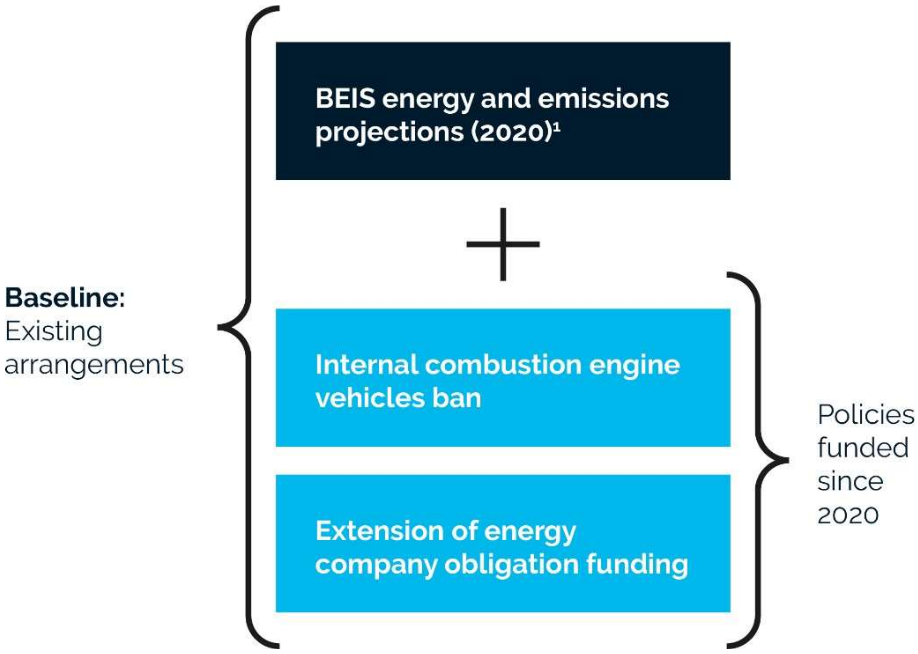
Co-benefits Methodology

1. Baseline carbon emissions

We set a baseline based on BEIS Energy and Emissions Projections (2021) being fully delivered under the existing arrangements, as well as policies that were published ahead of the release of the Government's Net Zero Strategy.

Figure 1: Baseline modelling



The business-as-usual (BAU) trajectory for city-scale production-based (PB) emissions, i.e. the carbon emitted either directly within the city-region's boundaries or indirectly via electricity use (Scope 1 and Scope 2 in GHG Protocol for Cities). Our focus is on all greenhouse gases measured as the mass of CO_2e.

1.1 Emissions data sources

Our starting point is historical local authority carbon emissions data. To develop a BAU trajectory, we project emissions forward by utilising city-region level population forecasts and national-level emissions scenarios[1]:

- Local authority level carbon emissions data disaggregated between domestic, industrial and commercial, and transport sectors and various subsectors is available from The Department for Business, Energy and Industrial Strategy (BEIS) - Time period covered 2005-2018
- Both UK- and LA-level population projections are regularly updated by the Office for National Statistics (ONS)
- UK-level projections of emissions and the carbon intensity of electricity supply are also available from BEIS covering both CO_2 and other GHGs and are disaggregated by nine sectors. Time period covered 1990 – 2040

1.2 Emissions projections

To develop a forecast of BAU emissions, we first match the BEIS national-level emitting sectors to the city-region level sectors, aggregating into clusters where necessary (see Table 1). Using these growth rates, we use the latest city-region level, per-capita emissions for each sector and project them forward to 2050. We, therefore, assume that the per-capita growth rates in emissions at the city-region and national-levels are the same for each sector/cluster.

Table 1: National-level sectors from the BEIS emissions scenarios matched to the city-region level, local authority emissions sectors

	National-level		**City-region level**	
	Disaggregation	**Time frame**	**Disaggregation**	**Time frame**
Emitting sector	Agriculture Industrial processes	1990-2040	Ind' & Com' (other fuels)	2005-2018

Waste management	
Business	
Public	
Energy supply	Ind' & Com' (electricity)
	Domestic (electricity)
Residential	Domestic (other fuels)
Transport	Transport
LULUCF	LULUCF

We then explored city-region level mitigation scenarios for emissions across the domestic, commercial and transport sectors. For each sector, we:

- Identify a range of applicable low carbon measures
- Assess their per-unit investment costs and energy savings
- Estimate their city-wide deployment potentials.

