which emissions reductions are increasingly required and can unlock opportunities for co-benefit creation.

Figure 1 The recommended Sixth Carbon Budget



Source: BEIS (2020) *Provisional UK greenhouse gas emissions national statistics 2019*; CCC analysis
Notes: Emissions shown include emissions from international aviation and shipping (IAS) and on an AR5 basis, including peatlands. Adjustments for IAS emissions to carbon budgets 1-3 based on historical IAS emissions data; adjustments to carbon budgets 4-5 based on IAS emissions under the Balanced Net Zero Pathway.

[1] CCC (2020). 'The Sixth Carbon Budget The UK's path to Net Zero', December 2020, p. 14.

Low carbon actions in scope of analysis

We model the impacts of low carbon actions (LCAs) assumed in each of the 6CB pathways relative to the 6CB baseline scenario. This includes energy efficiency measures, behaviour change measures and demand reduction measures (e.g. for high carbon actions).

The CCC's 6CB consists of five pathways which define the UK's potential journeys to net zero under different levels of technological advancement and public engagement:

- **Balanced Net Zero Pathway -** The recommended central pathway that assumes decisive policy to drive progress through the 2020s.
- **Headwinds Pathway -** Policies are only able to have a small impact on bringing forwards the societal changes and innovation required to reach net zero.
- **Tailwinds Pathway -** Policies have a significant impact on bringing forwards the societal changes and innovation required to reach net zero.
- **Widespread Engagement Pathway -** Higher levels of societal and behaviour change, reducing demand for high-carbon activities and increased uptake of LCAs.
- **Widespread Innovation Pathway -** Higher levels of innovation, reducing costs of low-carbon technologies.

These pathways have been developed against the 6CB **baseline scenario**, which accounts for existing climate action without further policy interventions beyond what has already been committed by the UK Government.

Each pathway and the baseline scenario has varying levels of implementation of a series of LCAs, such as heat pumps in homes or reducing the kilometres driven in internal combustion engine (ICE) vehicles. The deployment of the LCAs considered by the CCC underpin our analysis and are set out in **Table 1**. These include LCAs assumed in the 6CB as well as additional actions (such as adaptation measures) to complement the 6CB. A detailed list of the LCAs assumed in the 6CB but not considered in this analysis is set out in the appendix. Detailed impact pathways are provided in section 2, linking the most material LCAs assumed in the CCC 6CB pathways to each co-benefit that they create. This analysis looks at the difference in co-benefits and their associated impacts in a given 6CB pathway compared to the 6CB baseline.

Table 1. Low carbon actions in scope of analysis

Sector	Low carbon action	Specific measures
Domestic buildings	Install energy-efficiency measures	Heat pumps, lighting, appliances, cooking
	Improve building fabric	Floor insulation, roof insulation, solid wall insulation, cavity wall insulation, other insulation
	Install low-carbon adaptation measures	External overshading, Mechanical ventilation with heat recovery (MVHR)
	Change behaviour	Use of windows and vents[1]
Transport	Shift to low-carbon vehicles	Shift from petrol or diesel ICE vehicles (car, van, motorcycle, small rigid, large rigid, articulated, bus) to hybrid EV, plug-in hybrid EV, battery EV, range-extended EV, hydrogen to fuel cell vehicle
	Reduce demand for road transport	Shift to active transport (walking, cycling) or public transport
	Improve driving behaviour	Driving at lower average speeds
Agriculture & land use	Change behaviour	Shift from red & processed meat and dairy consumption to greater vegetable consumption

[1] Note that the use of windows and vents is only included in our analysis as a sensitivity test to dampness.

Longlist of co-benefits

We identified a longlist of 18 potential co-benefits from climate action across the buildings, transport and agriculture & land use sectors.

There is a wide range of potential positive and negative co-benefits from climate action. In scoping this analysis, we considered a longlist of 18 co-benefits across the buildings, transport and agriculture & land use sectors, set out in **Box 1**. We focused on these key public-facing sectors as they are some of the largest GHG-emitters in the UK: the residential buildings and transport sectors accounted for 51% of UK territorial CO_2 emissions in 2022 alone.[1]

The distribution of positive and negative co-benefits of climate actions may not be equally distributed over the course of the transition. Those who take action on climate may not be the same groups who benefit from climate action and the wider impacts it creates beyond just carbon abatement and direct cost savings. While this is only one distributional dimension of net zero, it is important to consider the positive and negative externalities of climate action that have implications for policy.

Other distributional lenses explored in this analysis include geographic, demographic and temporal. We set these out in more detail on the following pages.

Box 1. Longlist of co-benefits

KEY: B Buildings sector; T Transport sector; A Agriculture & land use sector

Air quality B T
Avoided air pollution from high-carbon, energy-intensive measures and behaviours in homes and transport

Comfort-taking B T
Increased well-being from consuming greater and more affordable energy (also known as ‘rebound’)

Congestion T
Change in time spent and vehicle operating costs incurred from a change in road traffic

Dampness B
Avoided excess moisture and humidity in homes from energy-efficient measures and behaviours

Diet change A
Shift away from meat and dairy to plant-based diets resulting from individual behaviour change

Energy security B T
Improved availability of energy sources at an affordable price resulting from uptake of energy efficient actions

Excess cold B
Avoided excessively low home temperatures from poor building fabric and/or energy inefficient measures

Excess heat B
Avoided excessive home temperatures from summer heat without cooling and adaptation measures

Hassle costs B T A
Reluctance or opportunity cost to change routines with low carbon actions

Natural capital A
Avoided degradation of nature from pollution or disruption from high-carbon activities

Noise B T
Avoided noise pollution from poor building fabric and energy-inefficient transport modes and behaviours

Physical activity T
Greater time spent exercising from uptake of active travel and public transportation

Road repairs T
Change in infrastructure costs incurred from a change in road traffic & vehicle weight

Road safety T
Change in number & severity of road accidents from a change in road traffic and energy-efficient driving behaviour

Social connectivity T
Improved well-being from greater interactions between communities

Soil quality A
Avoided degradation of soil from pollution from high-carbon activities

Supply chain effects B T A
Avoided disruption to supply chain activities and trade from reduction in demand for energy-intensive activities

Water quality A
Avoided degradation of water through pollution from high-carbon activities

[1] UK Government (2023). ‘2022 UK greenhouse gas emissions, provisional figures’, March 2023 (2) It also has important fiscal implications as noted in detail in the Treasury’s Net Zero Review (2021).

Co-benefits in scope of analysis

We undertook a shortlisting exercise to narrow the list of co-benefits in the scope of analysis on the basis of 4 criteria.

Following consultation with stakeholders across the CCC, Department for Environment, Forestry & Agriculture (Defra), the Office for National Statistics (ONS), HM Treasury, Department for Energy Security & Net Zero (DESNZ) and academics from the University of Leeds, University College London and London School of Hygiene & Tropical Medicine, we shortlisted the longlist of co-benefits against the following criteria:

- **Modelling feasibility.** How feasible is it to model this co-benefit? What evidence exists? What limitations are we aware of?
- **Uncertainty.** How likely is this co-benefit to materialise over the long term? Are there any key dependencies on low carbon actions or policy that influences this likelihood?
- **Materiality.** How material is this co-benefit likely to be over the long term? What is the scale of the impact resulting from the co-benefit?
- **Policy priorities.** To what extent is managing the impact of this co-benefit a matter of public interest and, by extension, a policy priority? Is there existing political leverage or commitments related to this co-benefit?

The assessment of the longlist of co-benefits against the shortlisting criteria was informed by **(a)** our prior research with UK Research & Innovation on the quantification of the co-benefits of local climate action[1] (e.g. modelling feasibility, maximising benefits) and **(b)** discussion with relevant stakeholders and with the CCC team

This resulted in a shortlist of 11 co-benefits to take forward in our analysis (set out in **Box 2** below). We provide a detailed write up of how the co-benefits score against the shortlisting criteria and rationale in the appendix.

Box 2. Shortlisted co-benefits

[1] UKRI (2022). 'Accelerating Net Zero Delivery: Unlocking the benefits of climate action in UK city-regions', March 2022.

Distributional effects considered

We estimate the distribution of impacts from climate action co-benefits to 15 different representative household archetypes and wider society.

We estimate the distribution of these impacts across UK households, using a set of 15 representative household archetypes developed by Frontier Economics in the Net Zero Distributional Impacts Model (NZDM) which explores the financial costs to households from decarbonising homes and transport. These household archetypes are based on Ofgem's energy consumer archetypes[1] and capture a range of characteristics, such as the property type and tenure of a household, whether a household owns a car, whether a household lives in a rural or urban place, and some demographic characteristics like relative income levels and average age of household members.

Using representative household archetypes with characteristics projected through to 2050 means this work can be used to explore a variety of the dimensions of the distribution of co-benefits: namely, demographically (e.g. based on income, sex, age, homeownership, car-ownership), geographically (e.g. based on rural-urban classification) and temporally (e.g. based on whether impacts accrue over the short or long term).[2]

While the 15 archetypes capture a wide range of diversity across UK households, they are notably not exhaustive as not every combination of household characteristics that exists in the underlying population will be captured in the pre-defined archetypes. However, the archetypes were defined to capture the key characteristics that make a household more or less likely to face higher costs or benefits from particular policies or policy packages. Frontier Economics conducted clustering analysis on key drivers of energy consumption and then overlaid these with representative demographic, and geographic characteristics based on correlation analysis. While this process may omit some households from the representative archetypes, it was necessary in order to estimate the most material distributional impacts of the net zero transition. For more information on the development of the household archetypes, see Frontier Economics' NZDM Methodology report.[3]

For household characteristics that have not been explored in the NZDM, we also add detail to the archetypes in order to inform the uptake of LCAs. For example, while car ownership is defined in the archetype definitions, bike ownership and the number of walking trips are not. We model the uptake of cycling and walking by each household archetype using assumptions defined in the CCC's underlying transport modal shift model, which are informed by national sources like the UK's National Travel Survey. These assumptions are consistent with the CCC's 6CB analysis and define different levels of uptake of active travel based on age, rural-urban classifcation and journey purpose.

We distinguish between direct impacts (improved health as a result of an action taken by oneself, such as homeowners benefitting from reduced excessively cold conditions indoors after insulating their homes) and indirect impacts (improved health as a result of an action taken by another individual, such as non-road users benefiting from lower exhaust pollution). Together, the direct and indirect impacts make up the total impacts to society.

[1] CSE (2020). 'Ofgem energy consumer archetypes: Final report', March 2020.
[2] Note that we do not adjust the definitions of the household archetypes over time and that the results are presented against the household archetypes as they are defined in the year 2020.
[3] Frontier Economics (2022). 'Net Zero Distributional Model: Methodology', September 2022, p. 19.

Distributional effects considered (ctd.)

We estimate the distribution of impacts from climate action co-benefits to 15 different representative household archetypes and wider society.

We also quantify the distribution of impacts both **(A)** between different household archetypes and **(B)** between individuals within a single household archetype.

(A) Distribution of impacts between different household archetypes

For each of the co-benefits, we estimate the distribution of direct and indirect impacts between different household archetypes (i.e. inter-archetype distribution). We find distributional effects where there are clear distinctions between the characteristics of household archetypes that are relevant to the creation or experience of a co-benefit. For example, household archetypes are defined as either car-owning or not. Only those that own cars are road users and will experience savings from reduced vehicle operating costs as a result of the (de)congestion co-benefit.

(B) Distribution of impacts between households within a single archetype

We estimate the distribution of direct and indirect impacts between individuals within a single household archetype (i.e. intra-archetype distribution). We find distributional effects for specific household characteristics for which we have a defined distribution for individuals within each archetype. These include EPC rating and rural-urban classification from Frontier Economics' clustering analysis. It also includes age, for which we are able to define distributions using UK population statistics from the Office for National Statistics.

These two lenses aid understanding of both the mean impact and total impact of climate action co-benefits to each household archetype:

- The mean impact to each household archetype captures the average value of co-benefits to a single household within that archetype. This value will naturally be skewed towards the representative characteristics defined for that archetype. For example, if a household archetype is defined to not own a car, the mean impact for this archetype will be based on assumptions that most households in that archetype do not drive, even if there are some households within that archetype that do drive. The closer a household is to the predefined characteristics of its archetype, the more representative the mean impact will be for that household.
- The total impact to each household archetype captures the sum of the co-benefits accruing to all households within that archetype. This value will encompass the impacts to all households within that archetype and is helpful in understanding the societal impact across all households.

The distribution of impacts between households within a single archetype (B) will help to tease out key differences to the mean impact, while the distribution of impacts between different household archetypes (A) will summarise the total impact to all households within an archetype (capturing intra-archetype differences) to aid comparison to other archetypes.

Distributional effects considered (ctd.)

We estimate the distribution of impacts from climate action co-benefits to 15 different representative household archetypes and wider society.

Table 2. Household archetype definitions

Archetype	Household characteristics						Building characteristics			Transport characteristics				
	Gross annual income (2019)	Starting population	Starting % of under 16s	Starting % of 16-34s	Starting % of 35-65s	Starting % of over 65s	On gas grid	Tenure	Housing type	Number of cars	Car types (ICE)	Car mileage in urban areas (km/car/yr)	Car mileage in rural areas (km/car/yr)	Availability of public transport in local area
A1	£32,673	5.3 million	26%	24%	29%	21%	Yes	Social renter	Mid Terrace	0	n/a	0	0	High
A2	£36,836	4.9 million	21%	17%	36%	26%	Yes	Social renter	Semi Detached	2	Both diesel	7,781	5,188	High
A3	£37,668	5.5 million	20%	31%	31%	18%	Yes	Private renter	Flat	0	n/a	0	0	High
A4	£26,022	1.6 million	17%	25%	44%	14%	Yes	Social renter	Mid Terrace	2	Both petrol	5,215	3,477	High
A5	£38,396	7.4 million	20%	18%	36%	26%	Yes	Owner occupier	Mid Terrace	2	Both diesel	7,781	5,188	High
A6	£40,582	1.1 million	20%	18%	42%	20%	Yes	Social renter	Detached	1	Diesel	7,781	5,188	High
A7	£40,811	1.3 million	19%	14%	53%	14%	Yes	Owner occupier	Semi Detached	1	Diesel	7.781	5,188	High
A8	£41,206	4.1 million	18%	12%	43%	27%	Yes	Owner occupier	Semi Detached	2	Both petrol	5,215	3,477	High
A9	£44,015	6.4 million	15%	11%	42%	36%	Yes	Owner occupier	Detached	1	Petrol	5,215	3,477	High
A10	£45,472	2.1 million	17%	8%	45%	30%	No	Social renter	Detached	1	Diesel	4,904	19,618	Low
A11	£45,836	3.1 million	17%	9%	43%	31%	No	Social renter	Detached	1	Diesel	4,904	19,618	Low
A12	£50,467	5.7 million	21%	17%	41%	21%	Yes	Owner occupier	Semi Detached	1	Petrol	5,215	3,477	High
A13	£51,820	5.2 million	18%	37%	33%	12%	Yes	Private renter	Flat	0	n/a	0	0	High
A14	£55,462	4.8 million	22%	20%	37%	21%	Yes	Owner occupier	Mid Terrace	2	Both petrol	5,215	3,477	High
A15	£56,710	4.3 million	19%	7%	42%	32%	Yes	Owner occupier	Detached	1	Petrol	5,215	3,477	High

Distributional effects considered (ctd.)

We estimate the distribution of impacts from climate action co-benefits to 15 different representative household archetypes and wider society.

Table 2 (ctd.). Household archetype definitions

Archetype	Building characteristics (ctd.)							Geographic characteristics					
	% of households in property of starting EPC rating A	% of households in property of starting EPC rating B	% of households in property of starting EPC rating C	% of households in property of starting EPC rating D	% of households in property of starting EPC rating E	% of households in property of starting EPC rating F	% of households in property of starting EPC rating G	% of households living in RUC band 1 (urban)	% of households living in RUC band 2 (urban)	% of households living in RUC band 3 (urban)	% of households living in RUC band 4 (rural)	% of households living in RUC band 5 (rural)	% of households living in RUC band 6 (rural)
A1	0%	2%	33%	50%	12%	2%	1%	62%	10%	27%	1%	0%	0%
A2	0%	5%	36%	40%	15%	2%	1%	14%	13%	58%	10%	3%	0%
A3	0%	2%	35%	45%	12%	2%	1%	22%	6%	70%	2%	0%	0%
A4	0%	3%	30%	46%	14%	2%	1%	56%	39%	5%	1%	0%	0%
A5	0%	2%	45%	33%	9%	1%	0%	13%	8%	68%	11%	1%	0%
A6	1%	40%	21%	11%	3%	1%	0%	26%	22%	28%	11%	12%	1%
A7	0%	2%	27%	45%	12%	2%	1%	25%	48%	23%	1%	3%	0%
A8	0%	7%	43%	33%	8%	1%	0%	83%	14%	3%	0%	0%	0%
A9	0%	3%	12%	27%	33%	12%	3%	2%	3%	72%	22%	1%	0%
A10	0%	2%	41%	25%	2%	0%	0%	1%	1%	5%	7%	75%	11%
A11	0%	3%	34%	47%	13%	1%	0%	0%	0%	12%	36%	49%	4%
A12	0%	3%	26%	36%	21%	5%	2%	3%	2%	79%	14%	2%	0%
A13	0%	3%	37%	22%	5%	1%	0%	93%	1%	5%	0%	0%	0%
A14	0%	2%	44%	37%	11%	2%	1%	85%	1%	14%	0%	0%	0%
A15	0%	3%	49%	39%	7%	1%	0%	33%	4%	46%	11%	6%	0%

Estimating impacts to the NHS

We also estimate the share of impacts from climate action co-benefits that could accrue to the NHS in the form of savings.

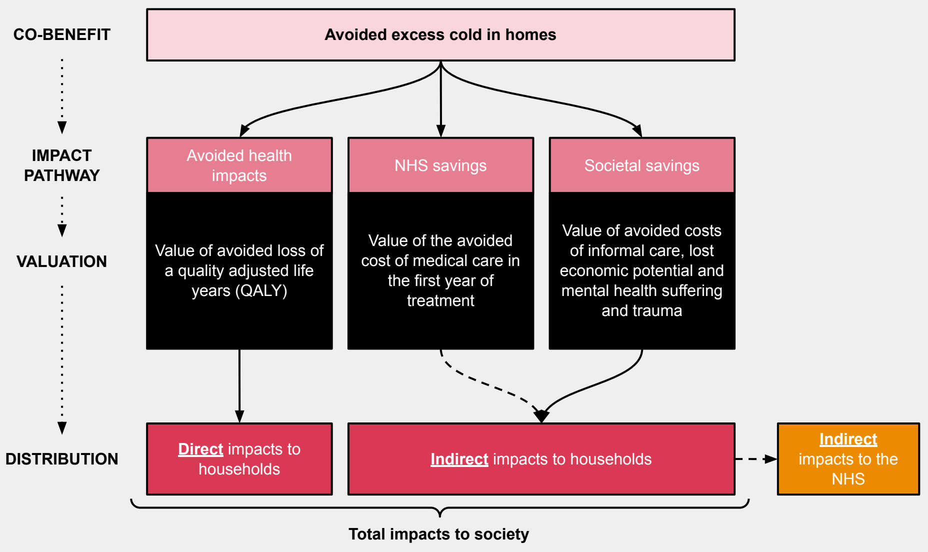
The primary focus of this analysis is to understand the health impacts from climate action co-benefits, with a secondary focus on wider economic, social and environmental impacts. A healthier population creates savings in healthcare, as medical treatment for avoided negative health outcomes is no longer needed and resources can be redeployed elsewhere.

In addition to quantifying the health impacts of co-benefits accruing to households, we also estimate the share of the indirect impacts to households (ultimately taxpayers) that may accrue to the NHS in the form of savings on medical treatment, resources or ambulance costs, assuming all households receive public medical care. While these savings may not translate expressly into reduced costs to the taxpayer to fund the NHS, they represent a social benefit in the form of reduced pressure on health services.

Note that in order to avoid the risk of double-counting, this is only possible where NHS savings have been explicitly quantified within the valuation sources we use. Therefore, not all associated NHS savings are quantified for all health impacts included in the analysis.[1]

We illustrate an example of how impacts from the excess cold co-benefit are categorised by beneficiary in **Box 3**.

Box 3. Example distribution of the impacts of the excess cold co-benefit



[1] NHS savings are quantified for the following co-benefits: excess cold, excess heat and dampness. They are not quantified for other co-benefits yielding health impacts (air quality, noise, road safety, physical activity and diet change).

Policy options considered

We assess how co-benefits are created and distributed across different groups in society under different policy options.

A key purpose of this model is to assess how climate action creates co-benefits under different policy scenarios. While it is difficult to predict when a policy might come into effect and how long it will continue, we have modeled a number of policy options to aid users' understanding of how the magnitude and distribution of a co-benefit changes with different assumptions around future net zero policy.

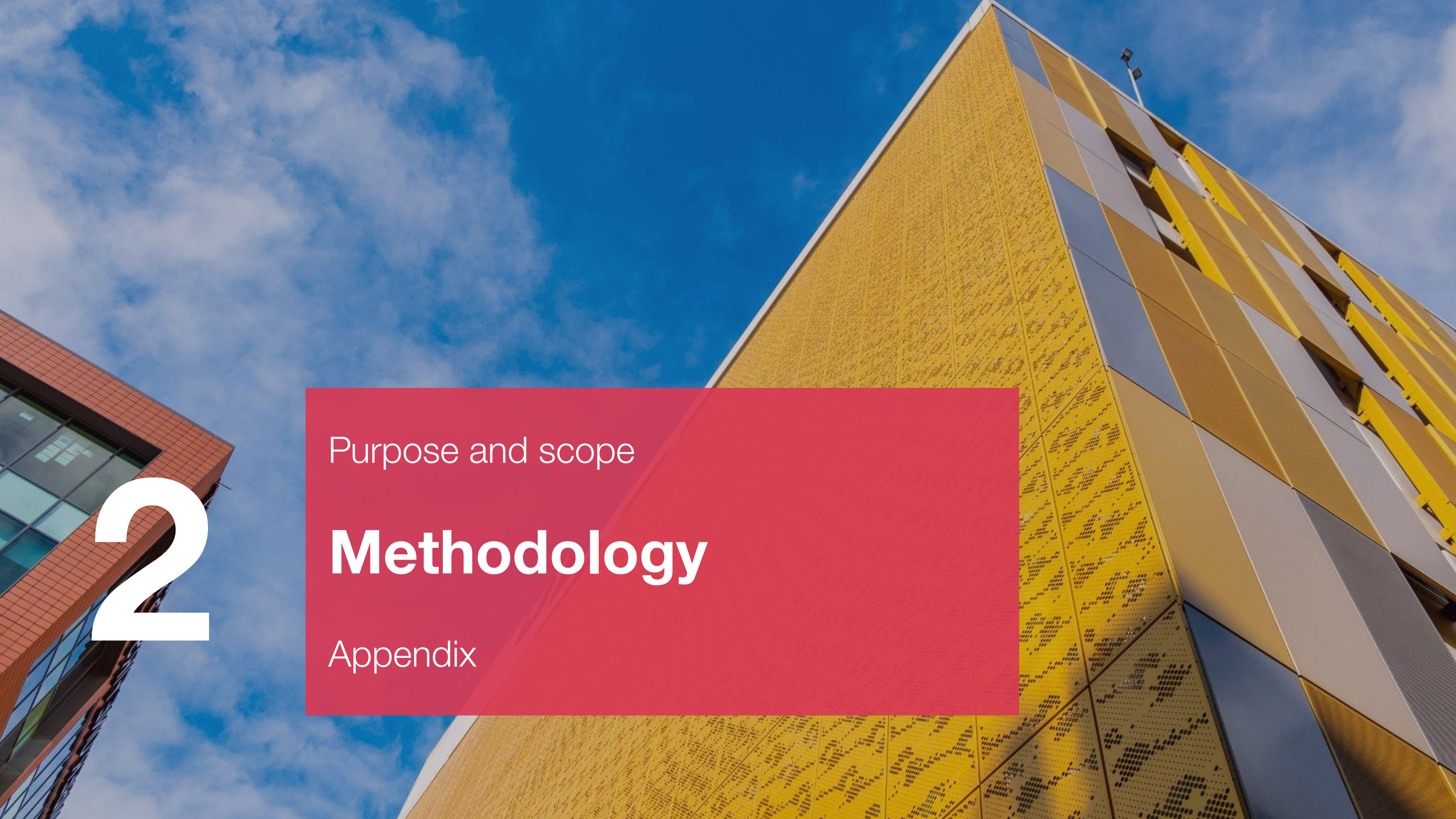
Principally, these assumptions influence what households take up LCAs and when in the transition to net zero LCAs are taken up to meet the total carbon abatement levels assumed in the 6CB (uniform across each pathway). For example, uptake of home retrofit (e.g. heat pump, insulation, etc.) may be targeted at households that live in social housing earlier than households living in other housing tenures. Where possible, we have kept these assumptions consistent with the user inputs available in the Net Zero Distributional Model (NZDM) developed by Frontier Economics. See **Table 3** opposite for all policy sensitivities included in the scope of this analysis. We have set the default options in the model to assume no targeting of policy.

This approach does not, however, account for policy ineffectiveness in incentivising LCA uptake. For example, we do not account for the possibility that a policy to incentivise greater active travel through subsidies for bike purchase may not achieve its target for various reasons (misinformation, poor public engagement, supply chain barriers). Instead, our analysis assumes a baseline level of uptake consistent with the CCC pathways, with any further sensitivities adjusting these uptake levels up or down over time and between groups.

Table 3. Policy sensitivities in scope of analysis

Sector	Policy sensitivity	Targeting options	Default
Domestic buildings	Uptake of housing retrofit by household income or tenure	Proportional distribution across archetypes	✓
		Prioritise low-income archetypes[1]	
		Prioritise social renter archetypes	
		Prioritise private renter archetypes	
		Prioritise owner occupier archetypes	
	Uptake of housing retrofit by EPC rating	Proportional distribution across archetypes	✓
		Prioritise households with lowest EPC rating	
Transport	Uptake of active travel by age	All ages from 16 to 84 years	✓
		Any range of ages from 16-18 up to 84 years in 5-year increments	
Agriculture & land use	Uptake of diet change by age	All ages (0 to 110 years) - option to exclude children under 11	✓
		Individuals aged 0 to 65 years - option to exclude children under 11	
		Individuals aged 0 to 40 years - option to exclude children under 11	
		Individuals aged 0 to 25 years - option to exclude children under 11	
	Uptake of diet change by sex	Male and female	✓
		Only male	
		Only female	

[1] A low-income archetype has been defined in the NZDM by Frontier Economics as households whose annual net household income is below the UK median household income for the selected year. We maintain the archetype definitions in this analysis.



2

Purpose and scope

Methodology

Appendix

Overview of approach

We take a 5-step approach to quantifying, valuing and distributing the impacts of the most material climate action co-benefits.

Given research into climate action co-benefits and their associated impacts has been piecemeal, with different methodologies used in research to date, we have taken a 5-step approach to assessing the scale and distribution of co-benefits in this work, summarised in **Box 4** below.

We set out these steps for each of the 11 co-benefits on the following pages.

Box 4. Our 5-step approach to assessing the value and distribution of climate action co-benefits

1

Scoping the analysis

Define the household archetypes, sectors and low carbon actions (LCAs) and co-benefits in scope through the development of detailed impact pathways

2

Define and/or develop methodologies

Research and agree the most appropriate methodologies for our shortlisted co-benefits and develop new methodologies where they do not currently exist

3

Quantification and valuation

Quantify and value the shortlisted co-benefits and their associated impacts at the national level, in line with HM Treasury Green Book appraisal guidance

4

Distributional analysis

Distribute the co-benefits across beneficiary groups (households and the NHS) using 15 representative household archetypes developed by Frontier Economics in the NZDM

5

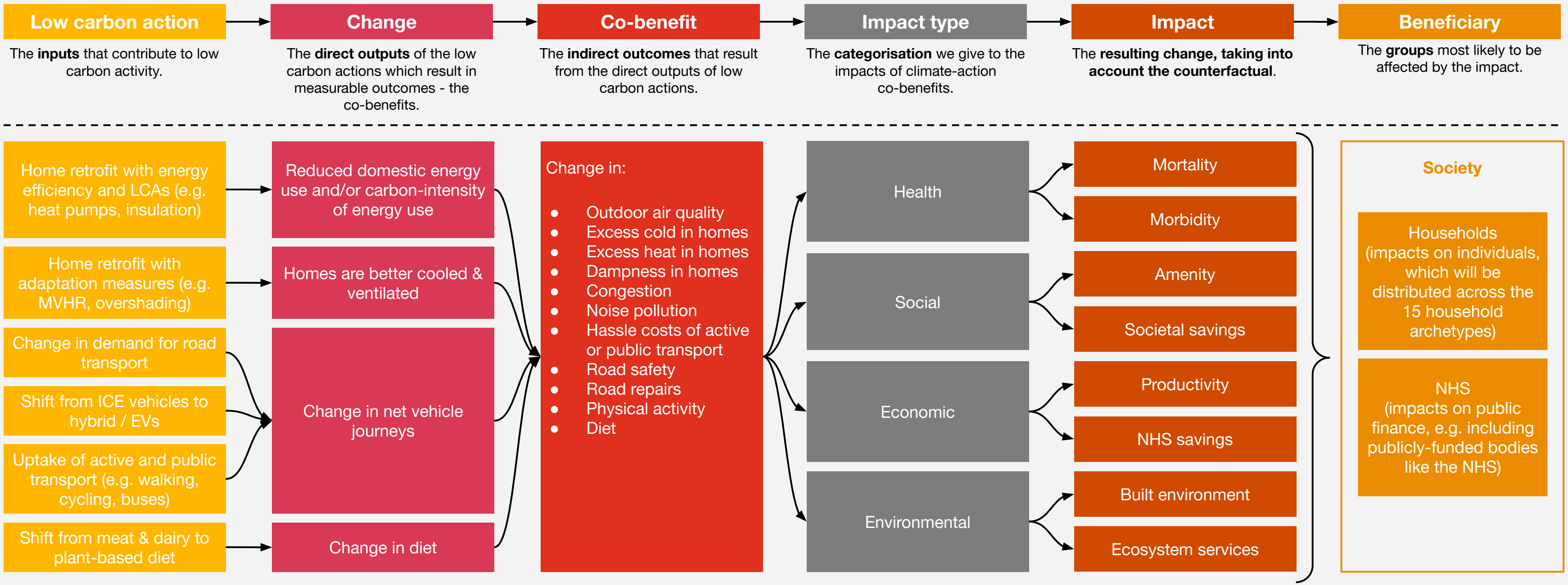
Sensitivity analysis

Conduct sensitivity tests on the results to account for key uncertainties in the default assumptions used within the methodologies

Simplified impact pathway

Impact pathways form the basis of our analysis, allowing us to map low carbon actions to the co-benefits and associated impacts that they create. Box 5 below sets out simplified impact pathways quantified in this analysis.

Box 5. Simplified impact pathways for domestic buildings, transport and diet change



General assumptions & limitations

Quantifying and distributing the impacts of climate action co-benefits is an inherently uncertain exercise, underpinned by a number of assumptions and limitations

Table 4. General assumptions

No.	Assumption
1	We assume the CCC's baseline scenario in the 6CB to be the counterfactual (or what would occur in the absence of any further planned climate action).
3	We assume the macroeconomic assumptions used in our analysis (e.g. central and health discount rates of 3.5% and 1.5%, respectively) remain constant over time.
2	We assume that the 15 household archetypes developed by Frontier Economics accurately reflect the makeup of the UK population.
3	We assume that not all impacts are experienced by the same group who creates the impact. To help the CCC tell the story of 'winners' and 'losers' of the net zero transition, we categorise the impacts quantified in this work as 'direct' and 'indirect': • **Direct:** We define an impact as direct if it is created and experienced by the same actor. Because we only assess low carbon actions taken by households in this work, direct impacts can only be experienced by the households who are making a change. • **Indirect:** We define an impact as indirect if it is created by one actor and experienced by another. Both households and the NHS can experience indirect impacts of co-benefits.
4	We assume that the low carbon actions defined in each CCC pathway takes place as described: we do not make any assumptions about how realistic this based on our reading of current or future policy, technological, macroeconomic or social assumptions.
5	We assume the co-benefits of interventions can be modelled without specific details of the policies and programs that are expected to be needed for their delivery.
6	We assume no between-sector interactions between the co-benefits of interventions.

Table 5. General limitations

No.	Limitation
1	We use a range of methods to calculate the impacts of climate action co-benefits. We have selected the approach for each co-benefit based on methodologies we know to be commonly accepted by the UK Government or academia and based on the methodologies that are available to capture the most material impacts within the scope of this analysis. There is, however, overlap across all health impacts. Therefore, we advise caution when interpreting the aggregate outputs of this analysis.
2	Our findings are based on the archetypes as defined in the NZDM developed by Frontier Economics. These include both specific and representative characteristics of household archetypes. For example, each household archetype has a unique distribution of homes by EPC rating, which allows us to estimate the intra-archetype impacts based on a home's energy efficiency. However, each household archetype only has one property type characteristic, which is a representative description of most homes in that archetype. Therefore, there may be households that fall outside of the predefined characteristics of an archetype. Where an intra-archetype distribution is not defined for a characteristic, we are not able to capture these nuances.
3	Our analysis should not be used to assess the full range of impacts to individual households but rather impacts in the round to a subset or whole population or an illustrative mean impact to a representative household archetype.
4	Aside from the rebound effect for transport for which there is a large body of evidence, we do not model second-order effects on shortlisted co-benefits. For example, a shift towards more plant-based diets may decrease UK meat production and increase crop production, leading to changes in cattle and sheep numbers and fertiliser use, and therefore changes i air quality (via methane and nitrous oxide releases),

Air quality

Avoiding air pollution and its associated impacts from high-carbon measures in homes and transport

Air quality | Overview

The air quality co-benefit resulting from reduced exposure to air pollutant emissions from car exhausts, gas boilers, cooking and other activities contributes to positive health, environmental and economic impacts.

- **What is the co-benefit?** The air quality co-benefit captures the avoided threat to health, the environment and economic productivity from exposure to outdoor air pollutant emissions.*

- **Why is it important?** According to the UK Government, air pollution is the largest environmental risk to public health, with human-made air pollution in the UK estimated to cause between 28,000 and 36,000 premature deaths every year.[1] It is particularly damaging in densely populated places and for vulnerable populations (young and elderly), contributing to both chronic and acute health conditions, with indirect impacts to the NHS and wider society.

- **What climate actions create the co-benefit?** Climate action in the buildings and transport sectors has the potential to impact air quality.[2,3] Air pollution, primarily from tailpipe emissions and combustion appliances - can be avoided through a number of low carbon actions, including shifting from ICE vehicles to EVs or taking up active modes of travel.

How do we quantify the co-benefit? We use UK air quality damage costs, developed by Ricardo[4] for Defra and aligned to HM Treasury Green Book appraisal methodology, to quantify and value the impacts of outdoor air quality resulting from the CCC's Sixth Carbon Budget scenarios. We quantify the impacts of $PM_{2.5}$, PM_{10}, NO_2 and SO_2, which are the most material ambient air pollutants, on the following impact pathways:

- Chronic mortality
- Acute morbidity
- Chronic morbidity
- Building & infrastructure resilience
- Ecosystem services
- Economic productivity

- **How do we distribute the co-benefit?** We distribute the impacts of the outdoor air quality co-benefit as indirect impacts across all household archetypes by the rural-urban classification of the areas in which the impacts are created, in proportion to the share of each archetype's population. This allows us to distribute the impacts based on where they are experienced.

* **Note:** Indoor air quality co-benefit is the avoided air pollution inside homes, which can also come from the use of combustion appliances (like gas cookers, stoves and boilers) as well as consumer products (like aerosols) and human bioeffluents. Indoor air pollution can also be avoided through low carbon actions, like installing energy-efficient appliances. However, for indoor air quality, we are constrained by gaps in the evidence around the dispersion and valuation of indoor air pollutants, despite ongoing work by government and academia to address these gaps. We have therefore descoped this from the analysis.

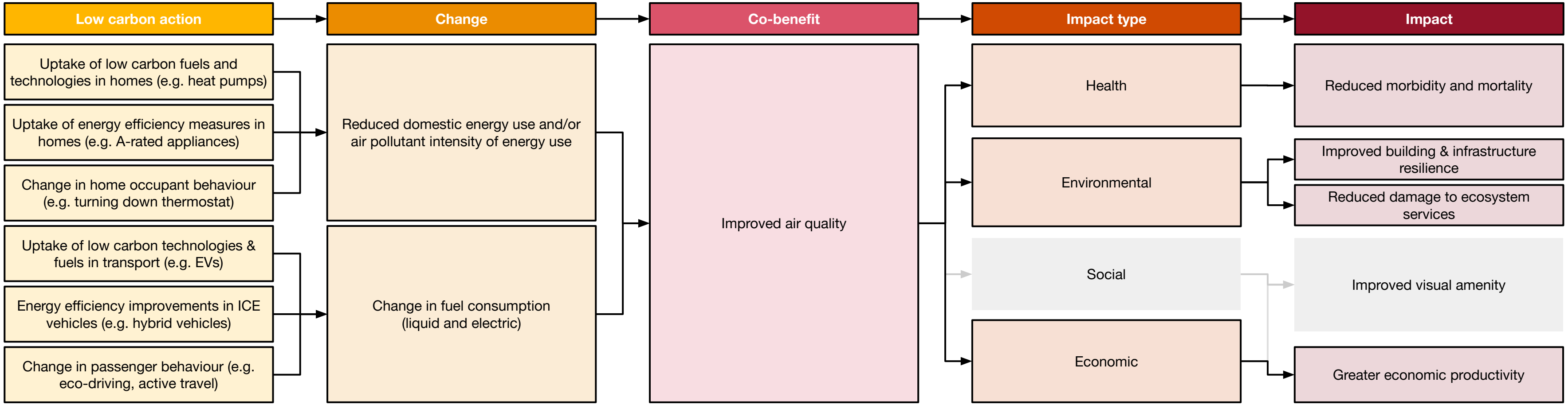
[1] UK Government (2022). 'Air pollution: applying All Our Health', February 2022.
[2] Note that there are also air pollutant emissions resulting from the agriculture & land use sectors (e.g. nitrogen from runoff); however, these are outside the scope of this analysis.
[3] Damaging pollutants found outdoors include fine particulate matter ($PM_{2.5}$, PM_{10}), nitrogen dioxide (NO_2), sulphur dioxide (SO_2), non-methane volatile organic compounds (NMVOCs) and particulate matter from ammonia (NH_3). Damaging pollutants found indoors include fine particulate matter ($PM_{2.5}$, PM_{10}), carbon monoxide (CO), nitrogen dioxide (NO_2), organic compounds (OCs), environmental tobacco smoke (ETS), secondhand smoke (SHS) and radon.
[4] Ricardo (2023). 'Air Quality damage cost update 2023 - FINAL Report', January 2023.

Air quality | Impact pathways

Decarbonising homes by reducing domestic energy use and fuel consumption leads to improved air quality, which results in reduced morbidity and mortality, improved visual amenity, reduced damage to buildings, materials and ecosystems and greater productivity.

Across the buildings and transport sectors,[1] energy savings can be made by taking up more energy-efficient measures and behaviours. These include installing heat pumps and A-rated appliances in homes, turning down room thermostats, shifting from ICE vehicles to electric or hybrid vehicles, and changing driving behaviour through speed-limiting technologies or eco-driving settings. All of these actions lead to improved air quality, as particulate emissions result in energy use. Improved air quality creates health, social, environmental and economic impacts in the form of reduced morbidity and mortality, improved visual amenity, reduced damage to buildings, materials and ecosystems, and greater productivity.

We summarise the key impact pathways for air quality below, although note that they are not exhaustive. We quantify only the coloured and outlined pathways due to scope and evidence constraints.



[1] Note that are also air pollutant emissions resulting from the agriculture & land use sectors (e.g. nitrogen from runoff); however, these are outside the scope of this analysis.

Air quality | Valuation methodology (1/4): Transport sector

We model the scale and distribution of outdoor air quality impacts from the transport sector based on the rural-urban classification of the areas where journeys are taken and which households living near transport systems experience the impacts of air quality as a result.

We estimate outdoor air quality impacts from the transport sector using six sources:

- CCC Sixth Carbon Budget transport model
- Frontier Economics Net Zero Distributional Impacts Model (NZDM)
- DfT Transport Appraisal Guidance databook[1]
- EMEP/EEA air pollutant emissions inventory guidebook[2]
- Air Quality Expert Group Non-Exhaust Emissions from Road Transport[3]
- Ricardo Air Quality Damage Costs, developed for Defra[4]

The CCC's 6CB assumes a number of low carbon actions (such as reduction in demand for road transport and shift to EVs) which change the total distance travelled in the transport sector annually in each pathway.

We begin with the CCC's assumptions around distance travelled - broken down by vehicle type (e.g. car, van, bus, etc.), powertrain (e.g. petrol ICE, diesel ICE, EV, etc.), and road type (e.g. motorways, A roads, other roads).

Using data from the UK's Road Traffic Statistics (TRA) and National Travel Survey (NTS) on the characteristics of typical vehicle journeys, we apportion distance travelled into one of four rural-urban classifications: London, inner & outer conurbations, other urban areas, rural areas). This allows us to estimate avoided air pollution based on where the journeys take place.

[1] DfT (2022). 'Transport Analysis Guidance', November 2022.
[2] EMEP/EEA (2019). 'Air pollutant emissions inventory guidebook', EEA Report No 13, 2019.
[3] Air Quality Expert Group (2019). 'Non-Exhaust Emissions from Road Traffic', 2019.

We multiply this data by average fuel and electricity consumption to estimate the total fuel and electricity consumed each year in each pathway, for each place classification, road type and vehicle type. We then multiply by air pollutant emissions factors, sourced from Ricardo.[2] This allows us to estimate the **tailpipe emissions** that contribute to air quality ($PM_{2.5}$, NOx, SO_2).

We also use the data on distance travelled to estimate **non-exhaust emissions** (PM2.5) from tyre, brake and road wear, by multiplying the change in distance travelled by non-exhaust emissions factors from the Air Quality Expert Group.[3]

We sum total air pollution from tailpipe emissions and non-exhaust emissions and multiply the sum by the UK air quality damage costs developed by Ricardo for Defra to estimate the total value of avoided air pollution by impact. These costs are estimated individually and capture health impacts (mortality, morbidity), environmental impacts (buildings, materials and ecosystem damage) and economic impacts (medical treatment costs, productivity).

We distribute these impacts based on where they are experienced, by mapping the rural-urban classification of air quality impacts to the rural-urban classification of each household archetype. Specifically, we distribute health impacts as direct impacts and environmental and economic productivity impacts as indirect impacts across all households in proportion to the

[4] Ricardo (2023). 'Air Quality damage cost update 2023 - FINAL Report', January 2023, Tables 5-2, 5-3, 7-1, 7-2, 7-3 and 7-4.

Air quality | Valuation methodology (2/4): Transport sector

We model the scale and distribution of outdoor air quality impacts from the transport sector based on the rural-urban classification of the areas where journeys are taken and what households living near transport systems experience the impacts of air quality as a result.

population of each archetype living in the rural-urban classification of where the air pollution is avoided.

We do not assume any shares of the air quality co-benefit impacts are attributable to the NHS, as the relevant impact pathways (economic productivity, acute morbidity hospital resource costs) have negligible contributions to the air quality damage costs.

These impacts are calculated in 2021 prices (the default price base year in the model) and discounted over time using the central (3.5% p.a.) and social discount rates (1.5% p.a.) as recommended by HM Treasury's Green Book appraisal guidance.[4]

The full calculation pathway is set out in **Box 6** below.

Box 6. Calculation pathway for outdoor air quality in the transport sector

(((**Electricity consumption for electric and hybrid vehicles** (kWh / vkm) ✖ **Particulate emissions factors** (grams / kWh)) ➕ (**Fuel consumption for ICE and hybrid vehicles** (litre / vkm) ✖ **Particulate emissions factors** (grams / litre))) ✖ **Unit conversion** (tonne / gram)) ➕ (**Particulate emissions from brake wear** (tonnes / vkm) ➕ **Particulate emissions from tyre wear** (tonnes / vkm) ➕ **Particulate emissions from road wear** (tonnes / vkm)) ✖ **Change in distance travelled by mode** (vkm) ✖ **Share of vkm travelled by rural-urban classification of journey** (%)

✖ **Air quality damage costs** (£ / tonne) ✖ **Share of damage costs by attributable impact pathway (e.g. mortality, ecosystem services, etc.)** (%) ✖ **Share of impacts by beneficiary** (%) = **Impacts from avoided air pollution in the transport sector by archetype, relative to the baseline scenario** (£ / archetype)

[1] ONS (2023). 'Healthcare expenditure, UK Health Accounts provisional estimates: 2022', May 2023.
[2] Ricardo (2023). 'Air Quality damage cost update 2023 - FINAL Report', January 2023, Tables 5-2, 5-3, 7-1, 7-2, 7-3 and 7-4.
[3] Note that we do not account for the fact that public funds are ultimately paid for by society.
[4] HMT (2022). 'The Green Book (2022)', November 2022.

Air quality | Valuation methodology (3/4): Buildings sector

We model the scale and distribution of outdoor air quality impacts from the domestic buildings sector based on where households are located in the UK and where domestic energy use is saved as a result.

Outdoor air quality in the buildings sector

We estimate outdoor air quality impacts from the domestic buildings sector using three sources:

- CCC Sixth Carbon Budget domestic buildings model
- Frontier Economics Net Zero Distributional Impacts Model (NZDM)
- Ricardo Air Quality Damage Costs, developed for Defra[1]

The CCC's 6CB assumes a number of low carbon actions (such as the uptake of heat pumps and A-rated appliances and a change in occupant behaviour, e.g. by turning down thermostats) that reduce the demand for energy use in homes overall. But it also assumes some growth in high carbon sources which lead to greater air pollution.

We multiply the annual uptake of these low carbon actions in each 6CB pathway by their associated annual energy use in each 6CB pathway. Note that the energy use per low carbon action differs under different 6CB pathways due to underlying CCC assumptions about the UK's energy mix implicit in each pathway. This gives us the annual energy use per low carbon action deployed, which we apportion further by the 15 household archetypes modelled in Frontier Economics' NZDM.

We multiply the change in total energy use by fuel type for each household archetype in the selected 6CB scenario (relative to the baseline scenario, which is the counterfactual in this analysis) by air pollutant emissions factors from Ricardo (2023). This results in the total (tonnes) air pollution avoided by air pollutant ($PM_{2.5}$, NOx, SO_2).

We multiply total air pollution for each pollutant by the UK air quality damage costs developed by Ricardo for Defra to estimate the total value of avoided air pollution by impact. These costs are estimated individually and capture health impacts (mortality, morbidity), environmental impacts (buildings, materials and ecosystem damage) and economic impacts (medical treatment costs, productivity).

We distribute these impacts based on where they are experienced, based on the rural-urban classification of the area in which each household archetype lives. Specifically, we distribute health impacts as direct impacts and environmental and economic productivity impacts as indirect impacts across all households in proportion to the population of each archetype living in the rural-urban classification of where the air pollution is avoided.

We distribute the share of economic productivity impacts that are estimated to be healthcare spending (based on UK National Accounts)[1], as well as the share of health impacts that are estimated to be hospital resource costs (based on evidence from Ricardo[1]), as indirect impacts to the NHS under the

[1] Ricardo (2023). 'Air Quality damage cost update 2023 - FINAL Report', January 2023, Tables 5-2, 5-3, 7-1, 7-2, 7-3 and 7-4.

Air quality | Valuation methodology (4/4): Buildings sector

We model the scale and distribution of outdoor air quality impacts from the domestic buildings sector based on where households are located in the UK and where domestic energy use is saved as a result.

assumption that these are 100% publicly funded.[1]

These impacts are calculated in 2021 prices (the default price base year in the model) and discounted over time using the central (3.5% p.a.) and social discount rates (1.5% p.a.) as recommended by HM Treasury's Green Book appraisal guidance.[2]

The full calculation pathway is set out in **Box 7** below.

Box 7. Calculation pathway for outdoor air quality in the domestic buildings sector

Σ (Electricity, gas, petroleum, solid fuel, final, bioenergy) (**Total change in energy consumption by fuel type for low carbon actions taken up** (TWh) ✖ **Particulate emissions factors** (tonnes / TWh)) ✖ **Share of low carbon action uptake by EPC rating for each household archetype** (%) ✖ **Air quality damage costs by pollutant** (£ / tonne) ✖ **Share of damage costs by attributable impact pathway (e.g. mortality, ecosystem services, etc.)** (%) ✖ **Share of impacts by beneficiary** (%) = **Impacts from avoided air pollution in the buildings sector by archetype, relative to the baseline scenario** (£ / archetype)

[3] Note that we do not account for the fact that public funds are ultimately paid for by society.
[4] HMT (2022). 'The Green Book (2022)', November 2022.

Air quality | Sensitivity analysis (1/2)

For outdoor air quality, we model low, central and high damage cost sensitivities, which collectively capture different combinations of the key impact pathways in relation to air quality and different likelihoods of each impact pathway occurring.

Valuation of avoided air pollution using Defra's air quality damage costs

Defra's air quality damage costs are underpinned by a number of assumptions around:

- Emissions dispersion modelling
- Interpretation of how changes in air pollution concentrations create impacts
- Valuation of those impacts

To test these sensitivities, in addition to the 'central' air quality damage costs which are used as the default option in our modelling, we have also included 'low' and 'high' costs, which have been developed by Ricardo (2023).[1]

Table 6 opposite sets out which impact pathways are included in the low, central and high cost sensitivities. The main differences are:

1. The high cost sensitivity includes **additional health impact pathways**: cardiovascular hospital admissions from $PM_{2.5}$ and NO_2, diabetes incidence from $PM_{2.5}$ and NO_2, asthma incidence in adults from NO_2 and bronchitis incidence from PM_{10}.
2. The low, central and high cost sensitivities capture **different odds ratios for each impact** (i.e. the probability that the impact will occur divided by the probability that the impact will not occur).

Overall, this changes the combination of impact pathways included within each damage cost scenario (i.e. assumes emissions are dispersed in such a way that exposure to pollutant concentrations create more impacts on health), as well as the relative value of that each impact pathway contributes to the overall damage cost for each pollutant (i.e. assumes different likelihoods of some impact pathways occurring over others, which changes the valuation of the avoided air pollution).

Table 6. Impact pathways included in low, central and high cost sensitivities[1]

Impact category	Impact pathway (pollutants)	Low	Central	High
Chronic mortality	Long-term exposure ($PM_{2.5}$, NO_2)	✓	✓	✓
	Deaths brought forward (SO_2, NO_2)	✓	✓	✓
Acute morbidity	Respiratory hospital admissions ($PM_{2.5}$, PM_{10}, SO_2, NO_2)	✓	✓	✓
	Cardiovascular hospital admissions (PM_{10}, SO_2, NO_2)			✓
Chronic morbidity	IHD incidence ($PM_{2.5}$)	✓	✓	✓
	Stroke incidence ($PM_{2.5}$)	✓	✓	✓
	Diabetes incidence ($PM_{2.5}$, NO_2)			✓
	Lung cancer incidence ($PM_{2.5}$, NO_2)	✓	✓	✓
	Asthma incidence in children ($PM_{2.5}$, NO_2)	✓	✓	✓
	Asthma incidence in adults (NO_2)			✓
	Bronchitis incidence (PM_{10})			✓
Buildings & materials damage	Building soiling (PM_{10})	✓	✓	✓
	Materials damage (SO_2)	✓	✓	✓
Ecosystems damage	Ecosystems damage (SO_2, NO_2)	✓	✓	✓
Productivity	Productivity ($PM_{2.5}$, PM_{10}, NO_2)	✓	✓	✓

[1] Ricardo (2023). 'Air Quality damage cost update 2023 - FINAL Report', January 2023, Table 6-1.

Air quality | Sensitivity analysis (2/2)

For outdoor air quality, we model low, central and high damage cost sensitivities, which collectively capture different combinations of the key impact pathways in relation to air quality and different likelihoods of each impact pathway occurring.

Table 7 below sets out the directional impact of these sensitivities relative to the central air quality damage costs, which is the default setting in the model.

Table 7. Directional impact of sensitivities relative to default assumption

Sensitivity	Directional impact	Description
High air quality damage cost scenario (relative to central costs)	⬆	Selecting the high scenario for air quality damage costs will apply higher damage costs to the energy used in the buildings and transport sectors, and vehicle kilometres driven in the transport sector. Holding all else constant, this will increase the number and value of the impacts of avoided air pollution considered in the analysis. For example, there are four additional impact pathways captured under the high air quality damage cost scenario than under the central scenario. Additionally, the value of avoided $PM_{2.5}$ in the high air quality damage cost scenario ranges from 2.6 - 2.85 times more £ per tonne of pollutant emitted in the buildings and transport sectors than under the central scenario.
Low air quality damage cost scenario (relative to central costs)	⬇	Selecting the low scenario for air quality damage costs will apply lower damage costs to the energy used in the buildings and transport sectors, and vehicle kilometres driven in the transport sector. Holding all else constant, this will decrease the value of the impacts of avoided air pollution considered in the analysis. For example, the value of avoided $PM_{2.5}$ in the low air quality damage cost scenario is about 0.4 times the £/tonne of pollutant emitted in both the buildings and transport sectors than under the central scenario.

Air quality | Assumptions & limitations

Quantifying the impacts of outdoor air quality resulting from climate action is an inherently uncertain exercise, underpinned by a number of assumptions and limitations.

Table 8. Air quality co-benefit assumptions

No.	Assumption
1	We assume that the impacts of SO_2 are constant across rural and urban places, as there is no geographical split provided for these damage costs.
2	We assume that air pollutant emissions per unit of energy consumed remain constant over time.
3	We assume that the relative share of damage costs by impact pathway remains constant over time. In other words, the relative shares of the valuations given per unit of air pollutant emitted for each impact (e.g. mortality, morbidity, damage to ecosystem services, etc.) do not change over time.
4	We assume that all battery electric vehicles (BEVs) and range extended vehicles (REEVs) emit the same volume of air pollutants per kWh of electricity consumed.
5	We assume that there are no additional non-exhaust emissions resulting from the relatively heavier weights of BEVs and REEVs per vehicle-kilometre travelled. In other words, we assume the same levels of non-exhaust emissions for ICE vehicles and EVs. This is because there is not a consensus amongst researchers on the general levels of tyre, brake and road wear from these vehicles.[1]
6	We assume that the central air quality damage cost scenario remains an appropriate indicator of the value of the impacts from avoided air pollution over time.

Table 9. Air quality co-benefit limitations

No.	Limitation
1	We do not quantify the impacts of non-methane volatile organic compounds (NMVOC) - e.g. pollution from the use of wood as a fuel source in homes - and NH_3 - e.g. ammonia emitted from catalytic converters in petrol cars - pollution. This is because our correspondence with Defra and Ricardo (who developed the air quality damage costs on behalf of Defra) has indicated that they have found no material pathways linking primary NMVOC and NH_3 exposure to human health impacts in the UK. Therefore, in the scope of this analysis, we consider impacts from these pollutants to be relatively insignificant compared to impacts from $PM_{2.5}$, PM_{10}, SO_2 and NO_2.
2	We do not assess the impacts of all relevant indoor air pollutants, namely CO_2, PM, OCs, ETS, SHS and radon.
3	We do not quantify the air quality impacts of the change in use of hydrogen and non-bio waste, as there is limited evidence on the air pollutant emissions associated with these fuel types. However, we include space within the model for these assumptions to be updated over time as new evidence comes to light.
4	We do not quantify the impacts of air pollutants in the agriculture and land use sector.
5	We do not account for all relevant impact pathways associated with the air quality co-benefit. For example, we do not quantify the change in amenity value (e.g. from smog) which could create social impacts (e.g. in terms of subjective well-being) or economic impacts (e.g. in terms of house prices). However, we do not consider this to be a material impact pathway, given the UK has a relatively small smog problem compared to other regions (e.g. Southeast Asia).

[1] OECD (2020), "The implications of electric vehicle uptake for non-exhaust emissions", in Non-exhaust Particulate Emissions from Road Transport: An Ignored Environmental Policy Challenge', OECD Publishing, Paris.

Excess cold

Avoided excessively low home temperatures from energy inefficiency and poor building fabric

Excess cold | Overview

The excess cold co-benefit captures the heath and other impacts from avoiding low indoor temperatures due to poor building fabric, especially in winter months.

- **What is the co-benefit?** The excess cold co-benefit captures the threat to health (through increased respiratory and cardiovascular illness and death) of individuals living in homes with low internal temperatures, and subsequently the impact that poor health has on the NHS and wider society.
- **Why is it important?** The UK Government's Housing Health and Safety Rating System (HHSRS) Guidance for Landlords[1] states that small risks of adverse health effects arise when indoor temperature drops below 19°C, with serious health risks including respiratory and cardiovascular conditions for the elderly occurring below 16°C, and great health risks including hypothermia for the elderly occurring below 10°C. These are classified as category 1 hazards by the HHSRS, as they pose serious and immediate risks to a person's health and safety.

  Excess cold typically affects occupants of older, energy-inefficient homes with poor heating, poor insulation and excess ventilation. More efficient new build or retrofitted properties cost less to heat to an adequate temperature and the cost of heating is a significant driver of low indoor temperatures.[2]

  In addition to distributional impacts by occupant age, the impacts of the excess cold co-benefit differ by household income. Because energy costs the same for everyone, people who have lower incomes pay relatively more for each degree of heating and therefore excess cold is a disbenefit borne almost exclusively by the poor. This dynamic can be seen in the outputs by representative household archetype with different median incomes.
- **What climate actions create the co-benefit?** Improving the fabric of homes with insulation and retrofitting homes with energy efficiency measures, such as efficient heating systems, helps to reduce excess cold.
- **How do we quantify the co-benefit?** We use PwC's proprietary GreenHouse Toolkit which uses building physics to model the average change in internal property temperature during winter months, as a result of low carbon actions assumed under the CCC's Sixth Carbon Budget. See the **appendix** for more information on the Toolkit. We then map the properties in the excess cold temperature range (less than 19°C) to the impacts quantified by BRE in their Cost of Poor Housing reports:[3,4] the number of quality-adjusted life years (QALYs) and NHS and societal savings (£) created when an HHSRS category 1 excess cold hazard is mitigated. This allows us to estimate the benefits to each home in line with the change in internal thermal temperature experienced. We adjust the potential savings based on the likely number of vulnerable people (65+ years of age) in each household archetype (as defined by Frontier Economics), so that we only account for benefits accrued in homes with potential beneficiaries.
- **How do we distribute the co-benefit?** We distribute the health impacts of avoided excess cold as: direct impacts to the households that take up low carbon actions; societal savings (indirect impacts) proportionally across all households; and NHS savings as indirect impacts to the NHS.

[1] HHSRS (2006). 'Housing Health and Safety Rating System Guidance for Landlords and Property Related Professionals', 2006.

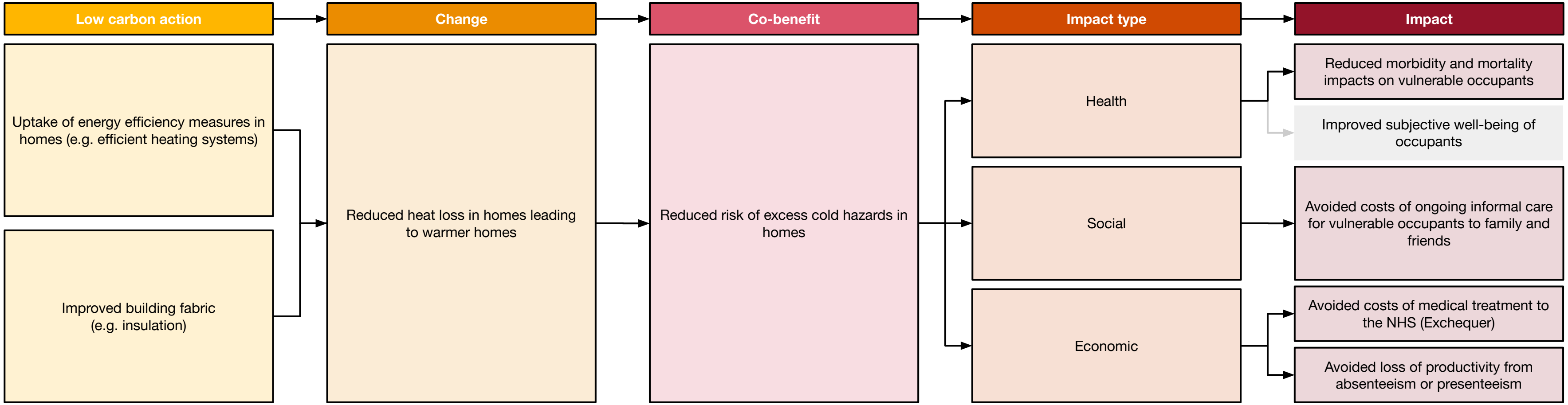
[2] BMJ (2021) Associations between indoor temperature, self-rated health and socioeconomic position in a cross-sectional study of adults in England, Table 2
[3] BRE (2016). 'The full cost of poor housing', 2016, Table 12.
[4] BRE (2022). 'The cost of poor housing in England - 2021 Briefing Paper', 2022, Table 1.