2. Financial costs & benefits and carbon reduction

2.1 Transport

.Analysis focuses on the intra-city transport most prevalent in towns and cities across the UK:

- Cars and taxis
- Heavy and light commercial vehicles
- Buses and coaches

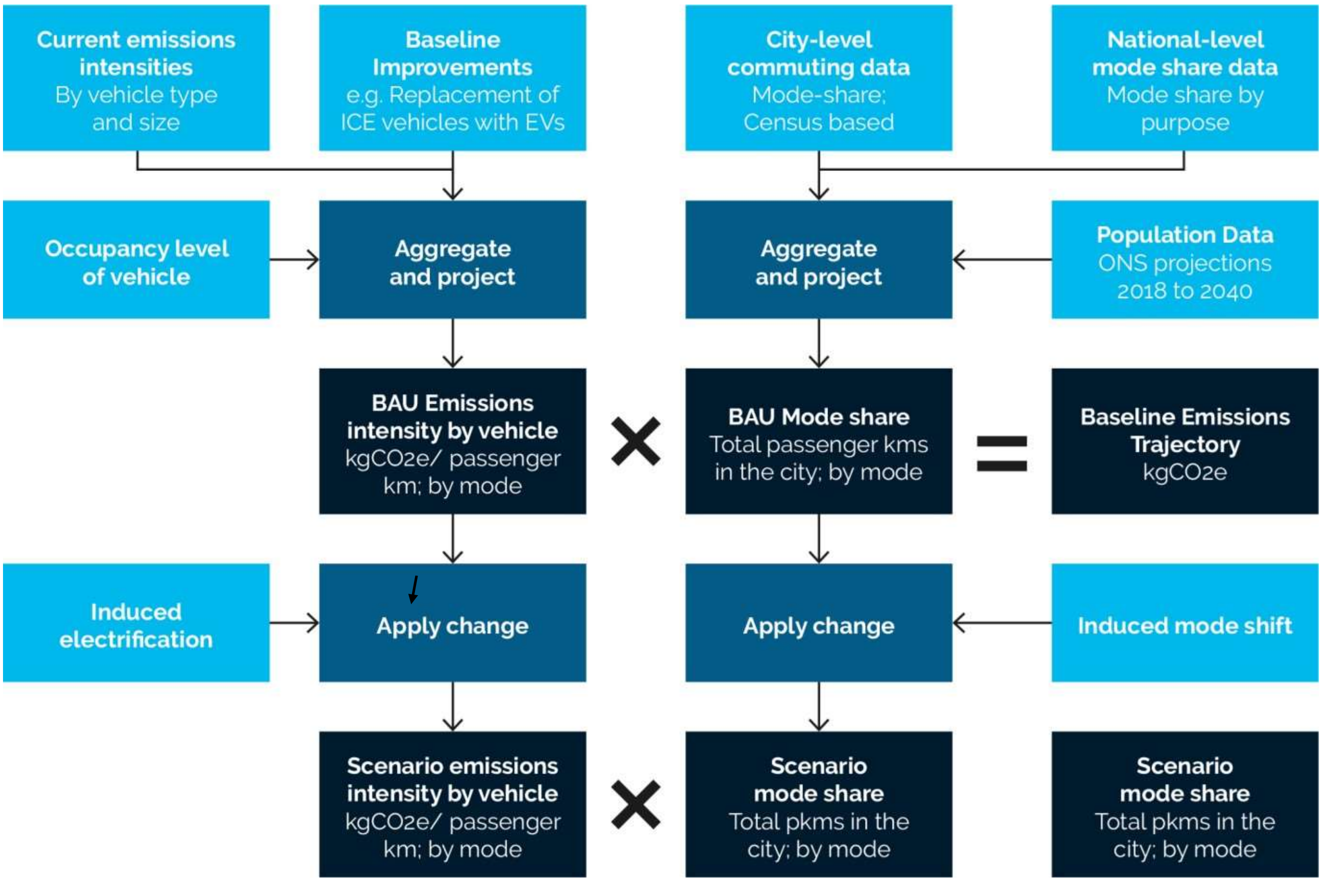
The transport model has been designed to estimate the costs, benefits and abatement potential of measures that change current travel patterns. Estimating total emissions in the transport sector involves compiling emissions intensities for each mode of transport (CO_2e/pkm) and city-region level mode share (pkms*) (see Figure 3).

First, we build a baseline based on existing travel patterns. Next to build a scenario we induce changes to the transport system:

- Substitution of trips for different trips (Shift)
- Efficiency gains due to electrification (Improve)
- Reduced number of trips due to network/logistical efficiencies (Avoid; only used for freight)

Comparing the changes in distance travelled and energy used from the baseline, based on what influenced the change, we can attribute costs and benefits to each low carbon measure such as shifting journeys from small petrol cars to walking or electrification of public buses

Figure 3: Flowchart outlining the transport sector methodology



In this study, rail, metro and tram travel are not considered These make up 2% of journeys in most UK cities,(but 15% in London, which we have not modelled). We also exclude any changes to urban form because of the deployment of low carbon measures (e.g. decreased journey times leading to changes in trip lengths).