Excess cold | Impact pathways

Reducing heat loss in homes through energy efficiency measures (such as insulation) leads to reduced excess cold, which results in reduced morbidity and mortality, improved subjective well-being, savings to the NHS and greater productivity.

Heat loss in homes can be reduced by taking up energy efficient measures (such as efficient heating systems) and improving building fabric (by insulating the home). These actions can help occupants to maintain a sufficient internal property temperature (i.e greater than or equal to 19℃) and ultimately reduce the risk of excess cold hazards in the home. Reduced excess cold creates health, social and economic impacts in the form of reduced morbidity and mortality impacts of vulnerable occupants (e.g. primarily the elderly), improved subjective well-being of occupants, avoided medical treatment costs to the NHS, avoided costs of ongoing informal care for vulnerable occupants, and avoided loss of economic productivity from absenteeism or presenteeism.

We summarise the key impact pathways for excess cold below, although they are not exhaustive. We quantify only the coloured and outlined pathways due to scope and evidence constraints.



Excess cold | Valuation methodology (1/3)

We model the scale and distribution of excess cold impacts from the domestic buildings sector based on the change in internal property temperature resulting from low carbon actions and BRE's research on the cost of poor housing in the UK.

We estimate excess cold impacts from the domestic buildings sector using three sources:

- CCC's Sixth Carbon Budget (6CB) domestic buildings model
- BRE's Cost of Poor Housing reports[1,2]
- PwC's GreenHouse Toolkit[3]

We model the low carbon actions assumed in the CCC's 6CB (such as uptake of heat pumps, insulation and other measures) for each of the property types (e.g. flat, mid terrace, semi-detached, detached) characterised within the 15 household archetypes in PwC's GreenHouse Toolkit for each starting EPC band. This results in average temperature change estimates (or the potential minimum property temperature during winter) for each combination of:

A. Low carbon action
B. Property type
C. Starting EPC band

We model the projected property temperatures under each 6CB pathway, then take a weighted average of the indoor temperature change, based on the uptake of low carbon actions, for each of the 15 household archetypes. This results in the likely change in property temperature for each archetype (by EPC band) under each 6CB pathway, relative to the lowest winter temperature in the baseline scenario.

To value the impacts from the mitigation of excess cold, we use BRE's research on health, social and economic impacts associated with the mitigation of HHSRS hazards of category 1 level (e.g. the most severe hazards resulting in health impacts). Note that category 2 hazards excess cold hazards also exist but these do not pose serious or immediate risk to health and we have not included these in our analysis.

BRE's valuations are based on models of the relationship between energy efficiency rating - as determined by the UK's Standard Assessment Procedure (SAP)[4] - and the likelihood of a harmful event with serious health outcomes occurring for the most vulnerable person that could live in that dwelling (as would be assessed under the HHSRS by a practitioner). BRE estimates the total value of the following impacts to the group of homes identified to have category 1 excess cold hazards by the HHSRS, based on the likelihood score given during the assessment:

- Reduction in quality-adjusted life-years (QALYs) experienced by the most vulnerable aged person that could be living in that dwelling (assumed to be 65, with a maximum of 16 years life expectancy)[5]
- Cost of medical treatment incurred by the NHS
- Cost of societal impacts (e.g. through informal care by family and friends, lost economic potential and mental health suffering and trauma)

[1] BRE (2016). 'The full cost of poor housing', 2016, Table 12.
[2] BRE (2022). 'The cost of poor housing in England - 2021 Briefing Paper', 2022, Table 1.
[3] This is PwC's proprietary building physics and economics model for the UK housing stock. See appendix for more information.

[4] This is the methodology used by government to assess and compare the energy and environmental performance and EPC band of dwellings in the UK.
[5] Office of the Deputy Prime Minister (2006). 'Housing Health and Safety Rating System', February 2006, p. 59, paragraph 2.02.

Excess cold | Valuation methodology (2/3)

We model the scale and distribution of excess cold impacts from the domestic buildings sector based on the change in internal property temperature resulting from low carbon actions and BRE's research on the cost of poor housing in the UK.

To apply these valuations to our analysis, we first estimate the average benefits per property by dividing the total benefits quantified by BRE by the number of properties identified to have a category 1 excess cold hazard by the HHSRS. For QALYs, we estimate the average QALYs per person based on average home occupancy from the ONS (around 2.4 people per home, on average).[1]

We extrapolate the findings for NHS each year to 2050, uplifting for 2% above inflation each year to reflect that the real value of formal and informal care is increasing year-on-year (e.g. from clinical workforce shortages, rising wages and other costs). This is consistent with the trend in real NHS costs.[2] Note that we keep the monetary value of a QALY constant.

For each individual year, we then map the average benefits per property across the temperature range associated with excess cold hazards (<19℃). BRE's research was done at the UK-wide level and does not specify the average change in property temperature experienced by homes with excess cold that have undergone remedial work. We therefore make the assumption that only when a property shifts from one extreme end of the excess cold temperature range (<10℃) to the other (>19℃), it will create the full value of average benefits per property. In practice, the average home will likely not experience such a drastic shift in temperature. As such, our findings can be taken as conservative, as the benefits may be greater.

We do not treat this temperature-benefits function as linear because the severity of health outcomes differs by temperature. Instead, we fit a sigmoid function to the excess cold temperature thresholds specified by HHSRS: we distribute the greatest benefits when properties are shifted from temperatures below 10℃, which is the threshold associated with great health risks (including hypothermia for the elderly), and further benefits when properties are shifted from temperatures below 16℃, which is the threshold associated with serious health risks (including respiratory and cardiovascular conditions for the elderly).[3]

Sigmoidal relationships have been found to have sufficient goodness-of-fit for the relationship between disease severity and exposure.[4] In the absence of further evidence, we also assume a sigmoidal relationship to avoided costs of care (NHS and societal savings).[4] Implicit in this assumption is that temperature is an indicator of the potential severity of health outcomes from excessively cold conditions in a home, which is consistent with the HHSRS thresholds (i.e. more severe health outcomes occur at lower temperatures).

[1] ONS (2022). 'Families and households in the UK: 2022', May, 2023.
[2] House of Commons (2019). 'NHS Funding and Expenditure', Briefing Paper: CBP0724, January 2019.
[3] UK Government (2019). 'Guide for tenants: Homes (Fitness for Human Habitation) Act 2018', 2019.
[4] Redelmeir et al. (2022). 'Testing for a sweet spot in randomized trials', *Medical Decision Making*, 2022 Feb, 42(2),: 208 - 216.

Excess cold | Valuation methodology (3/3)

We model the scale and distribution of excess cold impacts from the domestic buildings sector based on the change in internal property temperature resulting from low carbon actions and BRE's research on the cost of poor housing in the UK.

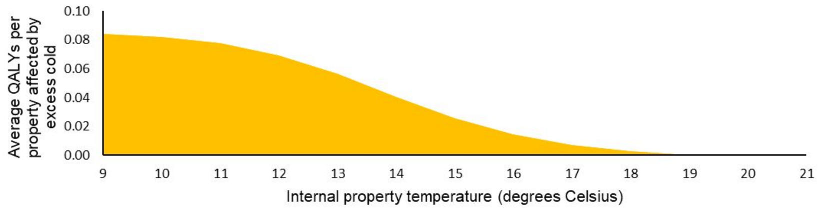
Figure 1 opposite presents the sigmoid function we use to distribute QALYs per property by temperature, which we then apportion further by average occupancy.

We distribute the QALY benefits directly to only the household archetypes undertaking the low carbon actions (it will be the occupants of the home who experience the health benefits from mitigated excess cold hazards) in proportion to the share of homes identified to have category 1 excess cold hazards in BRE's research by tenure.[1]

By contrast, we distribute the societal benefits as indirect benefits to all household archetypes in proportion to the population within each archetype. These include informal care savings, avoided loss of economic potential and avoided costs of mental health suffering and trauma. While some of these benefits will accrue to the occupants of the home, others (such as avoided informal care costs) may accrue to those in other household archetypes. Therefore, in the absence of further evidence, we distribute societal savings uniformly across the UK population.

Finally, we distribute the NHS savings as direct impacts to the NHS in the form of savings leading to reduced pressure on health services.

Figure 1. Average QALYs per property in 2025 by property temperature



Box 5. Calculation pathway for impacts of excess cold in homes

Change in minimum winter property temperature by household archetype & EPC band (Δ°C / archetype) ✖ ((**Change in average QALYs per person per change in property temperature** (ΔQALYs / person / Δ°C) ✖ **Population forecast by archetype by EPC band** (# people / archetype) ✖ **Value of a statistical life-year** (£ / QALY)) ➕ (**Change in average NHS savings per change in property temperature** (Δ£ / household / Δ°C) ➕ **Change in average societal savings per change in property temperature** (Δ£ / household / Δ°C))) ✖ **Number of households per archetype by EPC band** (# households / archetype) ✖ **Share of households with cat. 1 excess cold hazard by tenure** (%) ✖ **Share of vulnerable population within archetype** (%) ➖ **Total value NHS savings** (£ / archetype) 🟰 **Total value of impacts from avoided excess cold in homes by archetype, relative to the baseline scenario** (£ / archetype)

[1] BRE (2023). 'The cost of poor housing in England by tenure', June, 2023.

Excess cold | Fuel poverty exploratory analysis

We estimate the number of homes shifted out of fuel poverty resulting from low carbon actions which reduce excess cold in homes.

Excess cold in homes contributes to fuel poverty in the UK. It is estimated that 10% of excess winter deaths are directly attributable to fuel poverty in England and 21.5% of excess winter deaths are attributable to cold homes.[1]

According to the definition used in England, fuel poverty occurs when a household is living in an energy-inefficient property (EPC D or below) and when spending the required amount to heat their home to an adequately warm temperature results in a residual income below the official poverty line (60% of median UK household income).[2]

Scope and data constraints prevent us from conducting a bottom-up analysis of homes shifted out of fuel poverty. However, we use the UK's annual fuel poverty statistics in relation to household income and the change in EPC rating resulting from low carbon actions, modelled in PwC's GreenHouse Toolkit, to provide an indicative number of homes shifted out of fuel poverty for each 6CB pathway. See **Box 6** for more details.

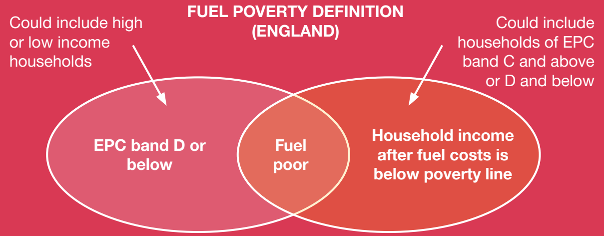
[1] Lee et al. (2022), 'Fuel poverty, cold homes and health inequalities in the UK', *IHE*, p. 19.
[2] DESNZ (2023). 'Fuel poverty statistics', April 2023.
[3] DESNZ (2023). 'Annual Fuel Poverty Statistics in England, 2023 (2022 data)', Table 2.3.

Box 6. Estimating homes shifted out of EPC band D and below

In quantifying excess cold, we estimate the projected property temperatures based on the assumed uptake of low carbon actions for each of the 15 household archetypes in the 6CB. We segment this output by EPC band and compare to the baseline distribution of households by EPC band, as originally defined in the household archetype definitions developed by Frontier Economics. This allows us to count the number of households shifted from EPC band D or below to EPC band C or above.

According to the English definition of fuel poverty, any household that is EPC band C or above is not classified as fuel poor. Therefore, the homes shifted out of EPC band D or below can be understood to be homes no longer at risk of being fuel poor. This count could however include high-income households who were unlikely to fall below the poverty line after heating their once inefficient home. To adjust for this, we apply the latest estimate of the proportion of low income households in EPC bands D or below (47.2% in 2022).[3] This allows us to estimate the minimum number of homes shifted out of fuel poverty for each 6CB pathway.

Note that Scotland, Wales and Northern Ireland use the 10% definition for fuel poverty, which defines a household as fuel poor if it needs to spend more than 10% of its income on energy to adequately heat its home. By definition, this would classify a greater number of households as fuel poor.



Excess cold | Sensitivity analysis

We model a number of policy options that can lead to a different rate of uptake of low carbon actions by households, depending on tenure, income or level of energy efficiency in the property.

We do not include sensitivity analysis for the impacts of excess cold, as BRE's Cost of Poor Housing set out a central estimate for excess cold hazards which form the basis of our analysis. These findings are the primary piece of research in this area for the UK, cited widely by government, charities and academics. However, this means that in contrast to bottom-up methods employed for co-benefits such as air quality. Where the total co-benefit for air quality can be infinite,defined by the size of change, this method is top-down with the total co-benefit defined and limited by BRE.

We do, however, include options for users to select different low carbon action uptake assumptions. Where possible, we have kept these consistent with the user inputs available in the Net Zero Distributional Impacts model.

For inter-archetype (across different archetypes) uptake, these are:

- **Even distribution across household archetypes** - This option assumes all household archetypes take up low carbon actions proportional to the number of homes within each archetype.
- **Prioritisation of social renter households** - This option assumes that households defined by the representative social renter archetypes (i.e. those on government-subsidised rent) take up low carbon actions at a relatively faster rate (e.g. earlier in the pathway to Net Zero by 2050) than other households.
- **Prioritisation of low-income households** - This option assumes that households defined by the representative low-income household archetypes take up low carbon actions at a relatively faster rate (e.g. earlier in the pathway to Net Zero by 2050) than other households.
- **Prioritisation of private renter households** - This option assumes that households defined by the representative private renter archetypes take up low carbon actions at a relatively faster rate (e.g. earlier in the pathway to Net Zero by 2050) than other households.
- **Prioritisation of owner occupier households** - This option assumes that households defined by the representative owner occupier archetypes take up low carbon actions at a relatively faster rate (e.g. earlier in the pathway to Net Zero by 2050) than other household archetypes.

We disaggregate the inter-archetype uptake for each of the 15 archetypes to determine the respective share of the uptake for each starting EPC band within each archetype. For intra-archetype (across households within a single archetype) uptake, these are:

- **Even distribution across households within a single archetype** - This option assumes that all households within a single archetype take up low carbon actions at the same rate (e.g. at the same point in time in the pathway to Net Zero by 2050). We set this as the default assumption in the model.
- **Prioritisation of low EPC rated households** - This option assumes that households with a low EPC rating (D or below) within a single archetype will take up low carbon actions at a relatively faster rate (e.g. earlier in the pathway to Net Zero by 2050) than those with a high EPC rating (C or above).

[1] ONS (2022). 'Families and households in the UK: 2022', May, 2023.

Excess cold | Sensitivity analysis (ctd.)

We model a number of policy options that can lead to a different rate of uptake of low carbon actions by households, depending on tenure, income or level of energy efficiency in the property.

Table 10. Directional impact of sensitivities relative to default assumptions in the CCC's 6CB Balanced Net Zero Pathway

Sensitivity	Directional impact	Description
Uptake of low carbon actions between archetypes		
Target LCA uptake by social renters first (relative to even distribution across households)	↓	Prioritising low carbon action uptake in social renter households decreases the total scale of the impacts resulting from reduced excess cold in homes.
Target LCA uptake by low-income households first (relative to even distribution across households)	↓	Prioritising low carbon action uptake in low income households decreases the total scale of the impacts resulting from reduced excess cold in homes.
Target LCA uptake by private renters first (relative to even distribution across households)	—	Prioritising low carbon action uptake in private renter households does not change the total scale of the impacts resulting from reduced excess cold in homes.
Target LCA uptake by owner occupiers first (relative to even distribution across households)	↑	Prioritising low carbon action uptake in owner occupied households increases the total scale of the impacts resulting from reduced excess cold in homes.
Uptake of low carbon actions between households within archetypes		
Target LCA uptake by households with low EPC ratings (relative to even distribution across households)	↑	Prioritising low carbon action uptake in households with low energy efficiency (as indicated by a low starting EPC rating) increases the total scale of the impacts resulting from reduced excess cold in homes.

*Scale of total impact in this case refers to the size of the change in monetised co-benefit in the UK, i.e. summed across all archetypes and attributes

Excess cold | Assumptions & limitations

Our estimates of the impacts of reduced excess cold in homes as a result of low carbon actions which increase energy efficiency and internal thermal temperature are underpinned by a number of assumptions and limitations.

Table 11. Excess cold co-benefit assumptions

No.	Assumption
1	The shapes of the functions linking benefits (QALYs, NHS and societal savings) to the change in property temperature were informed, where possible, by the temperature thresholds at which serious health risks are present, provided by the HHSRS guidance for landlords.[1] In the absence of further evidence, we assume that the accrual of benefits follows a sigmoid function to fit these thresholds.
2	In quantifying the QALY benefits, we assume an average home occupancy of 2.4 people per home, sourced from ONS data[2] which has remained unchanged over the last decade.
3	We assume that the health benefits from reduced excess cold remain constant over time (i.e. there are no changes to the typical medical treatment for health outcomes of excess cold that would lead to material changes in the average QALYs per person estimated by BRE in 2016).
4	We assume that 72%, 25% and 3% of the excess cold co-benefit is experienced by social renters, private renters and owner occupiers, respectively, which we infer from BRE analysis on excess cold hazards in England.[3]
5	To model the effects of climate change, we assume the Met Office's RCP8.5 regional climatic forecasts and using the Perturbed-Physics Model (ID #r001i1p02242).[3] While RCP8.5 is frequently referred to as a 'business as usual' climate scenario, it has come under criticism by some researchers for its assumptions around high future emissions and expansion in coal use.[4] Therefore, our estimates of co-benefits may be taken as conservative.
6	If a property's lowest winter temperature is within the excess cold temperature range, we assume that property is impacted by excess cold at that intensity for the whole winter and distribute the benefits on that basis.
7	We assume BRE's valuations of the impacts of reduced excess cold in homes are accurate and robust.

Table 12. Excess cold co-benefit limitations

No.	Limitation
1	We estimate the average benefits (QALYs, NHS and societal savings) per household archetype. This means that the results should be used to assess the likely impacts of reduced excess cold for a population or sub-population, but should not be used to assess the individual impacts of a household as these could be more or less than the average values used in this analysis.
2	BRE's research on average QALYs per property affected by excess cold is based on the average age of the most vulnerable aged person that could live in that dwelling. For excess cold, QALYs are estimated for people aged 65+, with a maximum of 16 years life expectancy. However, excess cold can also affect younger, albeit less vulnerable, occupants with a longer life expectancy, which would result in a greater average QALY benefit per property. Therefore, our estimates of QALYs created should be taken as conservative.
3	The HHSRS ratings (on which BRE's findings are based) do not take into account the affordability of energy. It is possible that there are vulnerable people who choose not to heat their homes to an adequate level to avoid serious health risks, and that these groups will also experience excess cold. These instances are not captured in our analysis, as we do not have a way of robustly identifying them.
4	Our analysis does not consider HHSRS hazards of category 2 or above. These hazards indicate a quality of housing that is significantly worse than average, which may be mitigated by uptake of a low carbon action. However these hazards do not pose immediate risks of health and well-being of households, although they may result in costs to the NHS if left unmitigated.
5	We do not account for all relevant impact pathways associated with the excess cold co-benefit. For example, we do not quantify the improved subjective well-being of occupants following the mitigation of excess cold hazards, as we do not have sufficient evidence to quantify this.
6	We do not account for behavioural feedback loops through comfort-taking (i.e. the fact that there will be imperfect use of low carbon actions which means that home occupants do not turn the benefit of low carbon actions entirely into lower energy bills).
7	We do not account for the fact that there may be improvements in the standard level of housing over time in a baseline scenario.

[1] HHSRS (2006). 'Housing Health and Safety Rating System Guidance for Landlords and Property Related Professionals', 2006.
[2] ONS (2022). 'Families and households in the UK: 2022', May, 2023.
[3] BRE (2023). 'The cost of poor housing in England by tenure', June, 2023.

Excess heat

Avoided excessively high home temperatures from lack of cooling and adaptation measures

Excess heat | Overview

The excess heat co-benefit captures the heath and other impacts from avoiding high indoor temperatures due to a lack of cooling, insulation, ventilation and passive adaptation measures in homes, especially in summer months.

What is the co-benefit? The excess heat co-benefit captures the threat to health (through increased respiratory and cardiovascular illness and death) of individuals living in homes with too high internal temperatures, and subsequently the impact that poor health has on the NHS and wider society.

Why is it important? The UK Government's Housing Health and Safety Rating System (HHSRS) Guidance for Landlords[1] states that small risks of adverse health effects including sleep disturbance and dehydration occur when indoor temperatures rise above 21℃, and serious health effects including trauma, cardiovascular and respiratory conditions, and increased risk of strokes and death occur when indoor temperatures risk above 25℃. These are classified as category 1 hazards by the HHSRS, as they pose serious and immediate risks to a person's health and safety.

Excess heat typically affects occupants of energy-inefficient homes with poor ventilation, higher thermal capacity (e.g. smaller dwellings like flats), large areas of south facing glazing and faulty or sub-standard heating controls. By contrast, more efficient new build or retrofitted properties with sufficient cooling measures (like overshading or air conditioning) and ventilation measures (like MVHR) are less likely to experience excess heat hazards. Because cooling adaptation measures are still nascent in the UK, the CCC and Arup have found that "the majority of existing UK homes are estimated to fail the current standard used in buildings regulations to limit overheating in new build homes".[2] Additionally, ineffective installation or use of ventilation measures can exacerbate excess heat in homes.

This comes at a cost to:

- The individual through increased mortality and morbidity, and a change in subjective well-being.
- The NHS through additional medical treatment costs.
- Wider society through higher ongoing costs of informal care (which may incurred by family and friends), reduced economic output (lost working days, lower productivity) and mental health suffering and trauma.

All of these factors are of value to society and can be given monetary valuations.

What climate actions create the co-benefit? Measures which help a household adapt to increasingly hot external temperatures in the summer. In this work we modelled mechanical ventilation with heat recovery (MVHR), external overshading, e.g. shutters or canopies, and the use of heat pumps as air conditioning units in summer months. Improving the fabric of homes with insulation also helps to reduce excess heat.

[1] HHSRS (2006). 'Housing Health and Safety Rating System Guidance for Landlords and Property Related Professionals', 2006.
[2] Arup (2022). 'Addressing overheating risk in existing UK homes', October, 2022.

Excess heat | Overview (ctd.)

The excess heat co-benefit captures the heath and other impacts from avoiding high indoor temperatures due to a lack of cooling, insulation, ventilation and passive adaptation measures in homes, especially in summer months.

- **How do we quantify the co-benefit?** We use PwC's proprietary GreenHouse Toolkit to model the average change in internal property temperature during summer months, as a result of low carbon actions assumed under the CCC's Sixth Carbon Budget (such as uptake of overshading and MVHR). See **appendix** for more information on the Toolkit.

  We then map the properties in the excess heat temperature range (greater than or equal to 21℃) to the estimates for health, social and economic impacts quantified by BRE in their Cost of Poor Housing reports.[3,4] These are the number of quality-adjusted life years (QALYs) and NHS and societal savings (£) created when an HHSRS category 1 excess heat hazard is mitigated. This allows us to estimate the marginal benefits to each home in line with the change in internal thermal temperature experienced.

  We also adjust the potential savings based on the likely number of vulnerable people in each household archetype, as defined by Frontier Economics in the Net Zero Distributional Impacts model. For excess heat, the vulnerable population is anyone 65 years or older. This is so that we only account for benefits accrued in homes with potential beneficiaries.

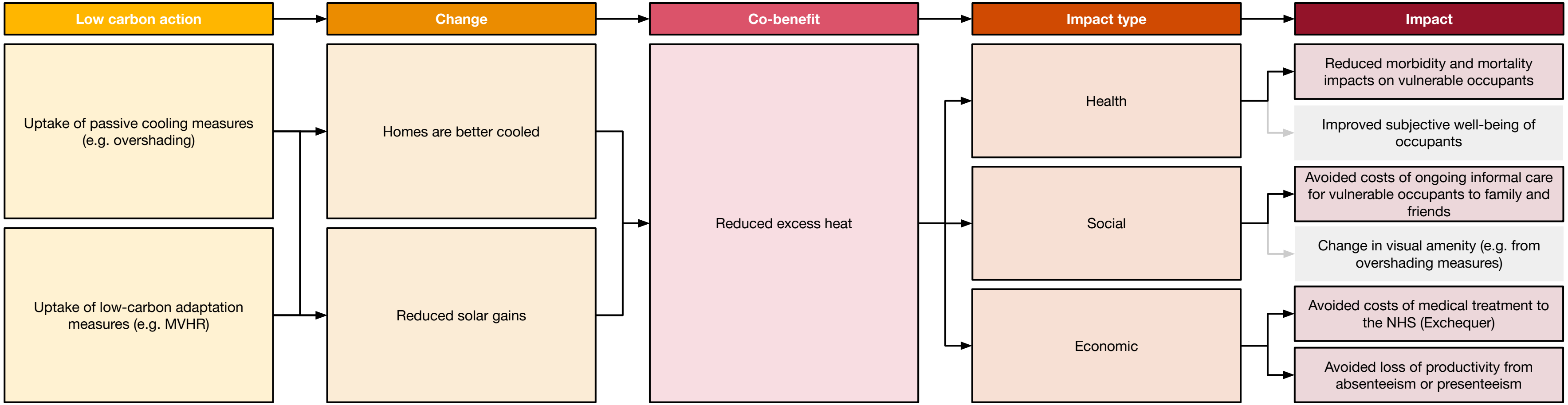
- **How do we distribute the co-benefit?** As with excess cold, we distribute the health impacts of avoided excess heat as: direct impacts to the households that take up the low carbon actions; societal savings as indirect impacts proportionally across all households; and NHS savings as indirect impacts to the NHS.

Excess heat | Impact pathways

Improving cooling and reducing solar gains in homes leads to reduced excess heat, which results in reduced morbidity and mortality, improved subjective well-being and greater productivity.

Homes can limit solar gains and maintain a sufficiently cool temperature in summer months with the use of passive cooling measures, such as overshading, and low-carbon adaptation measures, such as Mechanical Ventilation with Heat Recovery (MVHR). Reduced excess heat creates health, social and economic impacts in the form of reduced morbidity and mortality impacts to vulnerable occupants (e.g. primarily the elderly), improved subjective well-being of occupants, avoided medical treatment costs to the NHS, avoided costs of ongoing informal care for vulnerable occupants, change in visual amenity of homes (e.g. from overshading), and avoided loss of economic productivity from absenteeism or presenteeism.

We summarise the key impact pathways for excess heat below, although they are not exhaustive. We quantify only the coloured and outlined pathways due to scope and evidence constraints.



Excess heat | Valuation methodology (1/3)

We model the scale and distribution of excess heat impacts from the domestic buildings sector based on the change in internal property temperature resulting from low carbon actions and BRE's research on the cost of poor housing in the UK.

We estimate excess heat impacts from the domestic buildings sector using three sources:

- CCC's Sixth Carbon Budget (6CB) domestic buildings model
- BRE's Cost of Poor Housing reports[1,2]
- PwC's GreenHouse Toolkit[3]

We model the low carbon actions assumed in the CCC's 6CB (such as uptake of heat pumps, insulation, MVHR, overshading and other measures) for each of the property types (e.g. flat, mid terrace, semi-detached, detached) characterised within the 15 household archetypes in PwC's GreenHouse Toolkit for each starting EPC band. This results in average temperature change estimates (or the potential minimum property temperature during summer months) for each combination of:

A. Low carbon action
B. Property type
C. Starting EPC band

To model the projected property temperatures under each 6CB pathway, we take a weighted average of these temperature change estimates, based on the uptake of low carbon actions for each of the 15 household archetypes. This results in the likely change in property temperature for each archetype (by EPC band) under each 6CB pathway, relative to the highest summer temperature in the baseline scenario.

To value the impacts from the mitigation of excess heat, we use BRE's research on health, social and economic impacts associated with the mitigation of Housing Health & Safety Rating System (HHSRS) hazards of category 1 level (e.g. the most severe hazards resulting in health impacts). Note that category 2 hazards excess heat hazards also exist but these do not pose serious or immediate risk to health. As they are not material, we have not included these in our analysis.

BRE's valuations are based on models of the relationship between energy efficiency rating - as determined by the UK's Standard Assessment Procedure (SAP)[4] - and the likelihood of a harmful event with serious health outcomes occurring for the most vulnerable person that could live in that dwelling (as would be assessed under the HHSRS by a practitioner). BRE estimates the total value of the following impacts to the group of homes identified to have category 1 excess heat hazards by the HHSRS, based on the likelihood score given during the assessment:

- Quality-adjusted life-years (QALYs) experienced by the most vulnerable aged person that could be living in that dwelling (assumed to be 65, with a maximum of 16 years life expectancy)[5]
- Cost of medical treatment incurred by the NHS
- Cost of societal impacts (e.g. through informal care by family and friends, lost economic potential and mental health suffering and trauma).

[1] BRE (2016). 'The full cost of poor housing', 2016, Table 12.
[2] BRE (2022). 'The cost of poor housing in England - 2021 Briefing Paper', 2022, Table 1.
[3] This is PwC's proprietary building physics and economics model for the UK housing stock. See appendix for more information.
[4] This is the methodology used by government to assess and compare the energy and environmental performance of dwellings in the UK.
[5] Office of the Deputy Prime Minister (2006). 'Housing Health and Safety Rating System', February 2006, p. 63, paragraph 3.02.

Excess heat | Valuation methodology (2/3)

We model the scale and distribution of excess heat impacts from the domestic buildings sector based on the change in internal property temperature resulting from low carbon actions and BRE's research on the cost of poor housing in the UK.

To apply these valuations to our analysis, we first estimate the average benefits per property by dividing the total benefits quantified by BRE by the number of properties identified to have a category 1 excess heat hazard by the HHSRS. For QALYs, we estimate the average QALYs per person based on average home occupancy from the ONS (around 2.4 people per home, on average).[1]

We extrapolate the findings for NHS and societal savings each year to 2050, uplifting for 2% inflation each year to reflect that the real value of formal and informal care is increasing year-on-year (e.g. from clinical workforce shortages, rising wages and other costs). This is consistent with the trend in real NHS costs[2]. Note that current periods of high inflation are not factored into our analysis and we keep the monetary value of a QALY constant year on year.

For each individual year, we then map the average benefits per property across the temperature range associated with excess heat hazards (>21°C). BRE's research was done at the UK-wide level and does not specify the average change in property temperature experienced by homes with excess heat that have undergone remedial work. We therefore make the assumption that only when a property shifts from one extreme end of the excess heat temperature range (e.g. 21.1°C) to the other (<25°C), it will create the full value of average benefits per property. In practice, the average home will likely not experience such a drastic shift in temperature. As such, our findings can be taken as conservative as the benefits may be greater.

We do not treat the temperature-benefits function as linear because the severity of health outcomes differs by temperature. Instead, we fit a sigmoid function to the excess heat temperature thresholds specified by HHSRS: we distribute the greatest benefits when properties are shifted from temperatures above 25°C, which is the threshold associated with great health risks (including trauma, cardiovascular and respiratory conditions, and increased risk of stroke or death), and further benefits when properties are shifted from temperatures above 21°C, which is the threshold associated with serious health risks (including sleep disturbance and dehydration).[3]

Sigmoidal relationships have been found to have sufficient goodness-of-fit for the relationship between disease severity and exposure.[4] In the absence of further evidence, we also assume a sigmoidal relationship to avoided costs of care (NHS and societal savings).

Given QALYs capture mortality, we assume a sigmoidal relationship between internal property temperature and average QALY gain. Implicit in this assumption is that temperature is an indicator of the potential severity of health outcomes from excessively warm conditions in a home, which is consistent with the HHSRS thresholds (i.e. more severe health outcomes

[1] ONS (2022). 'Families and households in the UK: 2022', May, 2023.
[2] House of Commons (2019). 'NHS Funding and Expenditure', Briefing Paper: CBP0724, January 2019.
[3] UK Government (2019). 'Guide for tenants: Homes (Fitness for Human Habitation) Act 2018', 2019.
[4] Redelmeir et al. (2022). 'Testing for a sweet spot in randomized trials', *Medical Decision Making*, 2022 Feb, 42(2),: 208 - 216.

Excess heat | Valuation methodology (3/3)

We model the scale and distribution of excess heat impacts from the domestic buildings sector based on the change in internal property temperature resulting from low carbon actions and BRE's research on the cost of poor housing in the UK.

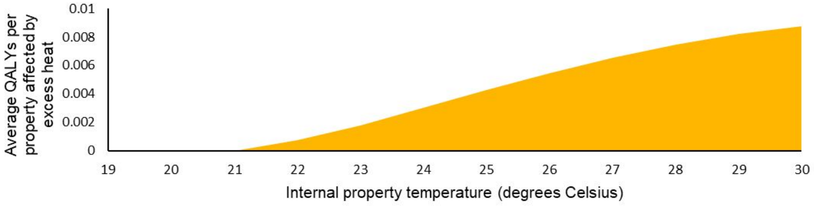
occur at higher temperatures). In the absence of further evidence, we also assume a sigmoidal relationship to avoided costs of care (NHS and societal savings).

Figure 2 opposite presents the sigmoid function we use to distribute QALYs per property by temperature, which we then apportion further by average occupancy. This allows us to estimate the plausible benefits to a property in proportion to the severity of the temperature change experienced (e.g. absolute change and change relative to the property's baseline temperature).

We distribute the direct QALY benefits only to the household archetypes undertaking the low carbon actions (it will be the occupants of the home who experience the health benefits from mitigated excess heat hazards) in proportion to the share of homes reported to experience overheating in the latest findings from the English Housing Survey by tenure.[1]

By contrast, we distribute the societal (indirect) benefits to all household archetypes in proportion to the population within each archetype.

Figure 2. Average QALYs per property in 2025 by property temperature



These include informal care savings, avoided loss economic potential and avoided costs of mental health suffering and trauma.

While some of these benefits will accrue to the occupants of the home, others (such as avoided informal care costs) may accrue to those in other household archetypes. Therefore, in the absence of further evidence, we distribute societal savings uniformly across the UK population. Finally, we distribute the NHS savings as direct impacts to the NHS in the form of savings leading to reduced pressure on health services.

Box 7. Calculation pathway for impacts of excess heat in homes

Change in max. summer property temperature by household archetype & EPC band (Δ°C / archetype)
✖ ((**Change in average QALYs per person change in property temperature** (ΔQALYs / person / Δ°C)
✖ **Population forecast by archetype by EPC band** (# people / archetype)
✖ **Value of a statistical life-year** (£ / QALY))
➕ (**Change in average NHS savings per change in property temperature** (Δ£ / household / Δ°C)
➕ **Change in average societal savings per change in property temperature** (Δ£ / household / Δ°C)))
✖ **Number of households per archetype by EPC band** (# households / archetype)
✖ **Share of households with cat. 1 excess heat hazard by tenure** (%)
✖ **Share of vulnerable population within archetype** (%)
➖ **Total value of NHS savings** (£ / archetype)
= **Total value of impacts from avoided excess cold in homes by archetype, relative to the baseline scenario** (£ / archetype)

[1] DLUHC (2023). 'English Housing Survey 2021 to 2022: social rented sector', July 2023, Chapter 4: Annex Tables.

Excess heat | Sensitivity analysis

We model a number of policy options that can lead to a different rate of uptake of low carbon actions by households, depending on tenure, income or level of energy efficiency in the property.

We do not include sensitivity analysis to adjust BRE's Cost of Poor Housing findings on excess heat, as there is limited evidence of the true cost of excess heat on society, despite the UK experiencing heat waves in recent years.

Additionally, we apply BRE's findings on a per property basis and the number of properties and people used in our estimations are driven by the CCC's 6CB pathway assumptions. This means that the scale of the impacts from avoided excess heat in homes is commensurate with the low carbon actions assumed within the 6CB.

We do, however, include options for users to select different low carbon action uptake assumptions.

For inter-archetype (across different archetypes) uptake, these are:

- **Uniform distribution across household archetypes** - This option assumes all household archetypes take up low carbon actions proportional to the number of homes within each archetype. We set this as the default setting in the model.
- **Prioritisation of social renter households** - This option assumes that households defined by the representative social renter archetypes (i.e. those on government-subsidised rent) take up low carbon actions at a relatively faster rate (e.g. earlier in the pathway to Net Zero by 2050) than other households.
- **Prioritisation of low-income households** - This option assumes that households defined by the representative low-income household archetypes take up low carbon actions at a relatively faster rate (e.g. earlier in the pathway to Net Zero by 2050) than other households.
- **Prioritisation of private renter households** - This option assumes that households defined by the representative private renter archetypes take up low carbon actions at a relatively faster rate (e.g. earlier in the pathway
- **Prioritisation of owner occupier households** - This option assumes that households defined by the representative owner occupier archetypes take up low carbon actions at a relatively faster rate (e.g. earlier in the pathway to Net Zero by 2050) than other household archetypes.

We disaggregate the inter-archetype uptake for each 15 archetypes to determine the respective share of the uptake for each starting EPC band within each archetype. For intra-archetype (across households within a single archetype) uptake, these are:

- **Uniform distribution across households within a single archetype** - This option assumes that all households within a single archetype take up low carbon actions at the same rate (e.g. at the same point in time in the pathway to Net Zero by 2050). We set this as the default assumption in the model.
- **Prioritisation of low EPC rated households** - This option assumes that households with a low EPC rating (D or below) within a single archetype will take up low carbon actions at a relatively faster rate (e.g. earlier in the pathway to Net Zero by 2050) than those with a high EPC rating (C or above).

[1] ONS (2022). 'Families and households in the UK: 2022', May, 2023.

Excess heat | Sensitivity analysis (ctd.)

We model a number of policy options that can lead to a different rate of uptake of low carbon actions by households, depending on tenure, income or level of energy efficiency in the property.

Table 13. Directional impact of sensitivities relative to default assumption

Sensitivity	Directional impact	Description
Uptake of low carbon actions between archetypes		
Target LCA uptake by social renters first (relative to even distribution across households)	↓	Prioritising low carbon action uptake in social renter households decreases the total scale of the impacts resulting from reduced excess heat in homes.
Target LCA uptake by low-income households first (relative to even distribution across households)	↓	Prioritising low carbon action uptake in low income households decreases the total scale of the impacts resulting from reduced excess heat in homes.
Target LCA uptake by private renters first (relative to even distribution across households)	—	Prioritising low carbon action uptake in low income households does not change the total scale of the impacts resulting from reduced excess heat in homes.
Target LCA uptake by owner occupiers first (relative to even distribution across households)	↓	Prioritising low carbon action uptake in low income households decreases the total scale of the impacts resulting from reduced excess heat in homes.
Uptake of low carbon actions between households within archetypes		
Target LCA uptake by households with low EPC ratings (relative to even distribution across households)	↓	Prioritising low carbon action uptake in households with low energy efficiency (as indicated by a low starting EPC rating) decreases the total scale of the impacts resulting from reduced excess heat in homes.

Excess heat | Assumptions & limitations

Our estimates of the impacts of reduced excess heat in homes as a result of low carbon actions which increase energy efficiency and decrease internal thermal temperature are underpinned by a number of assumptions and limitations.

Table 14. Excess heat co-benefit assumptions

No.	Assumption
1	The shapes of the functions linking benefits (QALYs, NHS and societal savings) to the change in property temperature were informed, where possible, by the temperature thresholds at which serious health risks are present, provided by the HHSRS guidance for landlords.[1] In the absence of further evidence, we assume that the accrual of benefits follows a sigmoid function to fit these thresholds.
2	In quantifying the QALY benefits, we assume an average home occupancy of 2.4 people per home, sourced from ONS data[2] which has remained unchanged over the last decade.
3	We assume that the health benefits from reduced excess heat remain constant over time (i.e. there are no changes to the typical medical treatment for health outcomes of excess heat that would lead to material changes in the average QALYs per person estimated by BRE in 2016).
4	We assume that 13%, 17% and 70% of the excess heat co-benefit is experienced by social renters, private renters and owner occupiers, respectively, which we infer from the latest EHS findings on reported overheating in England.[2]
5	To model the effects of climate change, we assume the Met Office's RCP8.5 regional climatic forecasts and using the Perturbed-Physics Model (ID #r001i1p02242).[3] While RCP8.5 is frequently referred to as a 'business as usual' climate scenario, it has come under criticism by some researchers for its assumptions around high future emissions and expansion in coal use.[4] Therefore, our estimates of co-benefits may be taken as conservative.
6	If a property's highest summer temperature is within the excess heat temperature range, we assume that property is impacted by excess heat at that intensity for the whole summer and distribute the benefits on that basis.
7	The uptake pathways for MVHR and overshading are not defined by the CCC in their pathways, and so we have assumed that these low carbon actions follow the deployment pathways of heat pumps as they have similar current uptake and almost all homes are eligible to receive them.

[1] BEIS (2021). 'Energy Follow Up Survey: thermal comfort, damp and ventilation - Final report', 2021, p. 5.
[2] DLUHC (2023). 'English Housing Survey 2021 to 2022: social rented sector', July 2023, Chapter 4: Annex Tables.

Table 15. Excess heat co-benefit limitations

No.	Limitation
1	We estimate the average benefits (QALYs, NHS and societal savings) per household archetype. This means that the results should be used to assess the likely impacts of reduced excess heat for a population or sub-population, but should not be used to assess the individual impacts of a household as these could be more or less than the average values used in this analysis.
2	BRE's research on average QALYs per property affected by excess heat is based on the average age of the most vulnerable aged person that could live in that dwelling. For excess heat, this is people aged 65+, with a maximum of 16 years life expectancy. However, excess heat can also affect younger, albeit less vulnerable, occupants with a longer life expectancy, which would result in a greater average QALY benefit per property. Therefore, our estimates of QALYs created should be taken as conservative.
3	Risks of poor health outcomes due to excess heat is a complex issue and researchers are still understanding the full impact of excess heat in the UK's relatively moderate climate. However, research has indicated that older people tend to be less aware of high internal temperatures.[1] As such, there may be cases where households experience excess heat but the impacts are not attributed to excessively hot living conditions. In these cases, some health, social and economic benefits will not be captured in BRE's research. This limitation may become more important over time, with an aging population and increasing risk of extreme temperature events in the UK.
4	Our analysis only considers HHSRS hazards of category 1. Hazards of category 2 or higher indicate a quality of housing that is significantly worse than average, which may be mitigated by uptake of a low carbon action. However these hazards do not pose immediate risks of health and well-being of households, although they may result in costs to the NHS if left unmitigated.
5	Our analysis does not consider uptake of air conditioning, as it is not a low carbon action (albeit an important adaptation measure in a warming climate) and uptake is not assumed within the 6CB pathways. If air conditioning were to be included in future analysis, this would increase the impacts of avoided excess heat.
6	Because we have undertaken this analysis at a UK-wide level, we do not consider how the impacts of the 'urban heat island effect' may exacerbate the impacts of excess heat in urban areas.
7	We do not account for all relevant impact pathways associated with the excess heat co-benefit. For example, we do not quantify the improved subjective well-being of occupants or the change in visual amenity from overshading measures, as we do not have sufficient evidence to quantify these impacts.
8	We do not account for behavioural feedback loops (i.e. the fact that there will be imperfect use of low carbon actions which means that home occupants do not turn the benefit of low carbon actions entirely into lower energy bills).

Dampness

Avoided excess moisture and humidity in homes from measures that improve temperature and ventilation

Dampness | Overview

The dampness co-benefit captures the health and other impacts from avoiding moisture in homes due to poor building ventilation rates, a lack of adaptation measures and occupant behaviours in homes, especially in winter months.

- **What is the co-benefit?** Dampness involves the presence of house dust mites and mould or fungal growths from excess moisture in the home.[1] Dampness also contributes to the deterioration of a building's fabric by causing paint to blister, mould to grow on walls, thermal insulation to become less effective and brickwork to crack.[2] In addition to damage to buildings & materials, it can also contribute to negative health risks, such as breathing difficulties, depression, anxiety, asthma rhinitis and fungal infection. Children aged 14 and younger have been identified as the group most vulnerable to negative impacts of dampness, although evidence suggests that older people are also at risk of poor health from dampness.[3]

- **Why is it important?** A study by Utilita Energy in January 2023 found that more than a fifth of UK homes are suffering from dampness and mould.[4] The latest results of the English Housing Survey indicate that dampness was most prevalent in the private rented sector, but also present in owner-occupied and social rented dwellings.[5] Additionally, low uptake and use of ventilation measures, particularly in winter months, can lead to damp conditions in homes. This comes at a cost to: **(a)** the individual through increased mortality and morbidity, and a change in subjective well-being, **(b)** the NHS through additional medical treatment costs, and **(c)** to wider society through higher ongoing costs of informal care (which may incurred by family and friends), reduced economic output (lost working days, lower productivity) and mental health suffering and trauma.

[1] Office of the Deputy Prime Minister (2006). 'Housing Health and Safety Rating System Operating Guidance', February 2006.
[2] BRE Group (2023). 'Diagnosing the causes of dampness in buildings', 2023.
[3] Office of the Deputy Prime Minister (2006). 'Housing Health and Safety Rating System', February 2006, p. 53, paragraph 1.02.
[4] The Independent (2023). 'More than a fifth of UK homes are suffering from damp', February 2023.

- **What climate actions create the co-benefit?** Dampness can be mitigated with measures and behaviours that improve energy-efficiency and ventilation. These include installation of mechanical ventilation with heat recovery and occupant use of natural and mechanical ventilation measures (e.g. windows, vents).

- **How do we quantify the co-benefit?** We use PwC's proprietary GreenHouse Toolkit which uses building physics to model the average change in internal property temperature during winter months, as a result of low carbon actions assumed under the CCC's Sixth Carbon Budget. See the **appendix** for more information on the Toolkit.

  We translate these temperatures to relative humidity (RH) using relationships identified in the literature.[6] We then map the properties in the RH range associated with dampness (70%+) to the estimates for health, social and economic impacts quantified by BRE in their Cost of Poor Housing reports.[7,8] These are the number of quality-adjusted life years (QALYs) and NHS and societal savings created when an HHSRS category 1 dampness hazard is mitigated. This allows us to estimate the marginal benefits to each home in line with the change in relative humidity experienced.

- **How do we distribute the co-benefit?** We distribute the health impacts of dampness as direct impacts to the households that take up low carbon actions, the societal savings as indirect impacts proportionally across all households, and the NHS savings as indirect impacts to the NHS.

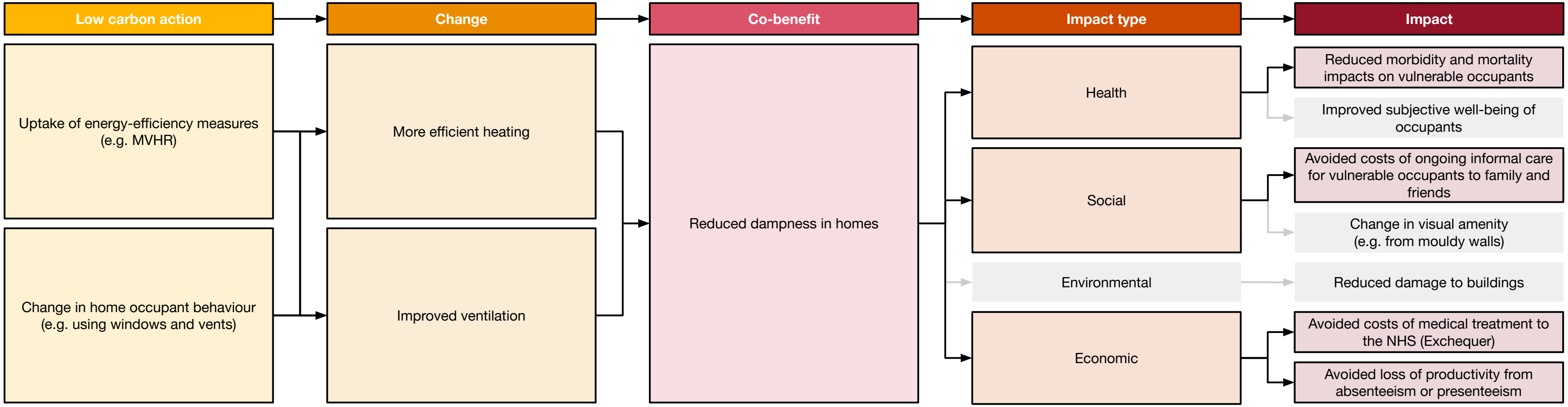
[5] DLUHC (2022). 'English Housing Survey 2021 to 2022: headline report', December 2022.
[6] Menneer et al. (2022). 'Modelling mould growth in domestic environments using relative humidity and temperature', *Building and Environment*, Vol. 208, 15 January 2022.
[7] BRE (2016). 'The full cost of poor housing', 2016, Table 12.
[8] BRE (2022). 'The cost of poor housing in England - 2021 Briefing Paper', 2022, Table 1.

Dampness | Impact pathways

Increasing internal temperatures in homes through energy efficiency measures (e.g. MVHR) and changing occupant behaviours (e.g. using windows & vents) leads to reduced dampness, which results in health, social, environmental and economic impacts.

Households can maintain lower levels of relative humidity in winter months with the use of energy-efficiency measures, such as MVHR which provides filtered air while maintaining heat. This is supported by using natural ventilation (e.g. windows) and mechanical ventilation measures (e.g. vents) when undertaking activities that increase moisture in the home (e.g. showering, cooking). These actions can help to reduce dampness in homes, which contributes to reduced morbidity, mortality and subjective-wellbeing impacts to vulnerable occupants, avoided medical treatment costs to the NHS and ongoing informal care costs to society, a change in visual amenity and reduced damage to buildings (e.g. from mould), and avoided loss of economic productivity.

We summarise the key impact pathways for excess heat below, although they are not exhaustive. We quantify only the coloured and outlined pathways due to scope and evidence constraints.



Dampness | Valuation methodology (1/2)

We model the scale and distribution of dampness impacts from the domestic buildings sector based on the change in internal property temperature, and consequently relative humidity levels, resulting from low carbon actions and BRE's findings on dampness in UK homes.

We value dampness impacts from domestic buildings using two sources:

- Quality-adjusted life-years (QALYs) experienced by the most vulnerable aged person that could be living in that dwelling (assumed to those aged 14 and younger)
- Cost of medical treatment incurred by the NHS
- Cost of societal impacts (e.g. through informal care by family and friends, lost economic potential and mental health suffering and trauma).

To apply these valuations to our analysis, we estimate the average benefits per property by dividing the total benefits quantified by BRE by the number of properties identified to have a category 1 dampness hazard by the HHSRS. For QALYs, we estimate the average QALYs per person based on average home occupancy from the ONS (around 2.4 people per home, on average).[1]

We extrapolate the findings for NHS and societal savings each year to 2050, uplifting for 2% inflation each year to reflect that the real value of formal and informal care is increasing year-on-year, which we assume to be consistent with the trend in real NHS costs.[2] We keep the monetary value of a QALY constant year on year.

For each individual year, we then map the average benefits per property across the relative humidity range associated with dampness hazards (<70%). BRE's research was done at the UK-wide level and does not specify the average change in relative humidity experienced by homes with dampness that have undergone remedial work.

We therefore make the assumption that only when a property shifts from one extreme end of the excess cold temperature range (e.g. 61%) to the other (e.g. <90%), it will create the full value of average benefits per property. In practice, the average home will likely not experience such a drastic shift in relative humidity. As such, our findings can be taken as conservative, as the benefits may be greater.

We do not treat this temperature-benefits function as linear because the severity of health outcomes differs by relative humidity level. Instead, we fit a sigmoid function to the dampness threshold specified by HHSRS: we distribute the greatest benefits when properties are shifted from relative humidity levels above 70%, which is the threshold associated with great health risks (including breathing difficulties, depression, anxiety, asthma, rhinitis and fungal infection).[3]

Sigmoidal relationships have been found to have sufficient goodness-of-fit for the relationship between disease severity and exposure.[4] Implicit in this assumption is that relative humidity is an indicator of the potential severity of health outcomes from damp conditions in a home, which is consistent with the HHSRS thresholds as described (i.e. more severe health outcomes occur at higher relative humidity levels). In the absence of further evidence, we also assume a sigmoidal relationship to avoided costs of care (NHS and societal savings).

[1] ONS (2022). 'Families and households in the UK: 2022', May, 2023.
[2] House of Commons (2019). 'NHS Funding and Expenditure', Briefing Paper: CBP0724, January 2019.
[3] UK Government (2019). 'Guide for tenants: Homes (Fitness for Human Habitation) Act 2018', 2019.
[4] Redelmeir et al. (2022). 'Testing for a sweet spot in randomized trials', *Medical Decision Making*, 2022 Feb, 42(2),: 208 - 216.

Dampness | Valuation methodology (2/2)

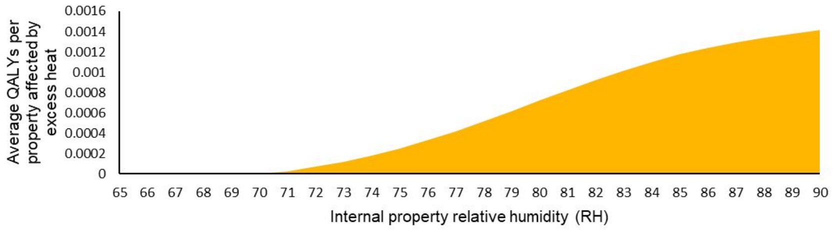
We model the scale and distribution of dampness impacts from the domestic buildings sector based on the change in internal property temperature, and consequently relative humidity levels, resulting from low carbon actions and BRE's findings on dampness in UK homes.

Figure 3 opposite presents the sigmoid function we use to distribute QALYs per property by relative humidity (RH), which we then apportion further by average occupancy. This allows us to estimate the plausible benefits to a property in proportion to the severity of the change in RH experienced (e.g. absolute change and change relative to the property's baseline RH).

We distribute the QALY benefits directly to only the household archetypes taking the low carbon actions (as it will be the occupants of the home who experience the health benefits from mitigated dampness hazards) in proportion to the share of homes identified to have category 1 excess cold hazards in BRE's research by tenure.[1]

By contrast, we distribute the societal benefits as indirect benefits to all household archetypes in proportion to the population within each archetype. These include informal care savings, avoided loss economic potential and avoided costs of mental health suffering and trauma.

Figure 3. Average QALYs per property in 2025 by relative humidity levels



While some of these benefits will accrue to the occupants of the home, others (e.g. avoided informal care costs) may accrue to those in other archetypes. Therefore, in the absence of further evidence, we distribute societal savings uniformly across the UK population. Finally, we distribute the NHS savings as direct impacts to the NHS in the form of savings leading to reduced pressure on health services.

Box 8. Calculation pathway for impacts of dampness in homes

Change in minimum winter property temperature by household archetype & EPC band (Δ°C / archetype) ✖ **Unit conversion** (ΔRH / Δ°C) ✖ ((**Change in average QALYs per person change in RH** (ΔQALYs / person / ΔRH) ✖ **Population forecast by archetype by EPC band** (# people / archetype) ✖ **Value of a statistical life-year** (£ / QALY)) ➕ (**Change in average NHS savings per change in RH** (Δ£ / household / ΔRH) ➕ **Change in average societal savings per change in RH** (Δ£ / household / ΔRH))) ✖ **Number of households per archetype by EPC band** (# households / archetype) ✖ **Share of households with cat. 1 dampness hazard by tenure** (%) ✖ **Share of vulnerable population within archetype** (%) ➖ **Total value NHS savings** (£ / archetype) = **Total value of impacts from avoided dampness in homes by archetype, relative to the baseline scenario** (£ / archetype)

[1] BRE (2023). 'The cost of poor housing in England by tenure', June, 2023.

Dampness | Sensitivity analysis

We model a number of policy options that can lead to a different rates of uptake of low carbon actions by households (depending on tenure, income or level of energy efficiency in the property) and different levels of ventilation in a property.

To calculate the dampness co-benefit, we apply BRE's findings on a per property basis. The number of properties and people used in our estimations are driven by the CCC's 6CB pathway assumptions, meaning the scale of the impacts from avoided dampness in homes is commensurate with the low carbon actions assumed within the 6CB. Higher temperatures during winter months are correlated with lower levels of dampness in homes.

However, dampness is also influenced by the levels of ventilation in a home, which varies by building construction and occupant behaviour. To capture this uncertainty, we present indicative ranges of how the impacts of dampness may change under different ventilation scenarios, sourced from Hamilton et al. 2015.[1] These are based on the EHS's Mould Severity Index (MSI), which ranks condensation mould growth. An MSI value of greater than 1 represents significant dampness levels resulting in some mould growth.[2]

- **Natural ventilation (e.g. through windows or vents, no added ventilation):** 26% <u>increase</u> in exposure to significant dampness
- **Mechanical ventilation prescribed by regulated buildings standards:** 17% <u>decrease</u> in exposure to significant dampness
- **Mechanical ventilation installed at the installer discretion:** 24% <u>increase</u> in exposure to significant dampness

We apply these adjustments to the total dampness co-benefits to estimate the range that could be seen, depending on the type of ventilation in a home.

[1] Hamilton et al. (2015). 'Health effects of home energy efficiency interventions in England: a modelling study', *BMJ Open* 2015; 5: e007298. Doi: 10.1136/bmjopen-2014-007298, p. 6, Table 3.
[2] Taylor and Symonds (2021). 'Estimating spatial variation of moisture risks in English and Welsh dwellings', 1st International Conference on Moisture in Buildings (ICMB21), UCL London 28-29 June 2021.

We also include options for users to select different low carbon action uptake assumptions. Where possible, we have kept these consistent with the user inputs available in the Net Zero Distributional Impacts model.

For inter-archetype (across different archetypes) uptake, these are:

- **Uniform distribution across household archetypes** - This option assumes all household archetypes take up low carbon actions proportional to the number of homes within each archetype.
- **Prioritisation of social renter households** - This option assumes that households defined by the representative social renter archetypes (i.e. those on government-subsidised rent) take up low carbon actions at a relatively faster rate (e.g. earlier in the pathway to Net Zero by 2050) than other households.
- **Prioritisation of low-income households** - This option assumes that households defined by the representative low-income household archetypes take up low carbon actions at a relatively faster rate (e.g. earlier in the pathway to Net Zero by 2050) than other households.
- **Prioritisation of private renter households** - This option assumes that households defined by the representative private renter archetypes take up low carbon actions at a relatively faster rate (e.g. earlier in the pathway
- **Prioritisation of owner occupier households** - This option assumes that households defined by the representative owner occupier archetypes take up low carbon actions at a relatively faster rate (i.e. earlier in the pathway to Net Zero by 2050) than other household archetypes.

Dampness | Sensitivity analysis (ctd.)

We model a number of policy options that can lead to a different rate of uptake of low carbon actions by households, depending on tenure, income or level of energy efficiency in the property.

We disaggregate the inter-archetype uptake for each 15 archetypes to determine the respective share of the uptake for each starting EPC band within each archetype. For intra-archetype (across households within a single archetype) uptake, these are:

- **Uniform distribution across households within a single archetype** - This option assumes that all households within a single archetype take up low carbon actions at the same rate (e.g. at the same point in time in the pathway to Net Zero by 2050). We set this as the default assumption in the model.
- **Prioritisation of low EPC rated households** - This option assumes that households with a low EPC rating (D or below) within a single archetype will take up low carbon actions at a relatively faster rate (e.g. earlier in the pathway to Net Zero by 2050) than those with a high EPC rating (C or above).