Table 2: Categories of low carbon measures in transport sector

Category of low carbon measure	Description
Avoid	Improving the efficiency of the transport system, including integrated land-use planning and transport to reduce trip length
More efficient logistics	Improving efficiency of the logistics system by better route planning or combiningtrips for multiple purposes
Shift	Moving from the most energy consuming urban transport modes towards more environmentally friendly modes
Car trips to walking	Walking generates no emissions so shifting reduces carbon emissions from trips otherwise taken by car
Car trips to cycling	Cycling generates no emissions so shifting reduces carbon emissions from trips otherwise taken by car
Car trips to buses	Buses generate emissions but lower energy consumption and higher occupancy mean emissions per passenger-km are lower than cars.
Improve	Enhancing the energy efficiency of transport modes, taking advantage alternative energy use
Electrification of private petrol and diesel vehicles	Petrol and diesel vehicles generate emissions on every journey and electrification provides an opportunity for the energy used to be generated via renewable sources
Electrification of distribution vehicles (HGV, OGV1 and OGV2)	Electrifying vehicles typically run on petrol or diesel provides an opportunity for the energy used to be generated via renewable sources
Electrification of buses and coaches	Electrifying buses and coaches previously run on petrol or diesel provides an opportunity for some the energy used to be generated via renewable sources

2.2 Financial costs and benefits

Costs and benefits are attributed to each low carbon measure by comparing the difference between the scenario and the baseline model runs to allow for system interactions. This difference in energy usage and/ or distance travelled which is used to attribute costs and benefits means that they are calculated as net. Table 3 lists the costs and benefits included in our analysis. All costs are discounted at a rate of 3.5% except for those related to logistics: because this would be a cost directly to the private sector, a discount rate of 7% is used.

Table 3: Financial costs and benefits in transport sector

Cost or benefit	Title	Description
Cost	Discounted Capital Cost - Charging Infrastructure	The cost of chargers is worked out based on the number of extra EV kilometres driven in each scenario

Cost or benefit	Title	Description
	Discounted Capital Cost - Vehicle Purchase	The net cost of: electric vehicles over ICE vehicles; extra buses required; and bike purchases
	Discounted Capital cost - Infrastructure	The cost of extra bike lanes and bus lanes required, based on a proportion of the extra bus riders and cyclists added
	Discounted non-fuel operating costs (buses)	The extra operating costs associated with running buses - chiefly drivers' salaries. This is a cost in most city- region/scenarios since more bus journeys are required.
Benefit	Discounted non-fuel operating costs (all vehicles)	Maintenance, oil, and tyres for all vehicles. This is a benefit in most city-region/scenarios since higher maintenance of buses is offset by much lower maintenance costs for cars, both because there are fewer cars and because EVs are cheaper to maintain.
	Discounted energy savings	The net cost of energy required to power the new journey patterns. This is a benefit in all city-region/scenarios since electricity is cheaper than petrol/diesel and walking/cycling is free

2.3 Key inputs and assumptions

To estimate a city's residents' travel activity we use a combination of city- and region-level data. Trips per person by mode and region are derived from the National Travel Survey (2017-2019) and average miles by mode from the 2011 census. These are adjusted for the local region, where city-region level mode share data is available. Population data are derived from ONS projections.

Data from the Department of Transport 'Transport Analysis Guidance' are used for vehicle occupancy and proportion of work and non-work trips. Following the process outlined in the flowchart in Figure 3 these inputs provide pkm by mode over the period 2021-2050.

The GHG emission intensity and cost of different travel modes are estimated using national datasets. The proportion of cars by fuel source and fuel and non-fuel operating costs by vehicle type are drawn from the Department of Transport 'Transport Analysis Guidance'. Energy prices are drawn from BEIS 2020 Updated Energy and Emissions Projections and vehicle emission factors are derived from the UK Government Emissions Factors for Company Reporting, excluding electricity grid emissions factor projections which are derived from BEIS 2018 Updated Energy & Emissions Projections.

A notable assumption is that we assume that it is possible to simply shift as much as ~40% of car trips onto buses or bikes under the current system. This figure of 40% comes from maximizing the total average distance walked and cycled per capita at 5.2km based on the assumptions detailed below. The assumptions used to estimate a city's residents' travel activity are provided in Table 4.

Table 4: Key assumptions in buildings model

Assumption	Description	Source
Trips per year per person	Average number of trips taken per person per year by mode for that region	Department for Transport Statistics - National Travel Survey - England: 2018/2019 (2 survey years combined)