Table 16. Directional impact of sensitivities relative to default assumption

Sensitivity	Directional impact	Description
Uptake of low carbon actions between archetypes		
Target LCA uptake by social renters first (relative to even distribution across households)	↑	Prioritising low carbon action uptake in social renter households increases the total scale of the impacts resulting from reduced dampness in homes.
Target LCA uptake by low-income households first (relative to even distribution across households)	↓	Prioritising low carbon action uptake in low income households decreases the total scale of the impacts resulting from reduced dampness in homes.
Target LCA uptake by private renters first (relative to even distribution across households)	—	Prioritising low carbon action uptake in low income households does not change the total scale of the impacts resulting from reduced dampness in homes.
Target LCA uptake by owner occupiers first (relative to even distribution across households)	↓	Prioritising low carbon action uptake in low income households decreases the total scale of the impacts resulting from reduced dampness in homes.
Uptake of low carbon actions between households within archetypes		
Target LCA uptake by households with low EPC ratings (relative to even distribution across households)	↑	Prioritising low carbon action uptake in households with low energy efficiency (as indicated by a low starting EPC rating) increases the total scale of the impacts resulting from reduced dampness in homes.

[1] ONS (2022). ‘Families and households in the UK: 2022’, May, 2023.

Dampness | Assumptions & limitations

Our estimates of the impacts of reduced dampness in homes as a result of low carbon actions which increase internal thermal temperature and reduce relative humidity are underpinned by a number of assumptions and limitations.

Table 17. Dampness co-benefit assumptions

No.	Assumption
1	The shapes of the functions linking benefits (QALYs, NHS and societal savings) to the change in property temperature were informed, where possible, by the temperature thresholds at which serious health risks are present, provided by the HHSRS guidance for landlords.[1] In the absence of further evidence, we assume that the accrual of benefits follows a sigmoid function to fit these thresholds.
2	In quantifying the QALY benefits, we assume an average home occupancy of 2.4 people per home, sourced from ONS data[2] which has remained unchanged over the last decade.
3	We assume that the health benefits from reduced dampness remain constant over time (i.e. there are no changes to the typical medical treatment for health outcomes of dampness that would lead to material changes in the average QALYs per person estimated by BRE in 2016).
4	We assume that 29%, 51% and 20% of the dampness co-benefit is experienced by social renters, private renters and owner occupiers, respectively, which we infer from BRE analysis on excess cold hazards in England.[2]
5	To model the effects of climate change, we assume the Met Office's RCP8.5 regional climatic forecasts and using the Perturbed-Physics Model (ID #r001i1p02242).[3] While RCP8.5 is frequently referred to as a 'business as usual' climate scenario, it has come under criticism by some researchers for its assumptions around high future emissions and expansion in coal use.[4] Therefore, our estimates of co-benefits may be taken as conservative.
6	If a property's lowest winter temperature is within the relative humidity range associated with dampness, we assume that property is impacted by dampness at that intensity for the whole winter and distribute the benefits on that basis.
7	We assume BRE's valuations of the impacts of reduced dampness in homes are accurate and robust.

Table 18. Dampness co-benefit limitations

No.	Limitation
1	We estimate the average benefits (QALYs, NHS and societal savings) per household archetype. This means that the results should be used to assess the likely impacts of reduced dampness for a population or sub-population, but should not be used to assess the individual impacts of a household as these could be more or less than the average values used in this analysis.
2	BRE's research on average QALYs per property affected by dampness is based on the average age of the most vulnerable aged person that could live in that dwelling. For dampness, QALYs are estimated for people aged 14 or younger, with a minimum of 67 years life expectancy. However, dampness can also affect older occupants with a shorter life expectancy. While we adjust the findings so that only properties with children receive the benefits of avoided dampness, including this older group of vulnerable occupants in the analysis would result in a (marginally) greater average QALY benefit per property. Therefore, our estimates of QALYs created should be taken as conservative. Note that although both dampness and excess cold are experienced in winter months, there is minimal risk of double-counting the impacts of these co-benefits because the vulnerable populations do not overlap.
3	The HHSRS ratings (on which BRE's findings are based) do not take into account the affordability of energy. It is possible that there are vulnerable people who choose not to heat their homes to an adequate level to avoid serious health risks. Because dampness is also a function of property temperature (as captured in our methodology), these groups may also experience dampness. However, these instances are not captured in our analysis, as we do not have a way of robustly identifying them.
4	Our analysis does not consider HHSRS hazards of category 2 or above. These hazards indicate a quality of housing that is significantly worse than average, which may be mitigated by uptake of a low carbon action. However these hazards do not pose immediate risks of health and well-being of households, although they may result in costs to the NHS if left unmitigated.
5	While we have considered internal temperature and moisture levels and, to an extent, external temperatures by isolating property temperatures during winter months, we have not considered external moisture levels (e.g. from periods of high rainfall) which could contribute to damp conditions in homes through rising or penetrating damp. However, we consider this to be a relatively small limitation given condensation is the most common type of damp experienced in the UK, above rising or penetrating damp.
6	We do not account for all relevant impact pathways associated with the dampness co-benefit. For example, we do not quantify the improved subjective well-being of occupants, as we do not have sufficient evidence to quantify these impacts.
7	We do not account for behavioural feedback loops (i.e. the fact that there will be imperfect use of low carbon actions which means that home occupants do not turn the benefit of low carbon actions entirely into lower energy bills).
8	We do not account for the fact that there may be improvements in the standard level of housing over time in a baseline scenario.

[1] HHSRS (2006). 'Housing Health and Safety Rating System Guidance for Landlords and Property Related Professionals', 2006.
[2] BRE (2023). 'The cost of poor housing in England by tenure', June, 2023.

Noise

Avoiding noise pollution through energy-efficient modes of transport

Noise | Overview

Avoided noise pollution from road traffic contributes to positive health and economic impacts for those living nearby.

- **What is the co-benefit?** Noise pollution is any unwanted sound that affects the health and well-being of humans and ecosystems.
- **Why is it important?** Noise pollution is recognised as the second largest environmental health risk in Europe (after air pollution) and a growing health risk in the UK.[1] Environmental noise has been found to affect sleep, cardiovascular health, birth and reproductive outcomes, cognition, mental health, well-being (e.g. through annoyance), quality of life and other health outcomes.[2] Noise pollution affects all geographies and particularly those who live near major roads, as the transport sector is the biggest source of noise pollution in the UK.[3]
- **What climate actions create the co-benefit?** In the transport sector, reduced demand for road transport and a shift in passenger behaviour towards active travel (i.e. walking, cycling) or public transportation contributes to reduced noise pollution. Additionally, uptake of hybrid or electric vehicles contribute to reduced noise pollution, relative to ICE vehicles, when driven at lower speeds. Noise pollution can also be reduced in the buildings sector, for example through the installation of window glazing. However, in this analysis, we only quantify avoided noise pollution from the transport sector, as this is the most material source of noise.
- **How do we quantify the co-benefit?** We use Geographic Information Systems (GIS) data on noise from roads in Great Britain to map noise pollution from road transport in the UK in the CCC's baseline scenario (e.g. the counterfactual), using an equivalent attribution method to account for noise pollution in Northern Ireland based on rural-urban classification and road type.

  We model noise pollution for each Sixth Carbon Budget pathway by applying a relationship between vehicle types and noise as specified by DfT[4] to estimate the marginal decibel change per vehicle kilometre traveled by vehicle type. We adjust noise levels for the impact of electric vehicles, which are quieter than ICE vehicles at lower speeds (e.g. in urban areas), using relationships identified in the literature.

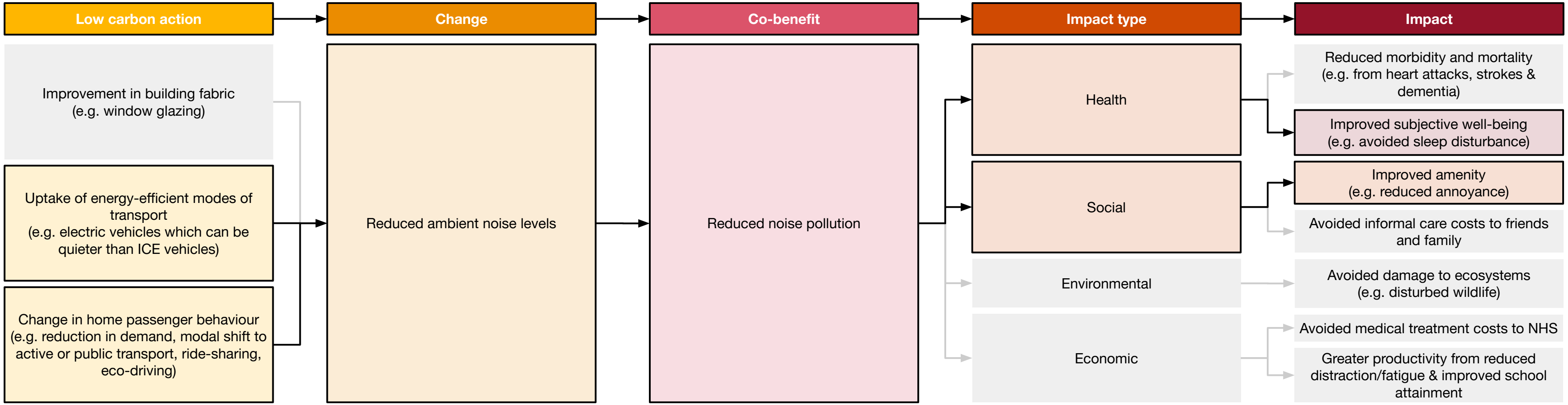
  We value the change in noise pollution from the Sixth Carbon Budget pathway to the baseline scenario using the Department for Transport's TAG noise assessment databook, namely the costs of sleep disturbance and loss of amenity from road transport noise pollution.
- **How do we distribute the co-benefit?** We distribute these impacts across households by mapping the rural-urban classification of the areas in which the noise is created to the rural-urban classifications of household archetypes. This allows us to distribute the benefits to the households that experience the impacts of noise pollution, rather than just those that create them.

[1] European Environment Agency (2021). 'Noise pollution is a major problem, both for human health and the environment', May 2021.
[2] Clark et al. (2020). 'Evidence for Environmental Noise Effects on Health for the United Kingdom Policy Context: A Systematic Review of the Effects of Environmental Noise on Mental Health, Wellbeing, Quality of Life, Cancer, Dementia, Birth, Reproductive Outcomes, and Cognition', Int J Environ Res Public Health. 2020 Jan; 17(2): 393.
[3] Environmental Protection UK (2023). 'Air pollution and transport', 2023.
[4] DfT (1988). 'Calculation of Road Traffic Noise', 1988.

Noise | Impact pathways

Improved building fabric, and a shift in passenger behaviour to EVs, active travel or public transportation all contribute to reduced noise pollution which results in reduced morbidity and mortality, improved subjective well-being, improved amenity value, avoided damage to ecosystems and greater productivity.

Ambient noise levels can be reduced in the buildings and transport sectors, by installing window glazing, switching to energy-efficient modes of transport (such as EVs), and changing passenger behaviour (by reducing demand, shifting to active or public transport, ride-sharing or eco-driving). With reduced noise pollution comes a range of health, social, environmental and economic benefits. These include reduced morbidity and mortality from heart attacks, strokes and dementia, improved subjective well-being through avoided sleep disturbance, improved amenity through reduced annoyance, avoided damage to ecosystems, avoided medical treatment costs to the NHS, and greater productivity. We summarise the key impact pathways for noise below, although note that they are not exhaustive. We quantify only the coloured and outlined pathways due to scope and evidence constraints.



Noise | Valuation methodology (1/2)

We model the scale and distribution of noise impacts from the transport sector based on decibels created (or avoided) per vkm travelled (or shifted) and the size of population that is local enough to experience the effects of the change in noise pollution.

We estimate noise impacts from the transport sector using:

- DfT Calculation of Road Traffic Noise (1988)[1]
- Campello-Vicente et al. 2017[2]
- Noise maps for GB[3,4,5]
- DfT Noise Assessment Workbook[6]
- DfT Transport Research Authority[7]
- DfT National Travel Survey[8]
- Population & rural-urban classification data

To estimate the value of avoided noise pollution, we use DfT's Transport Appraisal Guidance data on distance travelled by vehicle type (including EVs), road type and rural-urban classification to understand where typical journeys in the UK take place. We apply these statistics to the CCC's 6CB assumptions on distance travelled by vehicle type and powertrain, enhancing their assumptions with data on road type and rural-urban classification.

We then estimate the level of noise (in decibels) created in the baseline scenario and 6CB pathways by multiplying the distance travelled per road type by a function of decibels per road type, as recommended in DfT.[1]

This estimation captures typical speeds of different vehicle types travelling on different roads, as well as the nonlinear path that noise travels (i.e. noise pollution is greater nearer the source). It does not, however, capture the difference in noise from EVs vs ICE vehicles (which is greatest at low speeds).

We therefore adjust for the impact of noise from EVs using relationships set out in Campello-Vicente et al. 2017.[2] This results in the change in the level of noise created based on the vehicle kilometres assumed by vehicle type in each 6CB pathway, relative to the baseline scenario.

To estimate the distribution of the change in noise pollution across households, we take the following steps:

1. We estimate the relative share of transport sector noise pollution in each lower super output area (LSOA). This allows us to estimate the total noise pollution experienced by the residential populations in each rural-urban classification. This is broken down by noise type (morning, daytime, nighttime) and noise band (<55 dB, 55-65 dB, 65-75 dB and >75 dB).
2. Next, we distribute this total noise pollution across household archetypes by each archetypes relative population share living in each rural-urban classification.
3. We do this for the baseline scenario (by extrapolating the findings from the 2019 noise maps) and for each 6CB pathway to calculate the change in noise pollution relative to the baseline.

We distribute the change in noise pollution proportionally across the populations in each household archetype.

[1] DfT (1988). 'Calculation of Road Traffic Noise', 1988.
[2] Campello-Vicente et al. (2017). 'The effect of electric vehicles on urban noise maps', *Applied Acoustics*, Vol. 116, Jan. 2017, pp. 59-64.
[3] UK Government (2022). 'Strategic noise mapping (2017)', December 2022.
[4] Scottish Government (2023). 'Welcome to Scotland's noise', 2023.
[5] Welsh Government (2017). 'Environmental Noise Mapping 2017 - Road traffic noise (dB) - major roads (LAeq, 16h) 2017', 2017.
[6] DfT (2023). TAG: environmental impacts worksheets - 'Noise workbook', May 2023.
[7] DfT (2022). 'Road traffic statistics (TRA)', September 2022.
[8] DfT (2022). 'National Travel Survey', August 2022.

Noise | Valuation methodology (2/2)

We model the scale and distribution of noise impacts from the transport sector based on decibels created (or avoided) per vkm travelled (or shifted) and the size of population that is local enough to experience the effects of the change in noise pollution.

We value the change in noise pollution using marginal external costs from DfT's WebTAG databook, which includes:

- the cost of sleep disturbance
- loss of amenity (e.g. annoyance).

We distribute the cost of sleep disturbance as a direct impact and the loss of amenity as an indirect impact to the individuals within each household archetype living in the areas in which the noise pollution is created from the local transport systems.

Due to scope and time constraints, we do not value any potential NHS savings or productivity benefits from improved school attainment resulting from avoided noise pollution, although we recognise that these would be interesting areas for future work.

The full calculation pathway is set out in **Box 9** below.

Box 9. Calculation pathway for avoided noise pollution from road transport

Distance travelled by vehicle type and powertrain in 6CB scenario (vkm) ✖ **Share of total distance travelled by road type and rural-urban classification** (%) ✖ **Typical noise pollution by vehicle and road type** (dB / vkm) ✖ (**Baseline modeled road noise** (dB) − (**Change in noise pollution from demand reduction or rebound of EVs** (dB) + **Change in noise created from EVs and ICE vehicles** (dB))) ✖ **Avoided marginal external costs of noise pollution** (£) = **Total value of impacts from avoided noise pollution, relative to the baseline scenario** (£ / archetype)

Noise | Sensitivity analysis

We model a number of policy options that can lead to a different rate of uptake of low carbon actions by households.

A key simplifying assumption in this methodology is that we use a median point estimate for noise levels to anchor each noise band, rather than a distribution of noise levels for each noise band. For noise bands without a lower or upper (e.g. >75 dB), we set the anchor to the value given (e.g. 75 dB). This is our default setting in the model.

However, model users have the functionality to edit these point estimates to view the effects of this assumption on the evaluation of noise when increased or decreased to the noise band's maximum or minimum bounds.

The directional impact of this sensitivity is set out in **Table 19** opposite.

Table 19. Directional impact of sensitivities relative to default assumption

Sensitivity	Directional impact	Description
Increasing noise band anchor (relative to default)	⬆	Increasing the noise band anchor relative to the default assumption will increase the value of the noise pollution impact (holding all else equal) because the marginal external costs of noise increase as decibel levels increase. This sensitivity may be used to understand the upper end of the range of possible impacts.
Decreasing noise band anchor (relative to default)	⬇	Decreasing the noise band anchor relative to the default assumption will decrease the value of the noise pollution impact (holding all else equal) because the marginal external costs of noise decrease as decibel levels decrease. This sensitivity may be used to understand the lower end of the range of possible impacts.

Noise | Assumptions & limitations

Quantifying the avoided impacts of noise pollution is based on a number of assumptions regarding where noise is created and how widely it is experienced. The key limitation to our approach is that it should not be used to assess individual impacts, but rather impacts to a population.

Table 20. Noise co-benefit assumptions

No.	Assumption
1	We assume that the populations of LSOAs are evenly distributed across their land areas.
2	We assume a 4 kilometre wide corridor of noise adjacent to motorways is due to the motorway. This is to distinguish between noise attributed to motorways and A roads.
3	We use strategic noise maps to capture daytime noise (L_{den}) and nighttime noise (L_{night}). We assume that daytime noise creates amenity impacts (i.e. annoyance when working from home), whereas nighttime noise creates sleep disturbance.[1]
4	We assume the initial noise level of a place is equal to the noise levels at the midpoint of that place. We use the lower bounds of the inequality where there is no maximum to the band specified.
5	We assume that the level of noise created by EVs remains constant over time (i.e. there are no significant improvements in EV technology that reduces their noise impact between now and 2050).
6	We account for driving speed in our analysis, as it is implicit in the GIS noise mappings by road type. We assume that the relationship between driving speed and noise levels remains constant over time (i.e. there are no significant improvements in vehicles that reduce the noise impact at different speeds between now and 2050).
7	We assume the same level of impacts experienced from a change in noise pollution for each person in an LSOA. LSOAs are a relatively granular geographical breakdown, ranging from 1,000 to 3,000 people, on average in the UK.[2] We therefore consider this to be a prudent assumption which is used to weight the noise pollution impacts across rural-urban classifications.

Table 21. Noise co-benefit limitations

No.	Limitation
1	The impact of noise on an individual's health and well-being is subjective and not everyone will experience the same adverse impact at a given level of noise. The costs used to value the impacts of noise on sleep disturbance and amenity are based on probabilities to measure the likely impacts in a population, and therefore should not be used to assess individual impact.[1]
2	We are able to capture the impacts from noise pollution on households living close to transport systems so far as the rural-urban classification of the journey taken maps to the rural-urban classification of the household living in that area. However, we are not able to capture the differences between a household living next to an A road, for example, and a household living several kilometres away from the A road if both households live in an area with the same rural-urban classification.
3	We assume the same level of impacts experienced from a change in noise pollution for each person in an LSOA. Given LSOAs are quite small in area, ranging from X-Y people, we consider this to be a prudent

[1] DfT (2023). TAG: environmental impacts worksheets - 'Noise workbook', May 2023.
[2] ONS (2021). 'Census 2021 geographies', 2021.

Congestion

Avoiding unproductive time spent in road traffic and cost to vehicles

Congestion | Overview

Avoided congestion from having fewer vehicles on the road results in improved journeys (in terms of journey time and quality as well as vehicle operating costs), contributing to positive social impacts for road users and economic impacts for the economy.

- **What is the co-benefit?** Congestion occurs when the demand for road travel exceeds the supply of roadways (i.e. when road systems are operating at or above capacity). It is traffic characterised by slower speeds, longer journey times, increased vehicular queuing and stopping and starting and less predictable journey times.
- **Why is it important?** Congestion culminates in the opportunity cost of time spent in congestion that could be spent doing other things, such as working or leisure activities. London remains the most congested city in the world, with the average driver losing an estimated 156 hours in 2022 to traffic.[1] Bristol, Manchester, Birmingham and Belfast also rank amongst the UK's most congested cities.[2] The Department for Transport (DfT) has forecast up to an 85% increase in congestion levels by 2040.[3] While congestion is immediately experienced by road users, it also affects non-road users, in particular employers and others who rely on individuals who commute by road: congestion primarily affects those who travel by private vehicle but also public transport where buses do not have priority lanes.
- **What climate actions create the co-benefit?** Low carbon actions such as reducing demand for road transport, shifting to active modes of travel (such as walking or cycling) and using public transport instead of private vehicles can all help to reduce congestion. Reduced congestion contributes to **(a)** positive social impacts for road users through improved journey experience when travelling, **(b)** economic productivity through time savings that may otherwise be spent on productive activities, like paid work, and **(c)** reduced vehicle operating costs: idling or driving at low speed reduces engine efficiency, using more fuel and requiring more maintenance.[4]

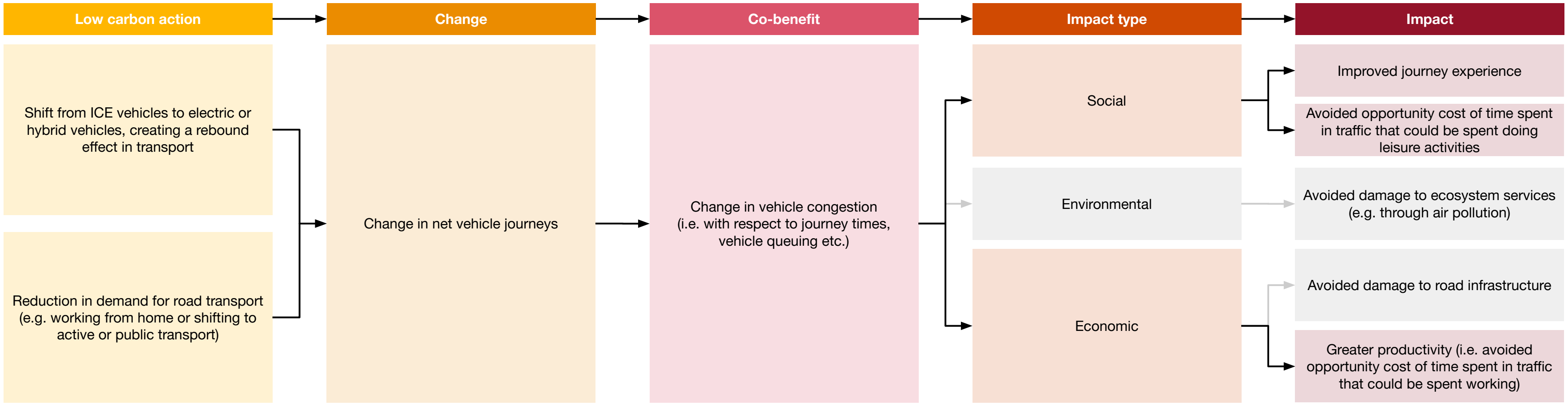
  However, low carbon actions (such as switching to EVs) can also lead to increased travel demand. This is referred to as comfort-taking or the 'rebound effect', where individuals drive more after shifting to a hybrid or electric vehicle because the cost of charging the vehicle has become relatively cheaper than paying for petrol or diesel. Comfort-taking effects are assumed in the 6CB for electric vehicles.
- **How do we quantify the co-benefit?** We estimate the net impacts of reduced congestion in the CCC's 6CB pathways, relative to the baseline scenario, using marginal external cost valuations from DfT's WebTAG for the perceived cost of time spent in congestion.[5] These include resource costs for paid working time (e.g. paid labour employment costs) and market costs for non-working time (e.g. value of doing leisure activities, valued using stated preference surveys).[6]
- **How do we distribute the co-benefit?** We distribute the impacts of congestion created by privately-owned cars as direct impacts to car-owning households, and the impacts of congestion created by commercial vehicles as indirect impacts proportionally across all households.

[1] Inrix (2022). 'Global Traffic Scorecard', 2022.
[2] BBC (2023). 'London remains world's most congested city, report claims', January 2023.
[3] Local Government Association (2017). 'A country in a jam: tackling congestion in our towns and cities', August 2017.
[4] DfT (2012). 'An introduction to the Department for Transport's congestion statistics', August 2012.
[5] DfT (2022). 'Transport analysis guidance', November 2022.
[6] DfT (2015). 'Provision of market research for value of travel time savings and reliability: Non-Technical Summary Report', August 2015.

Congestion | Impact pathways

Reducing net vehicle journeys can help to decarbonise transport and reduce vehicle congestion, contributing to social and economic impacts.

Across the different 6CB pathways, congestion levels can either increase or decrease depending on the low carbon actions taken. Shifting from ICE vehicles to electric or hybrid vehicles, for example, can result in greater (albeit lower emission) numbers of vehicles on the road, leading to increased congestion levels in particular when road pricing favours electric vehicles. By contrast, reducing demand for road transport (e.g. by shifting to active or public transport) can result in decreased congestion levels. With a change in congestion comes social, environmental and economic impacts. These include improved journey experience, avoided "lost time" that could be spent doing leisure or work activities and avoided damage to road infrastructure and ecosystems. We summarise the key impact pathways for congestion below, although they are not exhaustive. We quantify only the coloured pathways due to scope and evidence constraints. Note that environmental impacts associated with congestion are captured in the road repairs and air quality co-benefits.



Congestion | Valuation methodology (1/2)

We model the scale and distribution of the impacts from road congestion based on the type of vehicle travelling, the characteristics of the road on which the vehicle is travelling (major or minor road, rural or urban area) and the typical severity of traffic experienced.

We estimate the impacts of congestion using four sources:

- CCC Sixth Carbon Budget (6CB) transport model
- DfT WebTAG databook[1]
- Road traffic statistics (TRA)[2]
- National Travel Survey (NTS)[3]

The CCC's 6CB assumes a number of low carbon actions (such as reduction in demand for road transport and shift to EVs) which change the total distance travelled by road vehicles annually in each pathway. Using data from TRA and NTS on characteristics of typical vehicle journeys, we apportion the distance travelled by:

- Vehicle type (small car, medium car, large car, van, small rigid vehicle, large rigid vehicle, articulated vehicle, bus, motorcycle).
- Road type (e.g. motorway, A road, other).
- Rural-urban classification (London, inner & outer conurbations, other urban areas, rural areas).
- Congestion band (severity of traffic on a scale of 1-5, with 1 representing free-flowing conditions and 5 representing standstill traffic).

We then calculate the change in distance travelled in the 6CB pathways, relative to the baseline scenario. This includes the change in distance travelled by both private and commercial vehicles.

[1] DfT (2022). 'Transport analysis guidance', November 2022.
[2] DfT (2022). 'Road traffic statistics (TRA)', September 2022.

We multiply the change in distance travelled by the projected marginal external costs (MECs) of time spent in congestion set out in DfT's WebTAG databook. Specifically, we apply the perceived costs of time per distance travelled by cars (e.g. private vehicles), inflated to 2021 prices in line with the price base year used in the Net Zero Distributional Model. These capture:

- Resource costs for paid working time (e.g. costs to an employer for paid labour).
- Market costs for non-working time (e.g. value of doing leisure activities, valued using stated preference surveys).
- Vehicle operating costs.

For commercial vehicles, we only apply the resource costs for paid working time.

The MECs are given as pence per vehicle kilometre spent in each congestion band, and vary by vehicle type, road type, rural-urban classification of the area travelled. The congestion band is the biggest determinant of costs but road type is a key factor in determining the congestion band: generally, there are fewer congestion costs incurred on motorways where there is more space (and consequently a lower risk of congestion) compared to A roads and other road types. Vehicle size is also a factor, with buses and rigid and articulated vehicles incurring greater vehicle operating costs with stop-start traffic.

[3] DfT (2022). 'National Travel Survey (NTS)', August 2022.

Congestion | Valuation methodology (2/2)

We model the scale and distribution of the impacts from road congestion based on the type of vehicle travelling, the characteristics of the road on which the vehicle is travelling (major or minor road, rural or urban area) and the typical severity of traffic experienced.

DfT assumes different car occupancies depending on the journey purpose (work, commuting, other) and time of day that a journey is taken (weekdays, weekends).[1] The MECs used to assess the benefits of avoided congestion are based on avoided vehicle kilometres travelled; however, inherent in the MECs are DfT's vehicle occupancy assumptions. We therefore assume the same vehicle occupancy rates as DfT per vehicle kilometre assumed in the CCC's 6CB pathways.

We distribute the working time share of the avoided congestion costs created by all vehicles (cars and commercial vehicles) as indirect impacts proportionally across all households. This is because these costs represent the costs to an employer for paid labour, so the benefit in avoiding these costs will be experienced by society (i.e. through a more productive economy).

We distribute the non-working time share of the avoided congestion costs (e.g. value of doing leisure activities) created by cars to only the household archetypes that own cars (as defined by Frontier Economics), based on their own driving patterns. For example, a rural household may drive more but experience less congestion due to the locality they drive in. Distributing the driving locations amongst the rural-urban classification of congestion bands allows for an archetypal distribution of the effects of congestion. This is because the non-working time share of avoided congestion costs is experienced by road users, rather than those working or living nearby congested roads.

We do not distribute any avoided costs of congestion to the Exchequer in the form of NHS savings, as there are no health impacts associated with the congestion co-benefit, which we value purely in terms of time (in line with the DfT's approach).

The full calculation pathway is set out in **Box 10** below.

Box 10. Calculation pathway for congestion co-benefit

(**Distance travelled by vehicle type in selected 6CB scenario** (vkm) − **Distance travelled by vehicle type in baseline scenario** (vkm)) × **Share of distance travelled by road type, rural-urban classification, vehicle type and congestion band** (%) × **Value of avoided congestion** (£ / vkm) × **Share of distance travelled by rural-urban classification for each archetype** (%) = **Savings from avoided congestion by archetype, relative to the baseline scenario** (£)

[1] DfT (2022). 'Transport analysis guidance', November 2022, Table A1.3.3.

Congestion | Sensitivity analysis

We model high and low sensitivities for distance travelled in standstill traffic, represented by congestion band 5, to capture the uncertainty around how traffic operates in these conditions.