Assumption	Description	Source
Distance travelled by mode annually	Average distance in miles travelled by mode annually across that region	Department for Transport Statistics - Average miles travelledbymode,regionand Rural-UrbanClassification: England - All areas
Total Oil Equivalent (TOE)	Total oil equivalent by transport mode is used to develop a baseline for motorised transport energy use in each local authority.	Total final energy consumption at regional and local authority level: 2005 to 2018. BEIS.
Maximum distance km cycling per person per day	2.7 km per person per day is assumed to be an upper limit for achievable cycling distance based on levels achieved in Denmark.	https://www.regionh.dk/english/traffic/cycling/Documents/17751Cykelregnskab_UK.pdf
Maximum distance km walking per person per day	2.5 km per person per day assumed to be an upper limit for walking distance most shift based on literature review.	https://www.nhsinform.scot/healthy-living/keeping-active/activities/walking
Distance per year per vehicle	Kilometres per vehicle (and by vehicle type) per year is held constant across cities and across time. If a scenario shifts trips to motorised transport the number of new vehicles is determined using the number of additional kilometres by that vehicle type divided by the average annual kilometres by that vehicle type.	Transport Statistics for Great Britain. Department for Transport
Fast chargers per BEV	One fast charger for 80 battery electric vehicles and one for every 5 goods and/or transit vehicles.	Nicholas, M. and Hall, D., 2018. Lessons learned on early electric vehicle fast-charging deployments. International Council on Clean Transportation, Washington.
% trips by mode (2018 post only)	Total final energy consumption at regional and local authority level: 2005 to 2018 (BEIS) is used to determine travel by motorised vehicles. To estimate travel by non-motorised modes NTS0103 is used to estimate the number of per person trips by bicycle and on foot. These values are regional and available only for English regions, as a consequence assumptions are made for cities in Wales, Scotland and Northern Ireland.	NTS0103: Average number of trips by main modes - index: England
Average trip distance	Average trip distances are assumed to be the same across cities.	NTS0105: Average distance travelledby main modes - index: England
Changes to urban form	We have assumed that the urban form of a city-region stays static, meaning that average trip lengths by mode remains constant. This means that any major infrastructure projects which could drastically change the way we travel are not accounted for.	
Occupancy	Car and vehicle occupancies through 2036. Values held constant from 2036 through 2050.	TAG Table A 1.3.3
Occupancy - buses	Alteration from TAG source. Increased occupancy of buses from 14 to 17. This is based on research undertaken by University of Leeds	Source: Williamson, R. F., Sudmant, A., Gouldson, A., & Brogan, J. (2020). A Net Zero Carbon Roadmap for Edinburgh. *Place-Based Climate Action Network: London, UK*, 1-30.

Assumption	Description	Source
Proportion of car, LGV & other vehicle kilometres using petrol, diesel or electricity	The proportions drawn from this dataset are assumed to hold for all cities.	TAG Table A 1.3.9 Special consideration for Petrol/Diesel (set at 1%)
Vehicle energy use	Vehicle efficiencies are assumed to be the same across cities.	TAG Table A 1.3.11
Vehicle efficiencies	Data from the TAG is used in conjunction with academic literature to provide values for different vehicle sizes.	TAG Data Table A 1.3.11 And Chkaiban, R., Hajj, E.Y., Bailey, G., Sime, M., Xu, H. and Sebaaly, P.E., 2020. Fuel and non-fuel vehicle operating costs comparison of select vehicle types and fuel sources: A parametric study. In Pavement, Roadway, and Bridge Life Cycle Assessment 2020 (pp. 284-293). CRC Press.
Share of kilometres by vehiclesize	This includes data to split heavy goods vehicles into types and passenger vehicles into large, medium and small	VEH0124: Licensed vehicles by make and model and year of first registration: United Kingdom
GHG emission factors	Scope 1 emissions factors are drawn from BEIS conversion factors. For Scope 2 emissions the reference scenarios for electricity production and generation sources are used to generate a baseline and annual conversion factors	Conversion factors 2021: full set (for advanced users). BEIS. Appendix J: Total electricity generation by source Appendix G: Major power producers' generation by source
Measures that are large in scale and diverse in scope	– **Shared electric vehicles** - Assumed that 10 EVs are replaced by an EV that is part of a shared scheme. This is a modifier used in the integrated scenario. This modifies costs only. – **Shared bike scheme** - Shared bikes are assumed to be utilised ten times the amount of a private bicycle therefore the cost of a shared bike is 0.77 times the cost of a regular bike. This is a modifier used in the integrated scenario. This modifies costs only.	https://www.transportenvironment.org/sites/te/files/publications/Does-sharing-cars- really-reduce-car-use- June%202017.pdf https://inclusivev.eu/wp-content/uploads/2018/03/Inc EV-Executive-Summary.pdf
Marginal capital cost per vehicle	The marginal cost of electric vehicle relative to ICE equivalent e.g. electric car to ICE car	TAG Table A 1.3.14
Cost per fast charger	Faster chargers are assumed to cost £75,000 based on literature and consultation. This cost is the same for all vehicle types.	Mathieu, L. "Roll-out of public EV charging infrastructure in the EU." Transport & Environment 7 (2018).
Cost per bicycle	£505 - Accounting for both the average cost of a bike alongside new entrant hard accessories	http://eprints.lse.ac.uk/38063/1/BritishCyclingEconomy.pdf

Assumption	Description	Source
Non-Fuel Resource Vehicle Operating Costs (NFOC)	The elements making up non-fuel vehicle operating costs include oil, tyres, maintenance, depreciation and vehicle capital saving (only for vehicles in working time). Following discussion with DfT, it was noted that NFOC contains a large depreciation component. DfT guidance can be found in the link below and the original document (1988) that NFOC is derived for is "Review of Operating Costs in COBA, EEA division of transport, 1990-91". This shows that NFOC parameter a is made up of 36% oil, tyres and maintenance and 64% depreciation, and that parameter b is 100% depreciation. Depreciation is a way of expressing capital costs on an annualised basis. Because our methodology is net, we only consider the additional capital costs of low carbon measures- e.g. an EV is X more expensive than an ICE car. This surplus is included in our capex calculations as an upfront cost and constitutes the only relevant capex for vehicles. Therefore, there should be no depreciation contained in any of our calculations. Therefore, for our calculations we use parameter a * 0.36 and do not use parameter b.	Table A 1.3.14: Non-Fuel Resource Vehicle Operating Costs https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.375.1581&rep=rep1&type=pdf
NFOC of electric vehicles	E-PSV, e-OGV1, and e-OGV are assumed to have half the operating costs of their ICE equivalent. Data from academic literature are used to provide values for different vehicle sizes.	TAG Table A 1.3.14 And Chkaiban, R., Hajj, E.Y., Bailey, G., Sime, M., Xu, H. and Sebaaly, P.E., 2020. Fuel and non-fuel vehicle operating costs comparison of select vehicle types and fuel sources: A parametric study. In Pavement, Roadway, and Bridge Life Cycle Assessment 2020 (pp.284-293). CRC Press.
NFOC for cars - share of cars	It has been assumed that all private vehicles has a utilisation for work at 18.2%	Table NTS0409 from DfT (2019 table)
Additional NFOC for buses	Further NFOC to account for additional costs based upon the CPT index. It has been assumed that for every £1 spent on fuel, £4.88 is spent on DRIVERS' wages, other labour and staff costs and insurance claims.	https://www.cpt-uk.org/media/ca2iuq21/change-in-bus-coach-industry-costs-for-the-12-months-to-31-december-2019.pdf
Reference energy prices	Retail prices are assumed for all vehicles.	BEIS 2018 Updated Energy & Emissions Projections (Retail prices table)
Cost of buses lanes per km	Assumed cost of additional bus lane capacity at £250,000 per km.	Greener Journeys/KPMG (2017)

Assumption	Description	Source
Capacity of a bus lane	A reasonable planning-level capacity for a dedicated transit lane is 80 buses per hour	https://nacto.org/publication/ transit-street-design-guide/introduction/why/desig ning-move-people/#:~:text=A%20reasonable%20planning%2Dlevel%20capacity,through%20a%20single%20transit%20lane.
Cost of cycling interventions	Assumption of £0.98m per additional km of additional cycling infrastructure based upon a mixture of schemes such as cycle superhighway, mixed strategic cycle routes and resurfaced cycle routes.	https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/742451/typical-costings-for-ambitious- cycling-schemes.pdf
Additional capacity of cycling infrastructure	Assumed that major shifts to cycling will require additional dedicated infrastructure to (a) handle additional bikes on the road (b) generate the interest and shift necessary. Given the high capacity of cycling infrastructure, as well as the option for cyclists to use roads and alternative infrastructure there is a high degree of elasticity between the shift to cycling and additional infrastructure required.	Link

2.2. Buildings sector

The purpose of these models is to estimate the financial costs, benefits and abatement potential of applying a variety of low carbon measures across 13 building archetypes in city-regions across the UK. The building's models have been separated into domestic and commercial sectors.

The methodologies for estimating annual carbon savings in the domestic and commercial sectors are outlined in Figures 4 and 5. Annual carbon savings per-unit of each measure are multiplied by the number of units deployed in the mitigation scenario (houses or m^2 of floor-space.

Per-unit carbon savings are obtained from the energy savings data we describe below and the associated emissions intensities. We also account for the interactions that occur when multiple low carbon measures are deployed within the same building, which can reduce the savings achieved in the case of, for example, solar photovoltaics and efficient lighting.