The key uncertainty for this co-benefit is quantifying the vehicle kilometres spent in congestion by different congestion bands. The DfT urges caution when applying MECs for traffic of congestion band 5. This is because there is currently little evidence as to how traffic operates in standstill conditions and the MECs have been developed with respect to current driving conditions, which could change with a large transformation to the UK transport system.[1]

On the latter, we take confidence in using congestion costs developed around current driving conditions because total vehicle kilometres travelled is c.3% less in the CCC's 6CB Balanced Net Zero Pathway (which is the CCC's central scenario).

However, across the other 6CB pathways, total vehicle kilometres range from a 17% reduction to an 18% increase. Therefore, we include three options in our analysis to test this uncertainty:

- **High scenario:** Apply the full values of the MECs for congestion band 5 to distance travelled in congestion band 5.
- **Central scenario (default):** Apply the MECs for congestion band 4 to distance travelled in congestion band 5
- **Low scenario:** Remove all distance travelled in congestion band 5 from analysis (i.e. these vehicle kilometres are not valued).

We present the central scenario as the default option in our analysis. This is a conservative assumption, as a strict reading of DfT guidance could be interpreted to justify the use of congestion band 5.

The high scenario can be used to analyse the upper range of impacts of congestion, particularly if DfT releases new data to indicate a significantly greater number of vehicle kilometres travelled on UK roads in congestion band 5.

The low scenario can be used to analyse the lower range of impacts of congestion, under the even more conservative assumption that standstill traffic is 'noise' that skews results and should not be captured (and valued) within long-term projections.

We set out the directional impact of these sensitivities relative to the central scenario (default) in **Table 22** below.

Table 22. Directional impact of sensitivities relative to default assumption

Sensitivity	Directional impact	Description
High scenario for congestion band 5	⬆	Selecting the high scenario for congestion band 5 will apply higher marginal external costs to the vehicle kilometres avoided in the most congested levels of traffic. Holding all else constant, this will increase the value of the impacts of avoided congestion in the analysis. For example, a car experiencing the most severe congestion on a rural A-road in 2025 avoids 2.4 times the costs (in time, fuel, etc.) under the high scenario for congestion band 5 than it would under the central scenario.
Low scenario for congestion band 5	⬇	Selecting the low scenario for congestion band 5 will remove all distance travelled in congestion band 5 from the analysis by valuing these avoided vehicle kilometres at £0/km. Holding all else constant, this will decrease the value of the impacts of avoided congestion in the analysis.

[1] DfT (2023). 'TAG Unit A5.4 Marginal External Costs', May 2023, p. 8, paragraph 2.4.5.

Congestion | Assumptions & limitations

Quantifying and distributing the avoided impacts of congestion is based on a number of assumptions regarding what vehicles are driven by households vs for commercial purposes and how impacts are experienced across members of society.

Table 23. Congestion co-benefit assumptions

No.	Assumption
1	We assume all cars are private vehicles and all vans, buses, rigid vehicles, articulated vehicles and motorcycles are commercial vehicles. We make this simplifying assumption to aid the distribution of impacts across beneficiaries but appreciate that this may not necessarily be the case for all vehicles. However, we do not include this as a sensitivity because other vehicle types are not defined in the 15 household archetypes developed by Frontier Economics.
2	We assume the same vehicle occupancy rates as DfT[1] per vehicle kilometre in the CCC's 6CB pathways. Note these vary depending on journey purpose and time.
3	We assume that the congestion bands set by DfT at five-year intervals remain appropropriate across household archetypes and over time.
4	We assume that changes in car vehicle type (e.g. EVs and autonomous vehicles) are not a key factor in creating congestion on roads - in other words, these vehicles create the same amount of congestion as the cars modelled by DfT.

Table 24. Congestion co-benefit limitations

No.	Limitation
1	Our analysis is (primarily) based on the relationship between car ownership, vehicle kilometres travelled and traffic occurrence. We do not account for other factors - for example, income[2] - that may contribute to one household archetype being more likely to be stuck in traffic. However, we expect that these differences will be largely captured in the uptake assumptions developed by Frontier Economics for household archetypes.
2	DfT's MECs are designed to be used to analyse impacts at the margin, rather than system-wide effects. We take confidence that the change in vehicle kilometres travelled in the CCC's 6CB Balanced Net Zero Pathway (which is the CCC's central scenario) relative to the baseline is c.3%. However, should this difference become greater in future carbon budgets, the CCC may wish to consult DfT on whether the MECs remain the most appropriate valuation source. Additionally, there is a broader need for network-level modelling to determining the impact of low carbon actions on traffic patterns.
3	We do not account for any uncertain effects of greater time spent working from home or, more broadly, changing work patterns in our analysis, above and beyond what is assumed in the CCC's 6CB pathways.

[1] DfT (2022). 'Transport analysis guidance', November 2022, Table A1.3.3.

[2] Government Office for Science (2019). 'Inequalities in Mobility and Access in the UK Transport System', March, 2019, p. 25: "[Low income households] make nearly 20% fewer trips and travel 40% less distance than the average household."

Hassle costs

Reluctance or opportunity cost to change routines with low carbon actions

Hassle costs | Overview

The hassle cost of increased travel time required when shifting from a private vehicle to active travel (e.g. walking, cycling) or public transport impacts the subjective-wellbeing of road users and wider productivity of the economy.

- **What is the co-benefit?** The hassle costs co-benefit captures reluctance or opportunity cost to change routines with actions required to transition to net zero. For example, people may be reluctant to shift a car journey to a bike journey or shifting from an ICE vehicle to an EV, as these changes may require more travel time or forward-planning (i.e. to map out EV charge points along a long car journey). Similarly, there may be an opportunity cost associated with retrofitting a home, particularly for measures like floor insulation which could be time-intensive and disruptive to daily routines. We refer to these in our analysis as hassle costs, but they do not represent financial costs. Rather, they represent the reduction in social value associated with climate action, which may be measured by time or convenience.

- **Why is it important?** Hassle costs pose a key barrier to taking up and maintaining more climate-friendly behaviours: the Behavioural Insights Team finds that 88% of a representative UK sample believe it is "often too hard to make more sustainable choices because of high costs, inconvenience, limited knowledge or other barriers".[1] Hassle costs may be greater for different groups across society. For example, the hassle associated with shifting a car journey to a walking journey for a household that lives in an urban area with amenities such as local shops located relatively nearby may be less than that for a household located in a rural area. Similarly, a low-income household may incur greater hassle costs than a high-income household when retrofitting their home if the remedial works requires them to miss work which may be less flexible.

- **What climate actions create the co-benefit?** The hassle costs co-benefit is created by low carbon actions across the buildings, transport and agriculture & land use sectors. Retrofitting a home, shifting to a new mode of transport, and changing diet all require individuals to change their routines and daily habits, both over the short or long term.

- **How do we quantify the co-benefit?** Due to scope and evidence constraints, we focus our analysis on the time cost associated with shifting from travelling by car to travelling by active or public transport: this low carbon action leads to greater time, on average, spent travelling by foot, bike or bus than would have been spent travelling by car. We convert the distance shifted (from car to active or public transport) under the CCC's 6CB pathways, relative to the baseline scenario, to time using average walking, cycling and bus speeds. We then value this time using marginal external cost (MEC) valuations from DfT's WebTAG for the perceived cost of time spent, based on journey purpose (commuting, business, other).[2]

- **How do we distribute the co-benefit?** We distribute the impacts of hassle costs created by privately-owned cars as direct impacts to car-owning households.

[1] BIT (2023). 'How to build a Net Zero society', January 2023, p. 22.

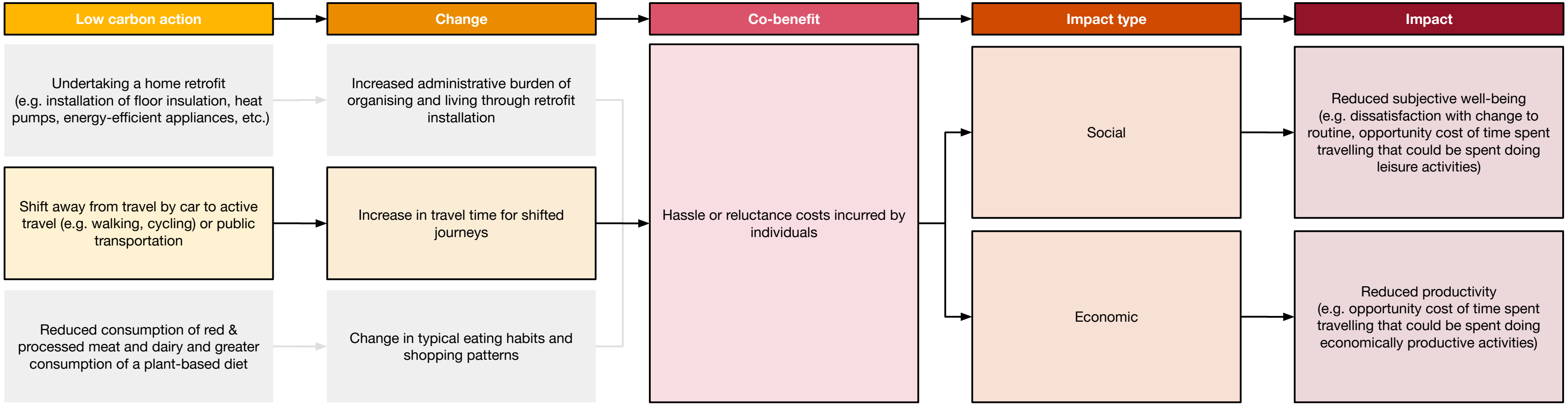
[2] DfT (2022). 'Transport analysis guidance', November 2022, Table A1.3.2.

Hassle costs | Impact pathways

Retrofitting a home, shifting to a new mode of transport, and changing diet all require individuals to change their routines and daily habits, both over the short or long term, which creates a negative co-benefit of hassle costs, or time that could be otherwise spent doing productive or leisure activities.

The hassle costs co-benefit of the net zero transition may be created in any disruptive change in behaviour across the buildings, transport and agriculture & land use sectors. Negative impacts include disruption to daily routines by, for example, retrofitting a home, shifting to a new mode of transport or changing diet. Hassle costs represent the social or economic opportunity cost of changing behaviour. These are negative impacts to subjective well-being or economic productivity.

We summarise the key impact pathways for hassle costs below, although note that they are not exhaustive. We quantify only the coloured pathways due to scope and evidence constraints. These are the hassle costs associated with a shift from car journeys to walking, cycling or public transportation journeys.



Hassle costs | Valuation methodology (1/2)

We model the scale and distribution of the impacts from hassle costs of shifting journeys by car to journeys by active or public transport based on the likelihood of "shiftable" journeys (as determined by journey purpose & length, time of day, age & rural-urban classification of individual).

We estimate the impacts of hassle costs of shifting from travelling by car to travelling by active or public transport using eight sources:

- CCC Sixth Carbon Budget (6CB) transport model
- DfT's National Travel Survey (NTS)[1]
- DfT National Statistics (2022)[2]
- WHO HEAT[2]
- Schleinitz et al. (2017)[3]
- Southampton City Council (2021)[4]
- TfL (2023)[5]
- DfT's WebTAG databook[6]

The CCC assumes a certain number of car journeys will be shifted to walking, cycling or bus journeys in each 6CB pathways. However, "shiftable" journeys depend on the journey purpose, length, time of day, rural-urban classification of the area travelled, and the age of the person travelling. For example, the CCC assumes that any car journey taken before 7am or after 8pm would likely not be shifted to a walking, cycling or bus journey.

We enhance these assumptions with data from the NTS to map these assumption across days of the week. This is because there are large differences in the types of journeys taken during weekdays (e.g. commuting, education) vs weekends (e.g. shopping, entertainment). This allows us to estimate the likelihood that a journey taken for a certain purpose, at a particular time of day on a specific day during the week will be shifted to either a walking, cycling or bus journey.

We multiply this likelihood by the distance shifted to each mode of transport (walking, cycling, bus), as specified for each 6CB pathway. This gives us the total additional distance travelled in walking, cycling and bus journeys as a result of car demand reduction. We apportion these distances by the household archetypes that are likely to take these journeys by applying the CCC's assumptions around the journey types and distances that are likely to be shifted, which vary by age group and rural-urban classification of the area in which individuals live.

With each shifted journey comes a change in the time spent travelling. This creates hassle costs for individuals who spend greater time, on average, travelling by foot, bike or bus than would have otherwise been spent travelling by car. We estimate the additional time spent travelling by multiplying the additional distance travelled by dividing by average travel speeds for each mode of transport (i.e. car, walking, cycling, bus), which are sourced from various government and academic reports. These are 38.7 km/hour for a car,[2] 4.8 km/hour for walking,[3] 14 km/hour for cycling,[3] 20 km/hour for electric cycling,[4] 14.8 km/hour for a bus in a rural area[5] and 15.5 km/hour for a bus in an urban area.[6]

[1] DfT (2022). 'National Travel Survey (NTS)', August 2022.
[2] DfT (2021). 'National Statistics: Travel time measures for local 'A' roads: January to December 2021 report', March 2022.
[3] WHO (2017). 'Health economic assessment tool (HEAT) for walking and for cycling', 2017.
[4] Schleinitz et al. (2017). 'The German Naturalistic Cycling Study - Comparing cycling speed of riders of different e-bikes and conventional bicycles', Safety Science, 92, 290-297. dx.doi.org/10.1016/j.ssci.2015.07.027.
[5] TfL (2023). 'Buses performance data', 2023.
[6] Southampton City Council (2021). 'Bus service improvement plan', October 2021, p. 15.
[7] DfT (2022). 'Transport analysis guidance', November 2022, Table A1.3.2.

Hassle costs | Valuation methodology (2/2)

We model the scale and distribution of the impacts from hassle costs of shifting journeys by car to journeys by active or public transport based on the likelihood of "shiftable" journeys (as determined by journey purpose & length, time of day, age & rural-urban classification of individual).

We value the additional time spent travelling by multiplying the additional distance travelled by the the projected marginal external costs (MECs) of time set out in DfT's WebTAG databook.[1] Specifically, we apply the perceived costs of time per hour travelled, inflated to 2021 prices in line with the price base year used in the Net Zero Distributional Model.

These capture:

- Resource costs for paid working time (e.g. costs to an employer for paid labour).
- Market costs for non-working time (e.g. value of doing leisure activities, valued using stated preference surveys).

The MECs were developed using stated and revealed preference surveys. They are given as £ per hour travelled, and vary by journey purpose (business, commuting, other). Non-work commutes incur the greatest cost, followed by business journeys and lastly other journeys.

We distribute the impacts of hassle costs created by journeys shifted from privately-owned cars as direct impacts to car-owning households. We only quantify this for trips shifted from private vehicles, as trips shifted from commercial vehicles would create efficiencies in logistics which we have not included due to scope constraints.

The full calculation pathway is set out in **Box 11** below.

Box 11. Calculation pathway for hassle costs co-benefit

(**Distance travelled by car in selected 6CB scenario** (vkm) − **Distance travelled by car in baseline scenario** (vkm)) ✖ **Share of shifted distance travelled by active & public transport (walking, cycling, bus)** (%) ✖ **Likelihood of shifted journeys taken by archetype based on purpose, length, time of day, age and rural-urban classification** (%) ÷ **Unit conversion based on mode of travel** (km / time) ✖ **Value of additional journey time by journey purpose** (£ / hour) = **Disbenefit from hassle costs by archetype, relative to the baseline scenario** (£)

[1] DfT (2022). 'Transport analysis guidance', November 2022, Table A1.3.2.

Hassle costs | Sensitivity analysis (1/2)

There are a wide range of possible journey types and ages that can take up the required shift from car travel to active travel or public transport, which impact the scale and distribution of the hassle costs co-benefit.

A key uncertainty in calculating the hassle costs co-benefit is estimating the additional time required for active travel journeys.

To allow for initial analysis we assume that journeys are shifted equally across archetypes and trip purposes. Trips are then distributed across age bands based upon their age brackets ability to travel as stated in Milner (2023)[1]. Edited sensitivities must lie within the constraints set out by the CCC's transport model which constrain levels of low carbon action uptake. These vary between pathway:

- **Age** influences if and how far a trip can be shifted.
- **Transport method** influences what journey distance can be shifted.
- **Time of day** influences if a trip can be shifted to another mode.
- **Trip purpose** influences whether a journey can reasonably be shifted.

The time disparity between a car trip and one taken via a different mode is dependent on the average speed. There is a wide range of uncertainty in estimating the time disparity, as some trips shifted to walking or cycling may also shorten in length (e.g. cycling to a local shop instead of driving to a larger supermarket). For simplicity, we do not adjust the journey lengths when trips are shifted from vehicle travel to walking, cycling or public transport.

Table 25. Directional impact of sensitivities relative to default assumptions

Sensitivity	Directional impact	Description
Shifting trips towards high resource cost purposes	↓	The value of time is affected due to the purpose of the trip that is being shift. An example would be instead of shifting a trip for leisure one is shifted for work purposes. If this trip took exactly the same time the business trip would still incur a higher social cost.
Shifting trips away from high resource costs purposes	↑	The value of time is affected due to the purpose of the trip that is being shift. An example would be instead of shifting a trip for business one is shifted for shopping. If this trip took exactly the same time the shopping trip would still incur a lower cost.
Increasing the speed of active travel and buses	↑	Increasing the speed of walking, cycling, e-cycling and buses would decrease the extra time it takes to use these methods, instead of a car. This would therefore decrease the additional cost of taking these trips by non-car modes.
Decreasing the speed of active travel and buses	↓	Decreasing the speed of walking, cycling, e-cycling and buses would increase the extra time it takes to use these methods, instead of a car. This would therefore increase the additional cost of taking these trips by non-car modes.
Increasing the speed of car trips	↓	If cars travel faster this would therefore increase the difference in time by shifting these trips to another method, thereby costing more.
Decreasing the speed of car trips	↑	If cars travel slower this would therefore decrease the difference in time by shifting these trips to another method, thereby costing more.

[1] Milner (2023). 'Impact on mortality of pathways to net zero greenhouse gas emissions in England and Wales: a multisectoral modelling study.', Jan 2023.

Hassle costs | Sensitivity analysis (2/2)

The scale of the hassle costs co-benefit is also sensitive to the valuation of travel time savings.

Another uncertainty in calculating the hassle costs co-benefit is the impact on the value of time incurred from modal shift. DfT published value of time estimates in its WebTAG database which we set as the default assumption in the model.

However, these values may appear to be quite high given they do not account for the benefit of health effects from active travel. For example, someone might be less bothered by shifting a car journey to a bike journey, even if the journey takes longer because they know that they are getting in exercise from which they derive satisfaction.

We therefore present two sensitivities to the value of time used to estimate hassle costs from modal shift:

- DfT's MECs less 20 percent
- DfT's MECs less 65 percent

These adjustments are based on evidence from choice experiments run by Flugel et al. 2021[1] on the valuation of travel time savings for journeys in which health impacts are also created.

The directional impact of these sensitivities relative to the default assumption (DfT's MECs unadjusted) are presented in **Table 26** opposite.

Table 26. Directional impact of sensitivities relative to default assumptions

Sensitivity	Directional impact	Description
DfT's MECs less 20 percent (relative to DfT's MECs unadjusted)	⬇	This sensitivity will reduce the scale of the hassle costs co-benefit relative to the default assumption by applying a lesser value of time to the additional travel time required to shift a car journey to a walking, cycling or bus journey (holding the journey distance constant). Note however that this co-benefit will still be negative (i.e. a social cost).
DfT's MECs less 65 percent (relative to DfT's MECs unadjusted)	⬇	This sensitivity will reduce the scale of the hassle costs co-benefit relative to the default assumption (and the 'DfT's MECs less 20 percent' sensitivity) by applying a lesser value of time to the additional travel time required to shift a car journey to a walking, cycling or bus journey (holding the journey distance constant). Note however that this co-benefit will still be negative (i.e. a social cost).

[1] Flugel et al. (2021). 'The effect of health benefits on the value of travel time savings in active transport', *Journey of Transport & Health*, Volume 21, June 2021, 101074.

Hassle costs | Assumptions & limitations

Quantifying and distributing the hassle costs of greater active and public transport is based is underpinned by DfT's valuations of time, which may not capture all relevant impacts. Additionally, a key limitation of this approach is how material the hassle costs of active and public transport remain over the long-term.

Table 27. Hassle costs co-benefit assumptions

No.	Assumption
1	In the default setting in the model, we assume that uptake of active travel is weighted by the population of an age band and their median distance of active travel, as stated in Milner (2023).[1]
2	We assume the distribution of journeys by journey purpose across household archetypes is in proportion to an archetype's population.
3	We assume that a shift in car journey to active or public modes of travel is only possible for archetypes that are defined by Frontier Economics to own a car.

Table 28. Hassle costs co-benefit limitations

No.	Limitation
1	DfT's MECs are designed to be used to analyse impacts at the margin, rather than system-wide effects. We take confidence that the change in vehicle kilometres travelled in the CCC's 6CB Balanced Net Zero Pathway (which is the CCC's central scenario) relative to the baseline is c.3%. However, should this difference become greater in future carbon budgets, the CCC may wish to consult DfT on whether the MECs remain the most appropriate valuation source. Additionally, there is a broader need for network-level modelling to determining the impact of low carbon actions on traffic patterns.
2	It is possible that the hassle cost of greater journey times through active or public modes of transport diminishes over time, particularly as active or public transport becomes the norm. In other words, over time, households may start to view longer journey times not as an opportunity cost of economically productive or leisurely time, and instead as a positive way of travelling by which they become more physically fit or manage to be productive in different ways that were not possible by car travel (e.g. leisurely time reading on the bus). We caution model users to be aware of the impacts that are valued for each co-benefit, recognising that not all relevant impacts are quantified as part of this work.

[1] Milner (2023). 'Impact on mortality of pathways to net zero greenhouse gas emissions in England and Wales: a multisectoral modelling study.', Jan 2023.

Road safety

The change in the number & severity of road accidents through changes to road traffic & energy-efficient driving behaviour

Road safety | Overview

Fewer road accidents resulting from fewer vehicles on the road contributes to positive health, social, environmental and economic impacts for road and non-road users.

- **What is the co-benefit?** The road safety co-benefit refers to the reduced number of road accidents resulting from a less congested transport system, which can be achieved while decarbonising the transport sector.
- **Why is it important?** Road accidents are estimated to cost the UK, on average, £2.13 million in fatalities, over £0.5 million in injuries and £20,000 in property damages per accident.[1] The value of prevention of reported road crashes in Great Britain is estimated by Government to be £33.4 billion.[2]

  Road accidents affect both road and non-road users. The majority of road accidents involve at least one car, but vulnerable non-road users also include pedestrians, cyclists and e-scooter users.
- **What climate actions create the co-benefit?** Low carbon actions to decarbonise the transport sector, such as reducing demand for road transport and shifting to active or public transport, can help to reduce road accidents, through fewer vehicles travelling on the road network.

  Avoided road accidents contribute to a number of health, social, environmental and economic impacts. These include: reduced mortality, morbidity and subjective well-being of road and non-road users, avoided NHS and societal costs (e.g. of policing, legal costs, and others associated with road accidents), avoided damage to vehicles, property & infrastructure, and avoided loss of economic productivity.
- **How do we quantify the co-benefit?** We estimate the net impacts of avoided road accidents in the CCC's 6CB pathways, relative to the CCC's baseline scenario, using marginal external cost (MEC) valuations from DfT's WebTAG databook. This gives values for fatalities, serious and slight injuries and property damages from road accidents.[3] These valuations include human costs (i.e. fatalities, injuries), medical and ambulance costs and the costs of lost economic output.[4] We multiply these MECs by the number of vehicle kilometres avoided by vehicle type, road type and rural-urban classification of the journey.
- **How do we distribute the co-benefit?** We distribute the health impacts of avoided road accidents involving private vehicles (i.e. cars) as direct impacts across all household archetypes based on the share of impacts attributable to road users (car drivers/passengers) vs non-road users (cyclists, pedestrians). We distribute the health impacts of avoided road accidents involving commercial vehicles as indirect impacts proportionally across all household archetypes by population. We distribute the value of medical & ambulance costs as indirect impacts to the Exchequer in the form of NHS savings. Finally, we distribute the value of lost economic output as indirect impacts proportionally across all household archetypes by population.

[1] International Transport Forum (2021). 'Road Safety Report: United Kingdom', p. 10.

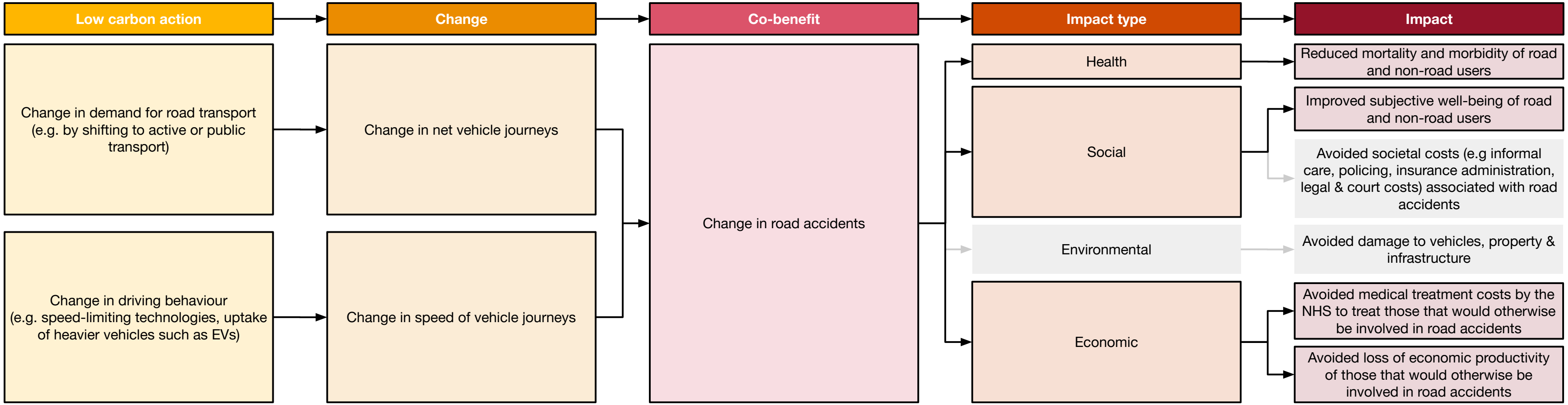
[2] TRL (2021). 'Safe Roads for All', August 2021.

[3] DfT (2022). 'Transport analysis guidance', November 2022.

Road safety | Impact pathways

Reducing demand for road transport and changing driving behaviour to more energy-efficient behaviour helps to reduce the number and severity of road accidents, improving road safety and contributing to health, social, environmental and economic impacts.

Reducing demand for road transport (e.g. by shifting to walking or cycling journeys or public transport) and changing individual driving behaviour (e.g. through uptake of heavier vehicles such as EVs, or the use of speed-limiting technologies) can all help to decarbonise the UK transport sector. These low carbon actions also help to reduce net vehicle journeys and the speed at which vehicle journeys are taken, resulting in fewer road accidents. With improved road safety comes health, social, environmental and economic benefits. These include reduced mortality, morbidity and improved subjective well-being of road and non-road users, avoided NHS and societal costs (e.g. of policing, legal costs, and others associated with road accidents), avoided damage to vehicles, property & infrastructure, and avoided loss of economic productivity by those who would have been involved in road accidents. We summarise the key impact pathways for the road safety co-benefit below, although note that they are not exhaustive. We quantify only the coloured and outlined pathways due to scope and evidence constraints.



Road safety | Valuation methodology (1/2)

We model the scale and distribution of the impacts from road safety based on the type of vehicle travelling and the characteristics of the road on which the vehicle is travelling (major or minor road, rural or urban area)

We estimate the impacts of road safety using four sources:

- CCC Sixth Carbon Budget (6CB) transport model
- DfT WebTAG databook[1]
- Road traffic statistics (TRA)[2]
- National Travel Survey (NTS)[3]

The CCC's 6CB assumes a number of low carbon actions (such as reduction in demand for road transport and shift to EVs) which change the total distance travelled by road vehicles annually in each pathway. Using data from TRA and NTS on characteristics of typical vehicle journeys, we apportion the distance travelled by:

- Vehicle type (small car, medium car, large car, van, small rigid vehicle, large rigid vehicle, articulated vehicle, bus, motorcycle).
- Road type (motorway, A road, other).
- Rural-urban classification (London, conurbations, other urban, rural).

We then calculate the change in distance travelled in the 6CB pathways, relative to the baseline scenario (the counterfactual). This includes the change in distance travelled by both private and commercial vehicles.

We multiply the change in distance travelled by the projected marginal external costs (MECs) of road accidents set out in DfT's WebTAG databook and inflated to 2021 prices, consistent with the price base year used in the Frontier Net Zero Distributional Model.

The MECs are given as pence per vehicle kilometre, and vary by vehicle type, road type, rural-urban classification of the area travelled. MECs of accidents are largest on A roads and other roads for heavier vehicles.

The MECs include human costs, medical and ambulance costs and the costs of lost economic output.[4] We use data from DfT[5] on reported collisions and casualties by vehicle type and road user to estimate the share of human costs (e.g. fatalities, injuries) that are attributable to road users (car drivers/passengers) vs non-road users (cyclists, pedestrians).

Specifically, we distribute 40% of human costs as direct impacts to the households that are defined by Frontier Economics to own cars, as this is the estimated share of road accidents involving only cars. We distribute the remaining 60% of human costs as indirect impacts across all household archetypes in proportion to archetype population, as this share of impacts is from road accidents involving at least one other party that was not travelling by car (e.g. cyclist, pedestrian).

We distribute the value of medical & ambulance costs as indirect impacts to the Exchequer in the form of NHS savings. Finally, we distribute the value of lost economic output as indirect impacts proportionally across all household archetypes by population.

[1] DfT (2022). 'Transport analysis guidance', November 2022.
[2] DfT (2022). 'Road traffic statistics (TRA)', September 2022.
[3] DfT (2022). 'National Travel Survey (NTS)', August 2022.
[4] DfT (2023). 'A valuation of road accidents and casualties in Great Britain: Methodology note', 2023.
[5] DfT (2022). 'Reported road collisions, vehicles and casualties tables for Great Britain', December 2022, RAS0601.

Road safety | Valuation methodology (2/2)

We model the scale and distribution of the impacts from road safety based on the type of vehicle travelling and the characteristics of the road on which the vehicle is travelling (major or minor road, rural or urban area)

The ratios used to distribute impacts are summarised in **Table 29** below.

Table 29. Distribution ratios of impacts from avoided road accidents

Vehicle	Human costs	Medical & ambulance costs	Lost economic output
Cars (private)	40% as direct impacts to all car-owning households (based on the share of car-only accidents), remaining 60% as indirect impacts to all archetypes in proportion to each archetype's population	100% to Exchequer in the form of NHS savings	100% as indirect impacts to all archetypes in proportion to each archetype's population
All other vehicles (commercial)	100% as indirect impacts to all archetypes in proportion to each archetype's population		

DfT assumes different car occupancies depending on the journey purpose (e.g. work, commuting, other) and time of day that a journey is taken (e.g. weekdays, weekends).[1] The MECs used to assess the benefits of avoided road accidents are based on avoided vehicle kilometres travelled; however, inherent in the MECs are DfT's vehicle occupancy assumptions. We therefore assume the same vehicle occupancy rates as DfT per vehicle kilometre assumed in the CCC's 6CB pathways.

The full calculation pathway is set out in **Box 12** below.

Box 12. Calculation pathway for road safety co-benefit

(**Distance travelled by vehicle type in selected 6CB scenario** (vkm) − **Distance travelled by vehicle type in baseline scenario** (vkm)) × **Share of distance travelled by road type, rural-urban classification and vehicle type** (%) × **Value of avoided accident by road type, rural-urban classification and vehicle type per distance travelled** (£ / vkm) × **Share of distance travelled by rural-urban classification for each archetype** (%) = **Total savings from avoided road accidents by archetype, relative to the baseline scenario** (£)

Road safety | Sensitivity analysis

We model high and low sensitivities for the marginal external costs used to value the road safety impacts to capture the uncertainty around how traffic patterns may differ over time with different vehicle and trip mixes.

The main sensitivity assumption for the road safety co-benefit is the marginal external costs (MECs) modeled by DfT. The MECs are defaulted to the central scenario based on the National Transport Model (NTM) central scenario. The dataset provides low and high sensitivities, which can be used to assess the impact on the total road safety co-benefit.

The directional impact of these are set out in **Table 30** opposite.

Table 30. Directional impact of sensitivities relative to default assumptions

Sensitivity	Directional impact	Description
Low MEC scenario	⬇	The low MEC scenario reduces the costs of accidents on the roads, this therefore decrease the benefits of removing these accidents. This is based on the DfT's NTM using scenario 6.
High MEC scenario	⬆	The high MEC scenario increases the costs of accidents on the roads, this therefore increases the benefits of removing these accidents. This is based on the DfT's NTM using scenario 7, which should be used with caution as this has assumptions around the uptake of EVs which don't necessarily match up with the CCC's pathways.

Road safety | Assumptions & limitations

Quantifying and distributing the avoided impacts of road accidents is based on a number of assumptions on vehicle type (e.g. private vs commercial) and members of society who experience the impacts (e.g. road and non-road users).

Table 31. Road safety co-benefit assumptions

No.	Assumption
1	We assume all cars are private vehicles and all vans, buses, rigid vehicles, articulated vehicles and motorcycles are commercial vehicles. We make this simplifying assumption to aid the distribution of impacts across beneficiaries but appreciate that this may not necessarily be the case for all vehicles. However, we do not include this as a sensitivity because other vehicle types are not defined in the 15 household archetypes developed by Frontier Economics.
2	We assume that the ratios of road accidents involving only cars (40%) and the (remaining) share of road accidents involving at least one other vehicle that is not a car (60%) out of total road accidents, which are based on 2021 DfT data[1] for Great Britain, remain constant over time.
3	We assume that all avoided human costs would have been borne by the individuals involved in the accidents, rather than family and friends who may need to provide informal care for those involved in accidents.
4	DfT's MECs for road accidents are based on assumptions around average vehicle occupancy rates as DfT[1] per vehicle kilometre, which vary depending on journey purpose and time. We assume the same vehicle occupancy rates as DfT in the CCC's 6CB pathways.
5	We assume that changes in car vehicle type (e.g. EVs and autonomous vehicles) are not a key factor in causing road accidents - in other words, these vehicles create the same amount of road accidents as the cars modelled by DfT.

Table 32. Road safety co-benefit limitations

No.	Limitation
1	Our analysis is (primarily) based on the relationship between car ownership, vehicle kilometres travelled and traffic occurrence. We do not account for other factors that may contribute to one household archetype being more likely to be involved in a road accident. For example, we do not account for the fact that young males are more likely to be involved in a road accident in the UK.[3] However, we expect that these differences will be largely captured in the uptake assumptions developed by Frontier Economics for each household archetype.
2	Due to scope and evidence constraints, we do not quantify the road safety impacts that are created from greater volumes of cyclists or pedestrians in this analysis. This is because there is large uncertainty around the number of non-motorised accidents with higher rates of cycling. For example, accidents per kilometre tend to be lower in places with the greatest levels of cycling ('safety in numbers effect'), but greater cycling kilometres under current transport conditions in the UK would lead to greater accidents. We therefore do not quantify these impacts as we cannot robustly estimate them within the scope of this work.
3	DfT's MECs are designed to be used to analyse impacts at the margin, rather than system-wide effects. We take confidence that the change in vehicle kilometres travelled in the CCC's 6CB Balanced Net Zero Pathway (which is the CCC's central scenario) relative to the baseline is c.3%. However, should this difference become greater in future carbon budgets, the CCC may wish to consult DfT on whether the MECs remain the most appropriate valuation source.
4	We estimate the distribution of road accident impacts across road and non-road users (e.g. cyclists, pedestrians) using data from DfT on reported road collisions and casualties by vehicle type and road user. However, it is possible, for example, that an accident takes place between two car-owning individuals, when one party is cycling rather than driving. In this instance, we would distribute the impacts proportionally across all archetypes rather than across only car-owning households. Our analysis should therefore be used to assess the likely impacts in a population, not individual impacts.
5	We do not account for the uncertain effects of greater time spent working from home or, more broadly, changing work patterns in our analysis, as these are not considered in the 6CB analysis.
6	We do not account for all relevant impact pathways associated with the road safety co-benefit. For example, we do not quantify the avoided societal costs (e.g informal care, policing, insurance administration, legal & court costs) or the damage to vehicles, property & infrastructure associated with road accidents.

[1] DfT (2023). 'Road Accidents & Safety Statistics', July 2023.

Road repairs

Change in infrastructure costs incurred from a change in road traffic & vehicle weight

Road repairs | Overview

Fewer road repairs resulting from a change in road use (i.e. a change in vehicle kilometres travelled on roads) creates economic savings through lower infrastructure maintenance.

- **What is the co-benefit?** The road repairs co-benefit refers to the reduced amount of damage to road infrastructure resulting from fewer vehicles on the roads, which can be achieved alongside decarbonising the transport sector.
- **Why is it important?** The UK spends roughly £192,000 per mile on maintaining strategic roads (e.g. motorways or major A roads) and roughly £6,000 per mile on fixing potholes on local roads each year.[1] With a UK road network of about 249,000 miles, this a significant cost to Government and ultimately the taxpayer.[2] There is an estimated £12 billion backlog of road repairs needed on local roads in the UK.[3]

  Much of this is due to significant wear and tear on road surfaces caused by heavy vehicles like buses and lorries, particularly in urban areas where traffic is greater. Climate action in the transport sector can increase or decrease the costs of road repairs, depending on what actions are taken.
- **What climate actions create the co-benefit?** The shift to hybrid and electric vehicles, which are typically heavier than ICE vehicles, can cause more damage to roads. This is particularly the case with hybrid or electric buses, which have heavy batteries. On the other hand, the shift to active modes of transport, such as walking or cycling, results in fewer vehicles on the road and therefore less damage to road infrastructure.

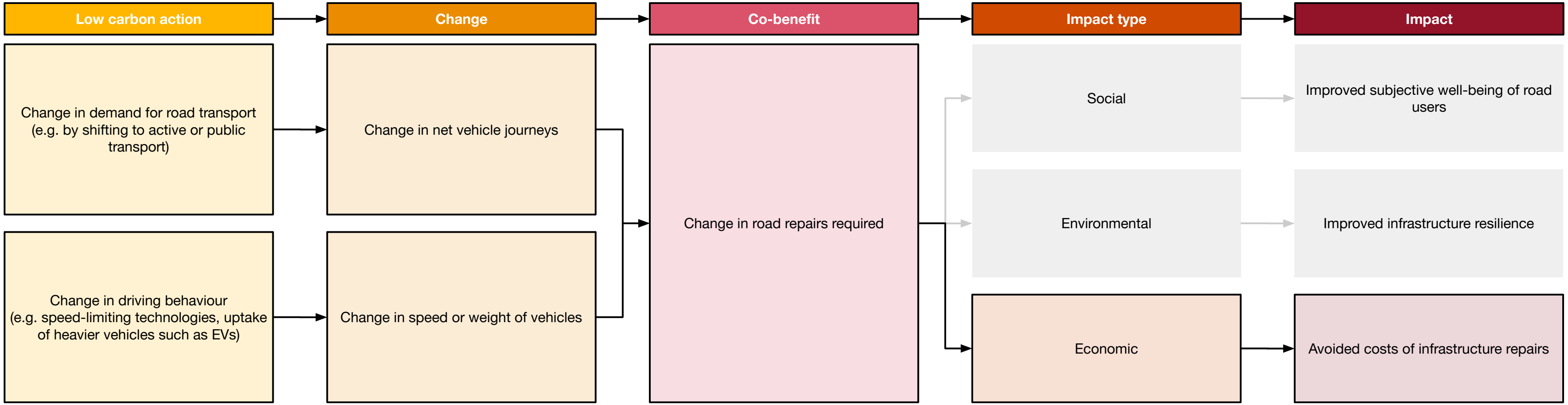
  Levels of vehicle demand reduction (i.e. the reduction in the number of cars on the road) are different in each 6CB scenario. This means that we see a wide range (positive and negative) for the road repairs co-benefit in our analysis, depending on the selected scenario.
- **How do we quantify the co-benefit?** We estimate the net impacts of reduced road repairs in the CCC's 6CB pathways, relative to the baseline scenario, using marginal external cost (MEC) valuations from DfT's WebTAG of avoided infrastructure maintenance costs.[4] These valuations are based on the number of vehicle kilometres avoided by vehicle type, road type and rural-urban classification of the journey.
- **How do we distribute the co-benefit?** Given road maintenance is funded through taxation, we distribute all impacts from avoided road repairs as indirect impacts across all households archetypes in proportion to the population of each archetype.

[1] LGA (2023). 'LGA analysis: Government spends 31 times more per mile on maintaining motorways than on repairing local potholes', March 2023.
[2] DfT (2022). 'Road lengths in Great Britain: 2021', March 2022.
[3] LGA (2023). 'LGA analysis: Government spends 31 times more per mile on maintaining motorways than on repairing local potholes', March 2023.
[4] DfT (2022). 'Transport analysis guidance', November 2022.

Road repairs | Impact pathways

Reducing demand for road transport and changing driving behaviour to more energy-efficient behaviour helps to reduce the number of road repairs required, which contributes to social, environmental and economic impacts.

Reducing demand for road transport (e.g. by shifting to walking or cycling journeys or public transport) and changing individual driving behaviour to be less energy-intensive (e.g. through the use of speed-limiting technologies, eco-driving settings or the uptake of EVs) can all help to decarbonise the UK transport sector. These low carbon actions also influence the number of net vehicle journeys and wear and tear on road surfaces, which results in a change in road repairs required. The most material impact resulting from a change in road repairs is a change in the costs of infrastructure maintenance, an economic (fiscal) impact experienced by the public bodies that maintain roads in the UK. A change in road repairs may also lead to improved subjective well-being of road users - for example, by avoiding potholes or delays - and improved infrastructure resilience. We summarise the key impact pathways for the road repairs co-benefit below, although note that they are not exhaustive. We quantify only the coloured and outlined pathways due to scope and evidence constraints.



Road repairs | Valuation methodology

We model the scale of the impacts from road repairs based on the type of vehicle travelling and the characteristics of the road on which the vehicle is travelling (major or minor road, rural or urban area). We distribute these impacts proportionally across all households.

We estimate the impacts of road repairs using four sources:

- CCC Sixth Carbon Budget (6CB) transport model
- DfT WebTAG databook[1]
- Road traffic statistics (TRA)[2]
- National Travel Survey (NTS)[3]

The CCC's 6CB assumes a number of low carbon actions (such as reduction in demand for road transport and shift to EVs) which change the total distance travelled by road vehicles annually in each pathway. Using data from TRA and NTS on characteristics of typical vehicle journeys, we apportion the distance travelled by:

- Vehicle type (e.g. small car, medium car, large car, van, small rigid vehicle, large rigid vehicle, articulated vehicle, bus, motorcycle).
- Road type (e.g. motorway, A road, other).
- Rural-urban classification (London, conurbations, other urban, rural).

We then calculate the change in distance travelled in the 6CB pathways, relative to the baseline scenario (the counterfactual). This includes the change in distance travelled by both private and commercial vehicles.

We multiply the change in distance travelled by the projected marginal external costs (MECs) of infrastructure repairs set out in DfT's WebTAG databook and inflated to 2021 prices, consistent with the price base year used in the Net Zero Distributional Model.

These are given as pence per vehicle kilometre, and vary by vehicle type, road type, rural-urban classification of the area travelled. MECs of road repairs are largest on 'other roads' (not motorways or A roads) for articulated vehicles.

The MECs of road repairs represent a reduction in road and highway maintenance costs. While these costs generally accrue to the Highways Agency or Local Government, they are ultimately borne by all central and local taxpayers (regardless of car ownership). Therefore, we distribute all impacts from avoided road repairs across all household archetypes in proportion to the population of each archetype, assuming a uniform cost per household.

Box 13. Calculation pathway for road repairs co-benefit

(**Distance travelled by vehicle type in selected 6CB scenario** (vkm) − **Distance travelled by vehicle type in baseline scenario** (vkm)) × **Value of avoided road repair by road type, rural-urban classification and vehicle type per distance travelled** (£ / vkm) = **Total savings from avoided road repairs by archetype, relative to the baseline scenario** (£)

[1] DfT (2022). 'Transport analysis guidance', November 2022.
[2] DfT (2022). 'Road traffic statistics (TRA)', September 2022.
[3] DfT (2022). 'National Travel Survey (NTS)', August 2022.
[4] DfT (2023). 'A valuation of road accidents and casualties in Great Britain: Methodology note', 2023.
[5] DfT (2022). 'Reported road collisions, vehicles and casualties tables for Great Britain', December 2022, RAS0601.

Road repairs | Sensitivity analysis

We model high and low sensitivities for the marginal external costs used to value the road repairs impacts to capture the uncertainty around how traffic patterns may differ over time with different vehicle and trip mixes.

The valuation method used for road repair is DfT's MECs. These are defaulted to the central scenario based on the National Transport Model (NTM) central scenario. There are low and high sensitivities provided, which can be used to assess the impact on the total co-benefit of road repairs.

The directional impact of these are set out in **Table 33** opposite.

Table 33. Directional impact of sensitivities relative to default assumptions

Sensitivity	Directional impact	Description
Low MEC scenario	↓	The low MEC scenario reduces the costs of road repairs and therefore use of the low MEC scenario decreases the benefits of avoiding infrastructure costs from road repairs. This is based off the DfT's NTM using scenario 6.
High MEC scenario	↑	The high MEC scenario increases the costs of road repairs and therefore the high MEC scenario increases the benefits of avoiding infrastructure costs from road repairs. This is based off the DfT's NTM using scenario 7, which should be used with caution as this has assumptions around the uptake of EVs which don't necessarily match up with the CCC's pathways.

Road repairs | Assumptions & limitations

Assessing the avoided impacts of road repairs is based on a limited number of assumptions. A key limitation to our approach is that it should not be used to assess individual impacts, but rather impacts to a population.

Table 34. Road repairs co-benefit assumptions

No.	Assumption
1	We assume all avoided costs of road and highway maintenance would have otherwise been borne by all households through general taxation or council tax, assuming a uniform cost per household. In other words, we do not adjust the relative share of avoided infrastructure maintenance costs borne by households based on income.
2	We assume that the number of vehicle kilometres travelled on a road is a suitable indicator of road wear and tear and that the relationship between vehicle kilometres and road wear and tear remains constant over time.
3	We assume that road wear from heavier vehicles such as hybrid and electric vehicles remains constant over time.
4	We assume that the road surface construction and tyres stay constant over time.

Table 35. Road repairs co-benefit limitations

No.	Limitation
1	We do not quantify the road repair impacts that are created from greater volumes of cyclists or pedestrians in this analysis. However, we do not expect this to be a material issue given the bikes are significantly lighter in weight than motorised vehicles.
2	DfT's MECs are designed to be used to analyse impacts at the margin, rather than system-wide effects. We take confidence that the change in vehicle kilometres travelled in the CCC's 6CB Balanced Net Zero Pathway (which is the CCC's central scenario) relative to the baseline is c.3%. However, should this difference become greater in future carbon budgets, the CCC may wish to consult DfT on whether the MECs remain the most appropriate valuation source.
3	We do not account for all relevant impact pathways associated with the road repairs co-benefit. For example, we do not quantify the improved subjective well-being of road users - e.g. through avoidance of potholes when driving or cycling. We also do not quantify the value of improved infrastructure resilience through less frequent maintenance required on roads (in a 6CB scenario where road usage decreases). There is, however, a lack of high quality empirical evidence that would allow us to quantify these effects.

Physical activity

Greater time spent exercising from uptake of active travel and public transportation

Physical activity | Overview

Greater physical activity from taking up active modes of travel (e.g. walking, cycling) contributes to positive health impacts for individuals and savings to the NHS and wider society.

- **What is the co-benefit?** The physical activity co-benefit refers to exercise derived from walking or cycling, whether for work or leisure purposes.
- **Why is it important?** The UK Government estimates that "physical inactivity is associated with 1 in 6 deaths in the UK and is estimated to cost the UK £7.4 billion annually (including £0.9 billion to the NHS alone)".[1] These costs are driven by increased dependency on welfare benefits (e.g. NHS treatment and home, residential and nursing care) and reduced economic productivity from long-term conditions developed as a result of physical inactivity.

  Different populations within the UK have different levels of physical activity. Men, for example, are more likely to report being physically active and physical activity tends to decrease with age. Additionally, research has found a positive association of physical activity and household income.[2]
- **What climate actions create the co-benefit?** In an effort to decarbonise the UK transport sector, shifting from private transportation to active modes of travel, such as walking or cycling, creates physical activity co-benefits. Greater levels of physical activity contribute to a number of health impacts, including reduced risk of all-cause mortality, cardiovascular disease and type 2 diabetes, reduced symptoms of depression and anxiety, and improved subjective well-being. A more active population can result in savings to the NHS from reduced costs of medical treatment and economic productivity benefits from reduced absenteeism and presenteeism at work. Note that we capture the net impact of longer journey times through active travel under the hassle costs co-benefit.
- **How do we quantify the co-benefit?** We apply the World Health Organisation's Health Economic Assessment Tool (WHO HEAT) methodology to estimate the reduced relative risk of all-cause mortality resulting from journeys shifted from car to walking or cycling trips.

  We use the National Life Tables from the ONS to convert these health impacts to avoided life years lost, and value these using HMT Green Book's value of a life-year (VOLY), uplifted to 2021 prices and discounted at the health discount rate (1.5% p.a.).

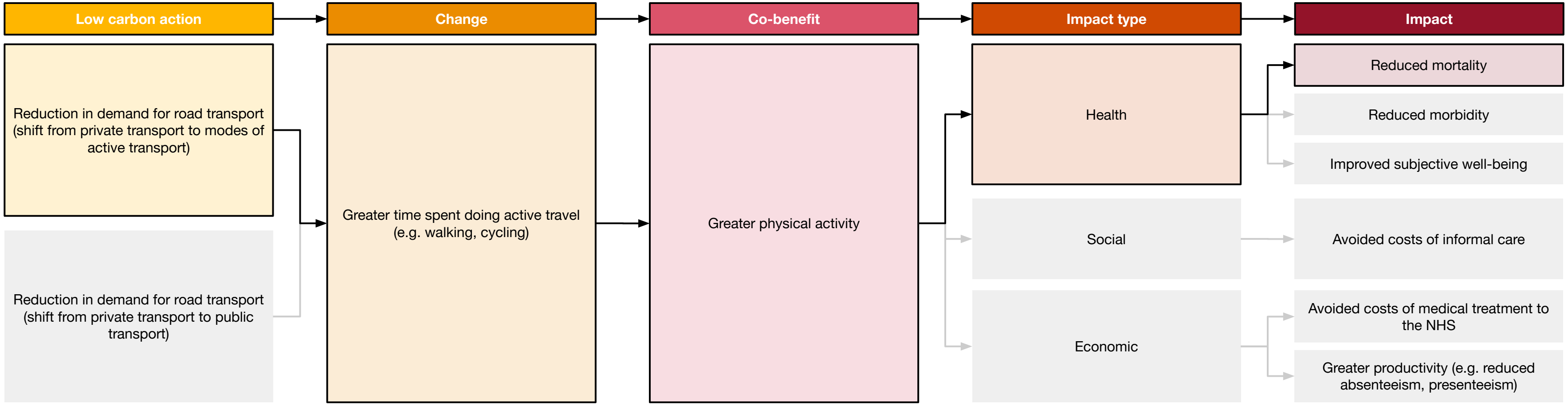
  Due to scope constraints, we do not quantify all impacts of the physical activity co-benefit (e.g. morbidity, NHS savings, societal savings).
- **How do we distribute the co-benefit?** We distribute the health impacts resulting from greater physical activity as direct impacts to the household archetypes with individuals making the behaviour change.

[1] UK Government (2022). 'Physical activity: applying All Our Health', March 2022.
[2] Scholes & Mindell (2012). 'Physical activity in adults', HSE 2012: Vol. 1, Chapter 2, p. 12.

Physical activity | Impact pathways

Shifting to active modes of travel can help to decarbonise transport and increase physical activity levels in the UK, contributing to health, social and economic impacts.

Shifting from travelling by car to active modes of travel - such as walking, cycling or using e-bikes - results in greater levels of physical activity. Shifting from private to public transportation can also result in greater levels of physical activity (albeit less than completing a full journey through active travel) when the small trips between bus stops or train stations are considered. Greater physical activity contributes to health, social and economic impacts. These include reduced all-cause and disease-specific mortality (e.g. from cardiovascular disease, type 2 diabetes and others), reduced morbidity and improved subjective well-being (e.g. from depression and anxiety), avoided costs of medical treatment to the NHS and informal care to family and friends, and greater productivity (e.g. from reduced absenteeism or presenteeism at work). We summarise the key impact pathways for physical activity below, although note that they are not exhaustive. We quantify only the coloured and outlined pathways (reduced mortality) due to scope and evidence constraints.



Physical activity | Valuation methodology (1/2)

We model the scale and distribution of physical activity impacts from the transport sector by estimating the change in relative risk of all-cause mortality from greater distance travelled by walking and cycling.

We estimate the impacts of physical activity using four sources:

- CCC Sixth Carbon Budget (6CB) transport model
- WHO Health Economics Assessment Tool (HEAT)[1]
- ONS National Life Tables[2]
- HMT Green Book[3]

The CCC's 6CB assumes a certain amount of vehicle kilometres from car journeys are shifted to active travel journeys. We convert these vehicle kilometres to walking and cycling kilometres by dividing them by average walking and cycling speeds:

- Average walking speed: 4.8 km/hour[1]
- Average cycling speed: 14 km/hour[1]
- Average e-cycling speed: 20 km/hour[4]

We then apportion the assumed additional distance travelled by active modes of transport by household archetype population to calculate the active travel distance per capita per archetype.

We apply assumptions from WHO HEAT on reasonable limits to the number of minutes the average person can spend on physical activity in a week. These are 460 minutes per week spent walking and 447 minutes per week spent cycling. This allows us to cap the distance that individuals can realistically travel by active modes. Note under some 6CB pathways when assumptions are shifted there are cases where individuals travel more than the capped amount. In these cases, we do not quantify or value the health impacts resulting from the physical activity undertaken beyond the WHO HEAT cap.

To calculate the health impacts of greater physical activity, we estimate the combined relative risk (RR) of all-cause mortality from walking and cycling using estimates from WHO HEAT, set out in **Table 36** below.[1]

Table 36. Relative risk estimates for physical activity

Active travel mode	Relative risk of all-cause mortality	Relative risk reference volume	Benefit cap
Walking	0.89	168 minutes / week	460 minutes / week
Cycling	0.90	100 minutes / week	447 minutes / week

We multiply the RR from walking by the RR from cycling to mitigate the risk of double-counting impacts from the two modes of travel. This means that if an individual takes up both walking and cycling, the health impacts will not necessarily be additive. This moderates the magnitude of the combined effect of physical activity across modes of active travel, which makes the estimate more conservative, rather than assuming the effects are additive. While this means that we do not isolate the benefits of walking and cycling …

[1] WHO (2017). 'Health economic assessment tool (HEAT) for walking and for cycling', 2017.
[2] ONS (2021). 'National life tables: UK', September, 2021.
[3] HMT (2022). 'The Green Book', November, 2022.
[4] Schleinitz K. et al. (2017). 'The German Naturalistic Cycling Study - Comparing cycling speed of riders of different e-bikes and conventional bicycles', Safety Science, 92, 290-297. dx.doi.org/10.1016/j.ssci.2015.07.027.

Physical activity | Valuation methodology (2/2)

We model the scale and distribution of physical activity impacts from the transport sector by estimating the change in relative risk of all-cause mortality from greater distance travelled by walking and cycling.

independently, this approach is consistent with approaches taken in Milner et al. 2023[1] and Modig et al. 2020.[2]

We account for a lag in benefits realisation by phasing in the full effect of the relative risk over time. In practice, this means the change in relative risk of all-cause mortality does not fully materialise until the lag period has passed.

This allows us to account for the fact that individuals need to sustain greater levels of physical activity over a period of time before they experience a change in health risks.

Next, we source all-cause UK mortality (by age and sex) from the ONS. We apply the lagged impact factors to all-cause mortality data to estimate the number of deaths resulting from the additional physical activity in the selected 6CB pathway, relative to the CCC's baseline scenario.

We then convert the change in deaths to a change in life years by multiplying deaths by average life expectancy (which varies by age and sex). This results in the avoided life years lost from greater physical activity. Note that we do this by cohorts defined by sex and 5-year age bands. This allows us to smooth any variability in individual levels of physical activity.

We value the avoided life years lost using the value of a life year (VOLY) from HMT Green Book,[3] uplifted to 2021 prices. We discount this value using the social discount rate (1.5% p.a.), which is lower than the central discount rate (3.5% p.a.) but recommended by the Green Book for health impacts. This means that the value of a life year does not depreciate as fast as other (e.g. economic or financial) impacts.

Finally, we distribute the impacts across each household archetype in proportion to the share of each archetype's population that takes up active travel. The full calculation pathway is set out in **Box 14** below.

Box 14. Calculation pathway for physical activity co-benefit

(**Total additional distance travelled by active modes by archetype** (km / year) ÷ **Average walking and cycling speeds** (km / hour) ÷ **Population per archetype** (# people / archetype) ✖ **Cap on minutes of physical activity (walking, cycling) per capita** (%)) ✖ (**Change in relative risk (RR) of all-cause mortality from walking** (%) / **Reference value for RR of all-cause mortality from walking** (min) ✖ **Change in relative risk (RR) of all-cause mortality from cycling** (%) / **Reference value for RR of all-cause mortality from cycling** (min)) ✖ **Share of combined RR applied each year to account for lag in benefits realisation** (%) ✖ **UK mortality by age & sex** (# deaths) ✖ **UK life expectancy by age & sex** (# deaths) ✖ **Value of a life year** (£ / year) = **Value of avoided life years lost, relative to the baseline scenario** (£ / archetype)

[1] Milner et al. (2023). 'Impact on mortality of pathways to net zero greenhouse gas emissions in England and Wales: a multisectoral modelling study', Lancet Planet Health 2023; 7: e128–36.
[2] Modig et al. (2020). 'Life expectancy: what does it measure?', BMJ Open 2020;10:e035932. doi:10.1136/ bmjopen-2019-035932.
[3] HMT (2022). 'The Green Book', November, 2022.

Physical activity | Sensitivity analysis

To capture the uncertainty in the behaviour change required to shift to active modes of travel, we model sensitivities for uptake of active travel by age, level of engagement and journeys by purpose for each archetype.

A key uncertainty of this analysis is estimating the share of the population most likely to shift from car journeys to active travel, particularly because an individual's likelihood of making this change depends on many factors such as age, journey purpose and rural-urban classification.

We therefore include a number of sensitivities to capture the range of active travel uptake that could result under different policy contexts. We focus our analysis on uptake of active travel by age and by journey purpose:

1. **Uptake of active travel by age groups.** We model options to target active travel uptake at individuals starting at 16-18 and increasing in 5-year intervals, ending at 80-84. This allows users the flexibility to customise the age range of individuals assumed to take up active travel. We set the default setting in the model as the full age range (16-84 years).
2. **Modal shift engagement level.** We model options to assume medium (central) and high engagement levels, as predefined by the CCC. A medium engagement level assumes 70% of trips are shifted to walking or cycling when the journey is taken for commuting, business, education, leisure, holiday or other work personal business. The high engagement level assumes the same plus an additional 20% of trips are shifted to walking or cycling when the journey is taken for shopping. Note that a 'low' engagement level scenario has not been defined by the CCC. We set the default setting in the model as the 'central' engagement level.

See the next slide for an explanation as to how we capture likelihood to take up active travel based on rural-urban classification.

Another uncertainty in this analysis is the period of time before benefits from greater levels of physical activity are realised. While researchers agree that there will be a lag before health benefits are seen, there is no consensus on the number of years this might take. We therefore model different options to allow users to assume different periods of time after which the full effect of diet change on relative risk of mortality will be experienced. These include **5 years**, **10 years** and **20 years**. We set the default option in the model to 10 years, as a central case.

We set out the directional impact of these sensitivities relative to the central case (default) in **Table 37** on the next slide.

[1] WHO (2017). 'Health economic assessment tool (HEAT) for walking and for cycling', 2017.

[2] Schleinitz K. et al. (2017). 'The German Naturalistic Cycling Study - Comparing cycling speed of riders of different e-bikes and conventional bicycles', Safety Science, 92, 290-297. dx.doi.org/10.1016/j.ssci.2015.07.027.