Figure 4: Domestic sector

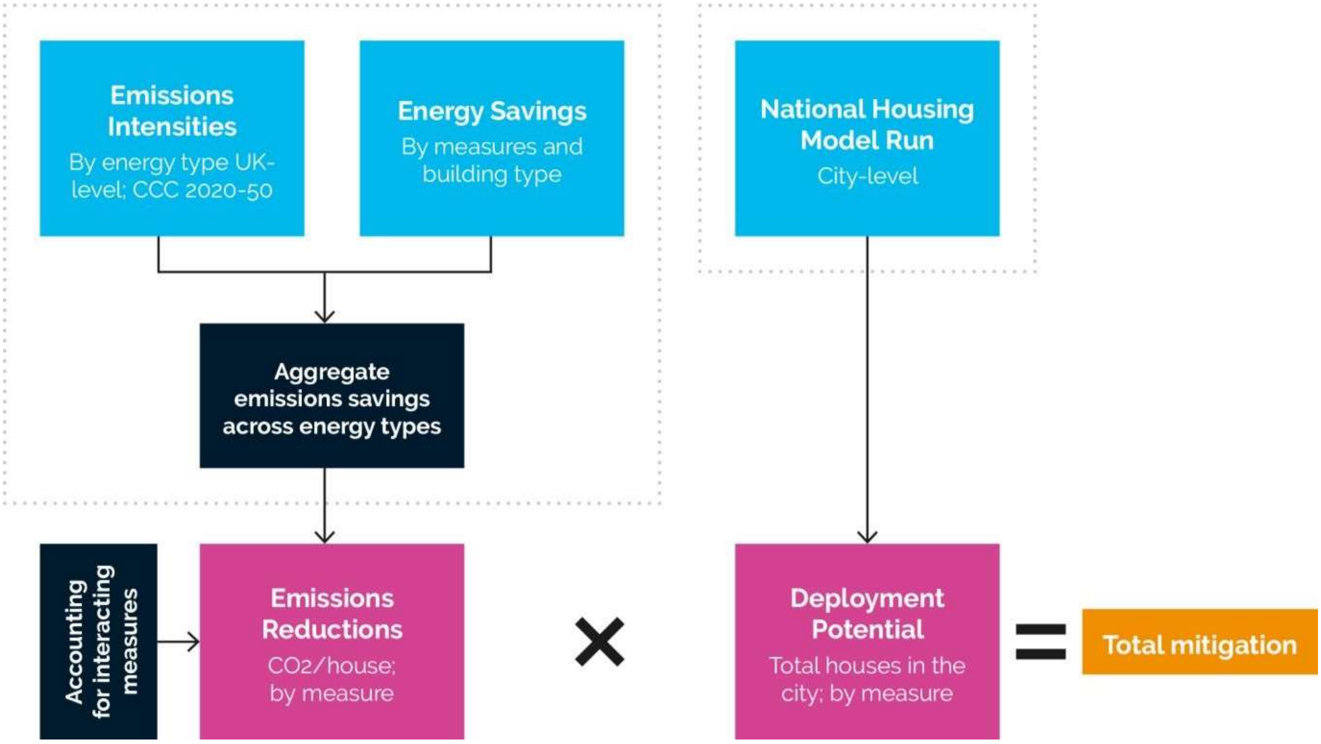
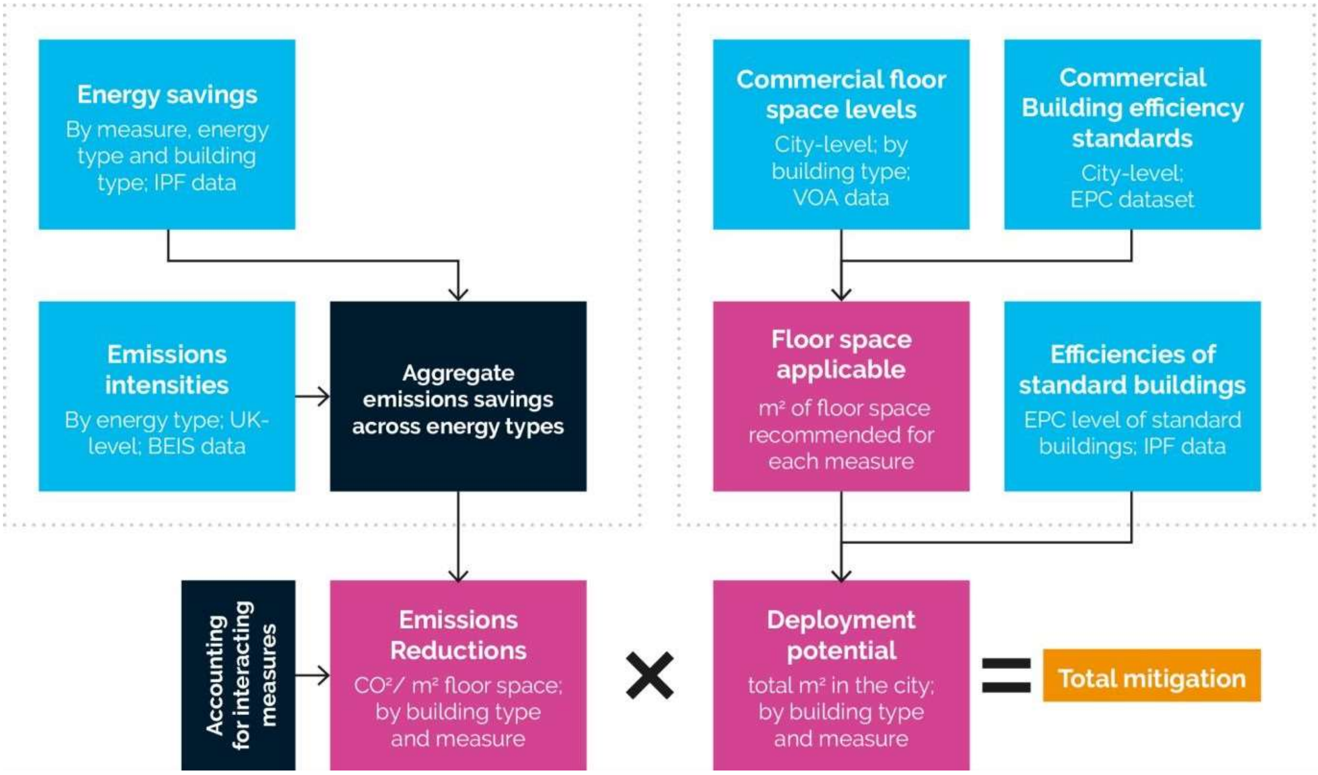


Figure 5: Commercial sector



2.1 Low carbon measures by category

3.1.1 Domestic buildings

In the domestic buildings sector, low carbon measures are deployed on a per home basis across seven archetypes:

- Bungalows
- Converted built flats
- Houses (detached, semi-detached, end of terrace, mid-terrace)
- Purpose built flats (high rise and low rise).

Table 5: Categories of low carbon measures applied to domestic buildings

Category of low carbon measure	Description
Energy efficiency	Upgrading gas ovens and appliances to energy efficient alternatives, gas hobs and ovens to induction alternatives, analogue to digital TVs, filament light bulbs to low energy lighting
Insulation	Increasing air tightness, replacing single with double glazing, external shading, improving insulation
Heating efficiency	Upgrading boilers to 95% efficiency, using heating controls, heat recovery, increasing efficiency of technology (e.g. DC drive fan coils, chilled beams)
Low carbon heat	Installing solar thermal or replacing gas boilers with air source heat pumps
Microgeneration	Solar PV, installing a wind turbine
Scale and scope domestic Measures	Area based commercial PV installation, area-based commercial retrofit scheme.

3.1.2 Public and commercial buildings

In the domestic buildings sector, low carbon measures are deployed on a floor area basis across six archetypes:

- Offices
- Retail space
- Industrial/warehouse units
- Community centres
- Education
- Healthcare spaces
- Hotels

Table 6: Categories of low carbon measures applied to public and commercial buildings

Category of low carbon measure	Description
Energy efficiency	Increasing energy efficiency of light bulbs, daylight and movement sensors, increasing efficiency of technology (e.g. variable speed pumps,

	chillers)
Insulation	Installing insulation (cavity wall, external wall, floor, internal wall, loft), draught-proofing, top up loft, triple glazing
Heating efficiency	Upgrading storage tanks and conventional boilers to gas combi-boilers, tank insulation, thermostats, radiator valves
Low carbon heat	Replacing storage tanks and conventional boilers with heat pumps, use of solar thermal
Behaviour change	Lowering thermostats, reducing heating for washing machines, reducing household heating by 10C, reducing standby consumption, turning unnecessary lighting off
Microgeneration	Solar PV
Scale and scope commercial low carbon measures	Area based commercial PV installation, area-based commercial retrofit scheme.

2.3 Financial costs and benefits

Table 7 lists the costs and benefits included in our analysis. Costs are discounted at a rate of 3.5%. However, if a cost is directly applicable to the private sector (e.g. measures applied to retail units) a discount rate of 7% is used.

Table 7: Calculated financial costs and benefits in buildings sector

Capital cost	The capital costs of low carbon measures are estimated in net present value terms over the period from 2022 to 2050 taking into account: - When the new low carbon measure is assumed to be deployed - The expected length of life of the low carbon measure before it requires replacement. Note - The total net present investment cost is applied on deployment between 2022 and 2030. This means that the cost of replacement is not realistically spread across the study period.
Energy savings	The deployment of each measure between 2022 and 2050 is multiplied by the estimated energy saving (for electricity, gas and other) associated with each low carbon measure, multiplied by the discounted energy cost forecast from BEIS As per BEIS Green Book guidance, we use long run variable costs, because energy prices include: - Fixed costs that will not change in the long run with a small sustained change in energy use, - Carbon costs, since these are valued separately, and - Taxes, margins, and other components which reflect transfers between groups in society

Unlike in the transport model (where it is assumed that the price of EVs is likely to fall to reach parity with ICE cars by 2035), the cost of all buildings measures in this study stays the same in real terms. This is because most buildings measures, such as insulation and boilers, are very mature technologies and less likely to be subject to significant innovation.

2.3.1 Key inputs and assumptions

2.3.1.1 Domestic sector

For the domestic sector the list of low carbon measures, their lifetimes, and their costs and energy savings (electricity, gas, and other fuels) are consistent with the UK's National Housing Model (NHM), which was developed by the *Centre for Sustainable Energy (CSE)*[4]. It is worth noting that these costs have been tested and updated each time the models have been used at local authorities, most recently in 2020.

The EPC data sets represent the full housing stock by local authority including information on current insulation levels, heating systems, etc. on a per property basis. Using EPC datasets in conjunction with these NHM outputs, we assess what

low carbon measures are appropriate for a particular city's domestic sector, how many houses each measure would be suitable for, we call this the deployment potential.
Using a s-curve deployment profile, each measure is deployed to its potential within the constraints set by the scenario. Therefore we can calculate what energy and emissions savings would be expected assuming the household maintains the same heating regime post-installation of each measure. The buildings stock is taken as static - i.e. we do not increase homes each year commensurate with likely house growth.

2.3.1.2 Public and commercial

The Public & Commercial buildings sector operates in largely the same manner as the domestic sector, where the basic unit of analysis is changed from individual homes to m^2 area of applicable non-domestic floorspace. For the commercial sector we obtain lists of low carbon measures and their lifetimes, costs, and energy savings (electricity and gas) from the review of the Investment Property Forum (IPF), which are appropriate throughout the UK. Measures are grouped into different building types with (marginal) costs and (multi-vectoral) energy savings detailed on a measure-by-measure basis. To calculate city-region level deployment potentials we utilise LA-level data describing:

- Existing commercial floor-space by building type from the Valuation Office Agency (VOA)
- EPC assessments reported for commercial building stock across LA.