Physical activity | Sensitivities (ctd.)

To capture the uncertainty in the behaviour change required to shift to active modes of travel, we model sensitivities for uptake of active travel by age, level of engagement and journeys by purpose for each archetype.

Table 37. Directional impact of sensitivities relative to default assumptions

Sensitivity	Directional impact	Description
Uptake of active travel by age group		
Narrower age range (relative to full age range: 16-84 years)	↓	Selecting a narrower age range will decrease the value of the health impacts associated with greater physical activity levels because a smaller population will be taking up walking and cycling. However, this effect is amplified if the narrower age range selected is older, as the health impacts are calculated using average life expectancy and older populations have a shorter life expectancy.
Modal shift engagement level		
High engagement (relative to medium/central engagement)	↑	Selecting the 'high' engagement scenario will increase the value of the health impacts associated with greater physical activity levels because a wider range of journeys will be shifted to active travel journeys, increasing the distance travelled by active modes of transport.
Lag period		
5 years (relative to 10 years)	↑	Selecting a lag period of 5 years (instead of the default 10 years in the model) will increase the value of the health impacts associated with greater physical activity because the full health benefits will be realised sooner and there will be less discounting in the short-term.
20 years (relative to 10 years)	↓	Selecting a lag period of 20 years (instead of the default 10 years in the model) will reduce the value of the health impacts associated with greater physical activity because not only will it mean that the full health benefit is not realised until 20 years of sustaining a greater physical activity levels, but also because the time value of money decreases over time and more discounting will be applied (i.e. we value things more in the short-term than we do in the long-term).

Physical activity | Assumptions & limitations

Assessing the impacts of physical activity is based on a number of assumptions regarding individual behaviour. A key limitation to our approach is that we only capture the mortality impacts from the physical activity co-benefit.

Table 38. Physical activity co-benefit assumptions

No.	Assumption
1	In our default setting for the model, we assume that all individuals (both male and female) aged 16 to 84 take up active travel.
2	In our default setting for the model, we assume a 'central' modal shift engagement level. Relative to the 'high' modal shift engagement level, the 'central' modal shift engagement level assumes a smaller share of journeys for all purposes are taken by public transport and a no journeys for shopping purposes are completed by walking or cycling. Note that these are assumptions defined in the CCC pathways.
3	We assume that all household archetypes are equally likely to take up active travel (by walking or cycling), regardless of the rural-urban classification of the area in which they live. However, the level at which the 6CB assumes the requirement on people to change mode of travel differs by rural-urban classification. In other words, a household living in a rural area is just as likely to take up active travel as a household living in an urban area, but is required to travel fewer kilometres via active transport to meet the demand reduction assumed in the 6CB. In practice, this means that households living in rural areas take up less active travel than households living in urban areas, as we would expect.
4	We do not assume any compensatory effects. In other words, we assume that those who shift their car journeys to active travel journeys continue to maintain their existing exercise routines as well.
5	We do not assume that bike ownership indicates a higher likelihood of taking up active travel, given bikes are relatively affordable to purchase and do not pose a material barrier to active travel uptake.
6	In our default setting for the model, we assume a lag period of 10 years before health impacts from physical activity are fully realised. This is to say that individuals must sustain higher levels of physical activity over as long as 10 years before their relative risk of all-cause mortality changes.
7	Consistent with the WHO HEAT methodology, we assume average weekly limits on the physical activity that can be valued from walking (460 minutes per week) and cycling (447 minutes per week). This means that any physical activity done above and beyond these average weekly limits are not valued.
8	We assume an average walking speed of 4.8 km/hour, an average cycling speed of 14 km/hour and an average e-cycling speed of 20 km/hour, and that these average speeds remain constant over time.
9	We assume that the relationships between physical activity and all-cause mortality remain stable over time.

Table 39. Physical activity co-benefit limitations

No.	Limitation
1	Shifting away from car travel in favour of active travel is largely driven by motivations to change individual behaviour, which can vary widely depending on the individual. However, we expect to smooth some of this variation in our analysis, which is based on cohorts of different ages and sexes, which are then aggregated up to 15 different household archetypes.
2	While all health impacts quantified in this analysis will have some level of overlap, we draw attention to the impacts of physical activity and diet change, which should not be taken to be additive. We calculate the mortality impacts of physical activity and diet change using a relative risk approach - for physical activity, we assess all-cause mortality and for diet change we assess cause-specific mortality. We have modelled the impacts in this way to take a consistent approach with the widely accepted WHO HEAT methodology for walking and cycling. There will be overlap between the two outputs because physical activity and diet change affect the risk of developing some of the same diseases, namely cardiovascular disease, type 2 diabetes and colon & rectum cancer. Therefore, we advise caution when interpreting the aggregate outputs of the analysis.
3	We do not account for impacts of additional active travel taken up by households who do not own a car in the baseline scenario. This is because the CCC's 6CB pathways assume only those households that own a car can shift to active travel. However, it is possible that greater uptake of active travel across the population with access to a car leads to greater investment in pedestrianised streets and cycle lanes (for example) which could encourage more active travel by individuals who already take up active travel. Therefore, our estimates of impacts of greater physical activity under each 6CB pathway should be taken as conservative.
4	We do not account for all relevant impact pathways associated with the physical activity co-benefit. For example, we only value mortality and we do not quantify the impacts of NHS savings from avoided medical care from inactive populations or increased productivity from a healthier population.

Diet change

Shift from meat & dairy consumption to plant-based diets resulting from individual behaviour change

Diet change | Overview

Reducing red & processed meat and dairy consumption and increasing vegetable consumption contributes to positive health impacts for individuals.

- **What is the co-benefit?** The diet change co-benefit captures the health impacts from a shift away from meat and dairy consumption and towards plant-based diets.
- **Why is it important?** The agriculture and land use sectors account for 12% of all UK emissions.[1] While current farming practices could be made more carbon-efficient, consumer behaviour in terms of diet choice - namely, consumption of meat and dairy - is the ultimate driver of these emissions.
- **What climate actions create the co-benefit?** A reduction in red & processed meat and dairy consumption and an increase in vegetable consumption leads to the health impacts created by the diet change co-benefit.
- **How do we quantify the co-benefit?** We use data on average consumption of red & processed meat, dairy and vegetables by sex and age from the National Diet & Nutrition Survey (NDNS) and diet change assumptions from the CCC's Sixth Carbon Budget (6CB) to estimate the expected change in intake by food group for each 6CB pathway.

  We use the latest estimates from the Global Burden of Disease (GBD) study to quantify the impact of diet change on mortality from ischaemic heart disease, type 2 diabetes and colon & rectum cancer, using a relative risk approach.

  This results in a change in total number of deaths over time. We multiply this by average life expectancy, which differs by sex and age, to estimate the number of avoided life years lost. We value this using HMT's Green Book value of a life-year (VOLY), inflated to 2021 prices.
- **How do we distribute the co-benefit?** We distribute the health impacts resulting from diet change as direct impacts to the household archetypes with individuals making the behaviour change. Due to scope constraints, we do not quantify the NHS and wider societal savings from healthier individuals. Therefore, we do not distribute any impacts to the Exchequer.

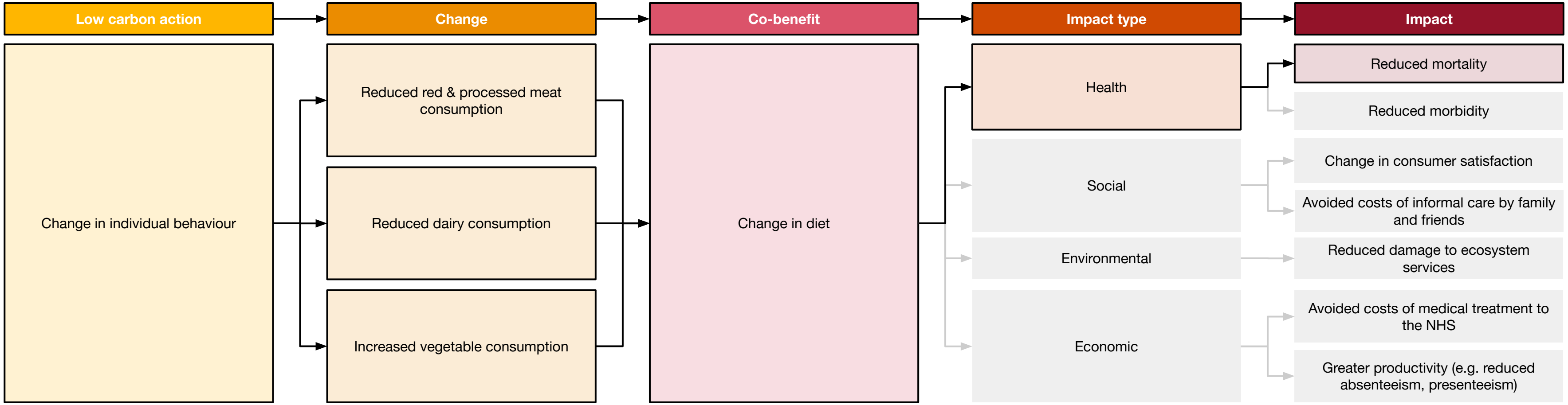
[1] CCC (2020). 'The Sixth Carbon Budget: Agriculture and land use, land use change and forestry', December 2020, p. 5.
[2] Springmann et al. (2018). 'Options for keeping the food system within environmental limits', Nature. 2018 Oct;562(7728):519-525. doi: 10.1038/s41586-018-0594-0. Epub 2018 Oct 10.
[3] BEIS (2021). 'BEIS Public Attitudes Tracker: Wave 37', May 2021, p. 464.
[4] Gillison et al. (2022). 'A rapid review of the evidence on the factors underpinning the consumption of meat and dairy among the general public', University of Bath, March 2022, DOI: 10.46756/sci.fsa.bmk523.
[5] BIT (2023). 'How to build a Net Zero society', January 2023, p. 106.

Diet change | Impact pathways

Shifting away from red & processed meat and dairy consumption and towards plant-based diets contributes to health impacts through reduced mortality.

Changing individual behaviour to eat less red & processed meat and dairy, and eat more vegetables can help to decarbonise the agriculture sector in the UK. It also contributes to health, social, environmental and economic impacts. These include **(a) reduced mortality and morbidity** from heart disease, colon & rectum cancer and type 2 diabetes, among others, **(b)** a change in consumer satisfaction (e.g. through new shopping habits), **(c)** avoided medical treatment and informal care costs of treating individuals of poor health, **(d)** reduced damage to ecosystems (e.g. through cattle farming), and **(e)** greater economic productivity (e.g. through reduced absenteeism and presenteeism at work).

We quantify only reduced mortality and morbidity in this analysis due to scope and evidence constraints. However, the wider impact pathway below summarises the key (though not exhaustive) impact pathways for diet change.



Diet change | Valuation methodology

We model the scale and distribution of diet change impacts by estimating the change in relative risk of cause-specific mortality from a change in red & processed meat, dairy and vegetable consumption.

We estimate the impacts of diet change using five sources:

- CCC Sixth Carbon Budget (6CB) agriculture model
- Global Burden of Disease (GBD) Study (2020)[1]
- PHE National Diet & Nutrition Survey (NDNS) (2020)[2]
- IHME GBD Compare (2019)[3]

One low carbon action in the agriculture and land use sectors that impacts the day-to-day lives of UK households is a change in diet. Research has found that dietary greenhouse gas emissions by those who eat meat and dairy are approximately twice as high as by those who eat plant-based diets.[4]

To quantify the health impacts associated with a climate-friendly shift in diet, we begin with data on the average daily consumption by age and food group (red & processed meat, dairy, vegetables) from the PHE's NDNS. We use this data to project the CCC's 6CB assumptions on diet change for each pathway on an annual basis. For example, this allows us to translate the CCC's assumptions of a 20% and 35% shift away from meat and dairy by 2030 and 2050, respectively, in the Balanced Net Zero Pathway to absolute values of average food intake each year.

We then adjust the average consumption according to each age group's likelihood of eating more or less of these food groups, using weightings for the age group's relative share of average intake for each food group, from the UK's National Diet & Nutrition Survey. This allows us to capture, for example, the fact that males aged 75+ tend to consume less meat (14% less meat) than the average male.

We redistribute the reduced meat and dairy consumption to the vegetables & potatoes food group, based on caloric intake, to represent a shift to plant-based diets, as assumed in the 6CB. Specifically, we convert the change in red & processed meat and dairy consumption to vegetable and potato consumption using average calorie content for those food groups.

This gives us estimated diet change uptake pathways for each food group (meat, dairy, vegetables), in grams consumed per day, by age and sex.

Next, we estimate the impact factor of developing a given disease from diet change (considering all relevant food groups).

Specifically, we consider the effects of a change in:

- Red & processed meat consumption on the relative risk of developing Type 2 Diabetes
- Red & processed meat and vegetables & potato consumption on the relative risk of developing ischaemic heart disease
- Red & processed meat and dairy consumption on the relative risk of developing colon & rectum cancer

[1] GBD Global Risk Factors Collaborators (2020). 'Global burden of 87 risk factors in 204 countries and territories, 1990–2019: a systematic analysis for the Global Burden of Disease Study 2019', Global Health Metrics, Vol. 396, Issue 10258, pp. 1223-1249, October 2020, Table S7.A.
[2] Public Health England (2020). 'NDNS: results from years 9 to 11 (2016 to 2017 and 2018 to 2019)', December 2020, Tables 7.6 and 7.7.
[3] IHME (2019). 'GBD Compare', 2019.
[4] Scarborough et al. (2014). 'Dietary greenhouse gas emissions of meat-eaters, fish-eaters, vegetarians and vegans in the UK', *Climatic Change*, 125, pp. 179–192 (2014).

Diet change | Valuation methodology (ctd.)

We model the scale and distribution of diet change impacts by estimating the change in relative risk of cause-specific mortality from a change in red & processed meat, dairy and vegetable consumption.

While there is evidence on a range of food groups, these are the key relationships identified relating to the food groups in scope of this analysis (red & processed meat, dairy and vegetable & potatoes) in the latest evidence from the GBD Study (2020). In cases where several dietary exposures affect the risk of developing the same disease, we multiply the risks together, as shown in **Box 15**. This moderates the magnitude of the combined effect of diet change across food groups, which makes the estimate more conservative, rather than assuming the effects are additive. This is consistent with approaches taken in Milner et al. 2023[1] and Modig et al. 2020.[2]

Box 15. Calculation of diet change impact factor

$$\textbf{Relative risk}_{\text{combined}} = \textbf{Relative risk}_{\text{red meat}} \times \textbf{Relative risk}_{\text{proc. meat}} \times \textbf{Relative risk}_{\text{milk}}$$

$$\textbf{Consumption multiplier}_{\text{combined}} = \sum (\Delta\textbf{Consumption}_{\text{food group}} \,/\, \textbf{Reference intake}_{\text{food group}})$$

$$\textbf{Impact factor} = \textbf{Relative risk}_{\text{combined}} \times \textbf{Consumption multiplier}_{\text{combined}}$$

We account for a lag in benefits realisation by staging in the full effect of the impact factor over time (default of 10 years). In practice, this means the change in relative risk of developing a disease associated with a specific food group does not fully materialise until the lag period has passed. This allows us to account for the fact that individuals need to sustain diet change over a period of time before they experience a change in health risks, as discussed in Milner et al. 2023.[1]

Next, we source all-cause UK mortality (by age and sex) from the ONS. We adjust this for cause-specific mortality (by age and sex) for ischaemic heart disease, type 2 diabetes and colon & rectum cancer from the IHME GBD Compare database. This allows us to estimate the average number of deaths from heart disease, diabetes and colon & rectum cancer that would occur regardless of a change in diet.

Then we apply the lagged impact factors to the cause-specific mortality data to estimate the number of deaths resulting from the change in diet both in the selected 6CB pathway and the CCC's baseline scenario, and we subtract one from the other to estimate the change in the number of deaths from the 6CB pathway (relative to the baseline scenario).

We then convert the change in deaths to a change in life years by multiplying deaths by average life expectancy (which varies by age and sex). This results in the avoided life years lost from diet change across the three food groups.

Finally, we value the avoided life years lost using the value of a life year (VOLY) from HMT Green Book, uplifted to 2021 prices. We discount this value using the social discount rate (1.5% p.a.), which is lower than the central discount rate (3.5% p.a.) but recommended by the Green Book for health impacts. This means that the value of a life year does not depreciate as fast as other (e.g. economic or financial) impacts.

[1] Milner et al. (2023). 'Impact on mortality of pathways to net zero greenhouse gas emissions in England and Wales: a multisectoral modelling study', Lancet Planet Health 2023; 7: e128–36.
[2] Modig et al. (2020). 'Life expectancy: what does it measure?', BMJ Open 2020;10:e035932. doi:10.1136/ bmjopen-2019-035932.

Diet change | Valuation methodology (ctd.)

We model the scale and distribution of diet change impacts by estimating the change in relative risk of cause-specific mortality from a change in red & processed meat, dairy and vegetable consumption.

We distribute the impacts to the households who are making the behaviour change, based on assumptions around the willingness of people to eat less meat and dairy:

- 29% of people are willing to eat less meat
- 16% of people are willing to eat less dairy

These assumptions come from the latest publication of the BEIS Public Attitudes Tracker[1] but do not define what "less" means to survey respondents.

Therefore, we apply these assumptions to the full population in each household archetype and distribute the impacts across each household archetype in proportion to each archetype's population.

The full calculation pathway is set out in **Box 16** below.

Box 16. Calculation pathway for diet change co-benefit

∑ Red & processed meat, dairy, vegetables (**Average daily intake by food group** (grams) ✖ **6CB change in intake by food group** (%) ÷ **Reference intake for relative risk (RR) of cause-specific mortality by food group** (grams)) ✖ (**RR of cause-specific mortality from change in red meat consumption** (%) ✖ **RR of cause-specific mortality from change in processed meat consumption** (%) ✖ **RR of cause-specific mortality from change in milk consumption** (%) ✖ **RR of cause-specific mortality from change in vegetable consumption** (%)) ✖ **Share of combined RR applied each year to account for lag in benefits realisation** (%) ✖ **UK cause specific mortality** (# deaths) = **Change in deaths by cause resulting from diet change across food groups** (# deaths)

∑ Ischaemic heart disease, type 2 diabetes, colon & rectum cancer (**Change in deaths by cause resulting from diet change across food groups** (# deaths)) ✖ **UK life expectancy by age & sex** (# deaths) ✖ **Value of a life year** (£ / year) ✖ **% of population willing to shift diet** (%) ✖ **Population per household archetype** (# people / archetype) = **Value of avoided life years lost per archetype, relative to the baseline scenario** (£ / archetype)

[1] BEIS (2021). 'BEIS Public Attitudes Tracker: Wave 37', May 2021, p. 464.

Diet change | Sensitivity analysis

To capture the uncertainty in the behaviour change required to shift diet, we model sensitivities for willingness to shift diet by age and sex, and the time it takes for health outcomes to result from diet change.

A key uncertainty of this analysis is the assumptions around a population's willingness to shift their diet, particularly because willingness to change does not guarantee a physical change to a person's behaviour. We set our default assumption in line with the findings from the latest release of the BEIS Public Attitudes Tracker.[1]

However, we also include a number of sensitivities to allow users to explore the range of impacts that could result under different policy contexts which might change the likelihood of different groups of people who take up diet change. These include:

1. **Age of population willing to shift diet.** We model options to target diet change uptake by different age groups: children (11 years and younger), under 25 years, under 40 years, under 65 years, and all ages.
2. **Sex of population willing to shift diet.** We model options to target diet change uptake at both sexes, just males or just females.

Another uncertainty in this analysis is the period of time before benefits from diet change are realised. While researchers agree that there will be a lag before health benefits are seen, there is no consensus on the number of years this might take. We therefore model different options to allow users to assume different periods of time after which the full effect of diet change on relative risk of mortality will be experienced. These include **5 years**, **10 years** and **20 years**. We set the default option in the model to 10 years, as a central case.

Table 40. Directional impact of sensitivities relative to default assumptions

Sensitivity	Directional impact	Description
Population willing to shift diet		
People 65 years and younger (relative to full age range: 0 - 110)	↓	Targeting people aged 65 years and younger (relative to all ages) reduces the total scale of impact of the diet change co-benefit.
People 40 years and younger (relative to full age range: 0 - 110)	↓	Targeting people aged 65 years and younger (relative to all ages and the <65 policy option) reduces the total scale of impact of the diet change co-benefit.
People 25 years and younger (relative to full age range: 0 - 110)	↓	Targeting people aged 65 years and younger (relative to all ages, the '65 and younger' policy option and the '40 and younger' policy option) reduces the total scale of impact of the diet change co-benefit.
Only 1 sex willing to shift diet (relative to both sexes)	↓	Targeting only1 sex to shift diet (relative to the default setting of both sexes) reduces the total scale of impact of the diet change co-benefit.
Lag period		
5 years (relative to 10 years)	↑	Selecting a lag period of 5 years (instead of the default 10 years in the model) will increase the value of the health impacts associated with diet change because the full health benefits will be realised sooner and there will be less discounting in the short-term.
20 years (relative to 10 years)	↓	Selecting a lag period of 20 years (instead of the default 10 years in the model) will reduce the value of the health impacts associated with diet change because not only will it mean that the full health benefit is not realised until 20 years of sustaining a change in diet, but it also because the time value of money decreases over time (i.e. we value things more in the short-term than we do in the long-term).

[1] BEIS (2021). 'BEIS Public Attitudes Tracker: Wave 37', May 2021, p. 464.

Diet change | Assumptions & limitations

Assessing the impacts of diet change is based on a number of assumptions regarding typical food consumption and willingness to shift diet. A key limitation to our approach is the lack of evidence and data on the wider implications of diets heavy in animal products.

Table 41. Diet change co-benefit assumptions

No.	Assumption
1	We assume that the average household that is willing to shift their diet begins that shift from the start of the 6CB pathway, receiving a phasing-in of potentially accrued benefits after the selected lag period. In other words, all diet change begins at the start of the pathway (e.g. in year 2020), rather than later in the pathway (e.g. in year 2040).
2	We assume that the key disease pathways identified in the latest Global Burden of Disease study relating to diet change (colon & rectum cancer, type 2 diabetes, ischaemic heart disease) will remain the key disease pathways affected by diet change over time and the relationships between the food groups and disease pathways will remain stable over time.[2]
3	We assume constant caloric intake over time (i.e. any calories that individuals no longer consume from meat or dairy will be supplemented by vegetables and potatoes).
4	We assume that individuals maintain a balanced diet across other food groups over time, as estimated by the National Diet and Nutrition Survey (i.e. average intake across grains, fruit and other food groups remains constant over time).
5	In our default setting for the model, we assume a lag period of 10 years before health impacts from diet change are fully realised. This is to say that individuals must sustain diet changes over as long as 10 years before their relative risk of developing heart disease, type 2 diabetes or colon & rectum cancer changes.

Table 42. Diet change co-benefit limitations

No.	Limitation
1	Shifting away from meat and dairy consumption and toward a plant-based diet is largely driven by motivations to change individual behaviour, which can vary widely depending on the individual. However, we expect to smooth some of this variation in our analysis, which is based on cohorts of different ages and sexes, which are then aggregated up to 15 different household archetypes.
2	While all health impacts quantified in this analysis will have some level of overlap, we draw attention to the impacts of physical activity and diet change, which should not be taken to be additive. We calculate the mortality impacts of physical activity and diet change using a relative risk approach - for physical activity, we assess all-cause mortality and for diet change we assess cause-specific mortality. We have modelled the impacts in this way to take a consistent approach with the widely accepted WHO HEAT methodology for walking and cycling. There will be overlap between the two outputs because physical activity and diet change affect the risk of developing some of the same diseases, namely cardiovascular disease, type 2 diabetes and colon & rectum cancer. Therefore, we advise caution when interpreting the aggregate outputs of the analysis.
3	There is generally a lack of evidence and data on the wider implications of diets heavy in animal products. As more research is conducted in this area, the impacts quantified in this analysis are subject to change.
4	Our analysis is based on average daily consumption data from the UK's National Diet and Nutrition Survey. While we incorporate a granular level of detail in the analysis (e.g. food intake specific to age and sex) to capture the range of differences in individual diets, diets vary widely day-to-day and many do not consume food in line with national guidelines, even if they report that they do. Therefore, a limitation to this analysis is the accuracy of the underlying data on UK food intake.
5	We do not account for all relevant impact pathways associated with the diet change co-benefit. For example, we do not quantify the impacts of NHS savings from avoided medical care or increased productivity from a healthier population.

[1] BEIS (2021). 'BEIS Public Attitudes Tracker: Wave 37', May 2021, p. 464.
[2] GBD Global Risk Factors Collaborators (2020). 'Global burden of 87 risk factors in 204 countries and territories, 1990–2019: a systematic analysis for the Global Burden of Disease Study 2019', Global Health Metrics, Vol. 396, Issue 10258, pp. 1223-1249, October 2020, Table S7.A.

A

Purpose and scope

Methodology

Appendix

Shortlisting the co-benefits of climate action

We undertook a shortlisting exercise to narrow the list of co-benefits in the scope of analysis on the basis of the following 4 criteria:

Maximising benefits
How material is this co-benefit likely to be over the long term? What is the scale of impacts resulting from the co-benefit?

Uncertainty
How likely is this co-benefit to materialise over the long term? Are there any key dependencies on low carbon actions or policy that influences this likelihood?

Policy priorities
To what extent is maximising this co-benefit a matter of public interest and, by extension, a policy priority? Is there existing political leverage or commitments related to this co-benefit?

Modelling feasibility
How feasible is it to model this co-benefit? What evidence exists? What limitations are we aware of?

Key: High Medium Low

Co-benefit	Maximising benefits	Uncertainty	Policy priorities	Modelling feasibility	Shortlist decision
Excess cold	High	High	High	Medium	High
Excess heat	Low	Medium	Low	Medium	High
Dampness	Medium	High	High	Low	High
Noise	Medium	High	Medium	Medium	High
Air quality	High	High	High	High	High
Physical activity	High	High	Medium	Medium	High
Hassle costs[1]	Low	Medium	Medium	Medium	High
Congestion	Medium	High	High	Medium	High
Road repairs	Medium	Low	Medium	Medium	High
Road safety	Medium	High	Medium	Medium	High
Diet change	Medium	Medium	Low	High	High
Social connectivity	Medium	Low	Low	Low	Low
Natural capital	High	Low	High	Low	Low
Water quality	Medium	Medium	Low	Medium	Low
Soil quality	Medium	Medium	Low	Medium	Low
Energy security	Medium	High	High	High	Low
Comfort taking	Low	High	High	High	Low
Supply chain effects	High	High	High	Low	Low

[1] While hassle costs scored relatively lower than other co-benefits, we considered it an important co-benefit to quantify in order to estimate net co-benefits, at least over the short-term.

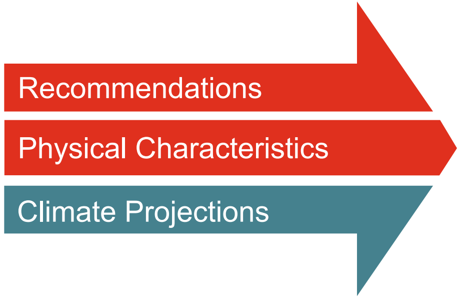
Low carbon actions considered in analysis

These are all of the measures included in the 6th Carbon Budget sectoral pathway models. Some measures were excluded from this analysis for various reasons, including immateriality and scope constraints.

Sector	Low carbon action	Excluded from analysis
Domestic Buildings	Low carbon district heat	Yes
Domestic Buildings	Resistive heating	Yes
Domestic Buildings	Storage heating	Yes
Domestic Buildings	Heat pumps	No
Domestic Buildings	Lighting	No
Domestic Buildings	Appliances	No
Domestic Buildings	Cooking	No
Domestic Buildings	Floor insulation	No
Domestic Buildings	Roof insulation	No
Domestic Buildings	Solid wall insulation	No
Domestic Buildings	Cavity wall insulation	No
Domestic Buildings	Other insulation	No
Domestic Buildings	External overshading	No
Domestic Buildings	Mechanical ventilation with heat recovery	No
Domestic Buildings	Use of windows and vents	No
Domestic Buildings	Household and garden machinery	Yes
Agriculture	Shift from red & processed meat and dairy consumption to greater vegetable consumption	No

Sector	Low carbon action	Excluded from analysis
Agriculture	Food waste	Yes
Agriculture	Crops and soils	Yes
Agriculture	Land release supply side measures	Yes
Agriculture	Livestock	Yes
Transport	Shift from petrol or diesel ICE vehicles (car, van, motorcycle, small rigid, large rigid, articulated, bus) to hybrid EV, plug-in hybrid EV, battery EV, range-extended EV, hydrogen to fuel cell vehicle	No
Transport	Shift to active transport (walking, cycling) or public transport	No
Transport	Shift to active transport (walking, cycling) or public transport	No
Transport	Driving at lower average speeds	No
Transport	Zero emission vehicles	Yes
Transport	Mobile machinery	Yes
Transport	Rail	Yes
Transport	Stationary machinery	Yes

PwC GreenHouse Toolkit



GreenHouse Building Physics

This module takes physical characteristics of the home and models yearly energy use and average internal temperature.

- The model takes into account over 120 parameters ranging from the floor area, to number of chimneys, to whether the curtains are closed at night.
- We can edit these parameters and re-model the building to observe the effect on the energy use and internal temperature of the building. This is used to model the impact of specific low-carbon measures.
- We also have detailed data on the costs and savings from such measures which are not used in this CCC analysis

1. Inputs
120 + characteristics affect the energy use of a home.

2. Low-Carbon Model
The model is first run with what an individual home looks like today, based on BSA* data. This gives an individual baseline for each home.

3. Retrofit Home
We then change the characteristics of the home to change the energy use, e.g. installing triple glazing

4. Low-Carbon Model
The Low-Carbon Model is then rerun with the characteristics of the home after retrofitting.

5. Temperature
The model calculates the average temperature each month in a property. This changes based on the measures retrofitted to a home and on future, regional climate forecasts

6. Energy
The home's energy use therefore changes after retrofitting. We capture this on a yearly basis to 2050. Emissions are calculated based on energy use by source.

7. Outputs
Calculations are run for every year to give a future prediction for the energy use and internal temperature for each of the UK's 29m homes, individually.

* Building stock analysis, from various different sources

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Thank you