We use these datasets together to estimate the floor-space in a city-region across each archetype. We assume that the area of commercial floor-space remains static across each of these archetypes. This appears reasonable as for the periods within which data are available there are only negligible changes in the distributions of EPCs of commercial buildings and existing commercial floor-space. We use the proportion of floorspace surveyed in EPC assessments that recommends a particular intervention and apply this to the total floorspace in a city

Table 8: Key Assumptionsin buildings models

Assumption	Description	Source
Heat pump costs	Conductedbriefreviewofthe Centrefor Sustainable Energy (CSE) measuresandinflatedallto2020prices All lookedreasonableexcept for heatpumps - these are potentiallycentraltothetransitionandlikelyto be in high demand and - subsequently - highsupply We found accurate up to date costs from the UK Government(seelink)andusedthesetoupdatethe cost of heatpumps	https://www.gov.uk/government/publications/cost-of-installing-heating-measures-in-domestic-properties
Heat pump cost reduction	Heat pump cost reduction has been applied in all scenariosin linewith the NZS: The NetZero Strategy stated that there is ambition to reduce the cost of heat pumps by at least 25-50% by 2025 and that price parity with gas boilersis reached by 2030. Therefore, the price of an average heat pumps used in the analysis falls each year to 2030 when it reaches the same real price as an average gas boiler	https://www.gov.uk/government/publications/net-zero-strategy
Heat pump deployment	Heat pump proportionality has been assigned per population in each city-region (based on the Government policy objective of 600,000 heat pumps provided each year from 2028 onwards), deployment starts in 2022 and exponentially increases to 2028 where the proportion of 600,000 heat pumps is deployed each year. The proportion of the original heat pump deployment across property types is calculated to split the updated deployment figure across property types	
District Heat Network deployment	Districtheatingnetworkscurrentlysupply3%ofthe UK's heatsupply: the aim is to increase the share to 20% by 2050. The NetZero Strategy assumesthat6% ofheatingsupply willbeprovidedbydistrictheating networks by 2035. To develop a deployment potential of district heat networks in the place agnostic scenario, proportionality is assigned per population in each city-region in the same manner as heat pump deployment. NB: this meansthatheatnetworksare assignedto cities based on population, but not based on the factors that will actually drive heat network deploymentatthe very local level: density, localheat sourcesandother local projectfeasibility factors	
Deployment potential figures	The deployment potential for each low carbon measure for each property type is calculated for each city-region based on EPC data, datais gathered on whether the low carbon measure could be deployed within a household and then aggregated up to the relevant low carbon measure group	https://epc.opendatacommunities.org/
S-curve deployment of buildings measures	In all scenarios, it is assumed that deployment of building measures starts slowly in 2022 and builds to a peak in the late 2020s before tapering off. An S-curve is applied here rather than a linear growth rate	

Assumption	Description	Source
Interactions methodology	We assume that measures that impact the heating of a home will interact. Given a household will use a certain amount of energy for heating, each low carbon measure will reduce the savings available for other measures. The following equations are applied to account for this: Corrected energy/carbon savings = original savings - original savings * (average house % savings w/o interactions - average house savings w/ interactions) Average house % savings w/o interactions = average number of interacting low carbon measures per house * average % savings per measure Average house savings w/ interactions = average savings per measure ^ number of low carbon measures Although cooling measures would also interact, there isn't enough and so the impact is negligible.	
Scale and scope low carbon measures	- District heating networks - The cost and benefits are based on figures from a case study in Tallaght. - Whole house retrofit - Measures that are replaced by a whole house retrofit are summed and compared with desk research values. It was found that this represented ~31% saving. This reduction is applied to other property types. The electricity, gas and other savings are reduced by approx 10% overall. - Low energy apartment retrofit - the same method is used and the same percentage reduction applied. - Area-Based Commercial Retrofit Scheme - Mean retrofit data comparing costs of typical schemes vs individual low carbon measures for a range of commercial typologies (5) is used as a cost reduction on the sum cost of low carbon measures. - Area-Based Commercial PV Installation - The average values of the three existing low carbon measures is used, and a costing improvement from economies of scale data for is used as a proxy for an area-based approach.	https://carbonneutralcities.org/wp- content/uploads/2018/05/1-London-Energiesprong-Transferability- Assessment.pdf, https://www.aecb.net/wp-content/uploads/2015/08/G oing-Deep.pdf, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/656866/BEIS_Update_of_Domestic_Cost_Assumptions_031017.pdf , https://www.codema.ie/images/uploads/docs/TDHS_Marketing_Brochure_for_Developers.pdf https://www.hw.ac.uk/uk/schools/doc/egis/TARBASE_ND_REPORT.pdf , https://www.london.gov.uk/sites/default/files/appendix_a_solar_action_plan.pdf, https://www.theguardian.com/environment/2016/may/19/london-borough-installs-6000-solar-panels-on- market

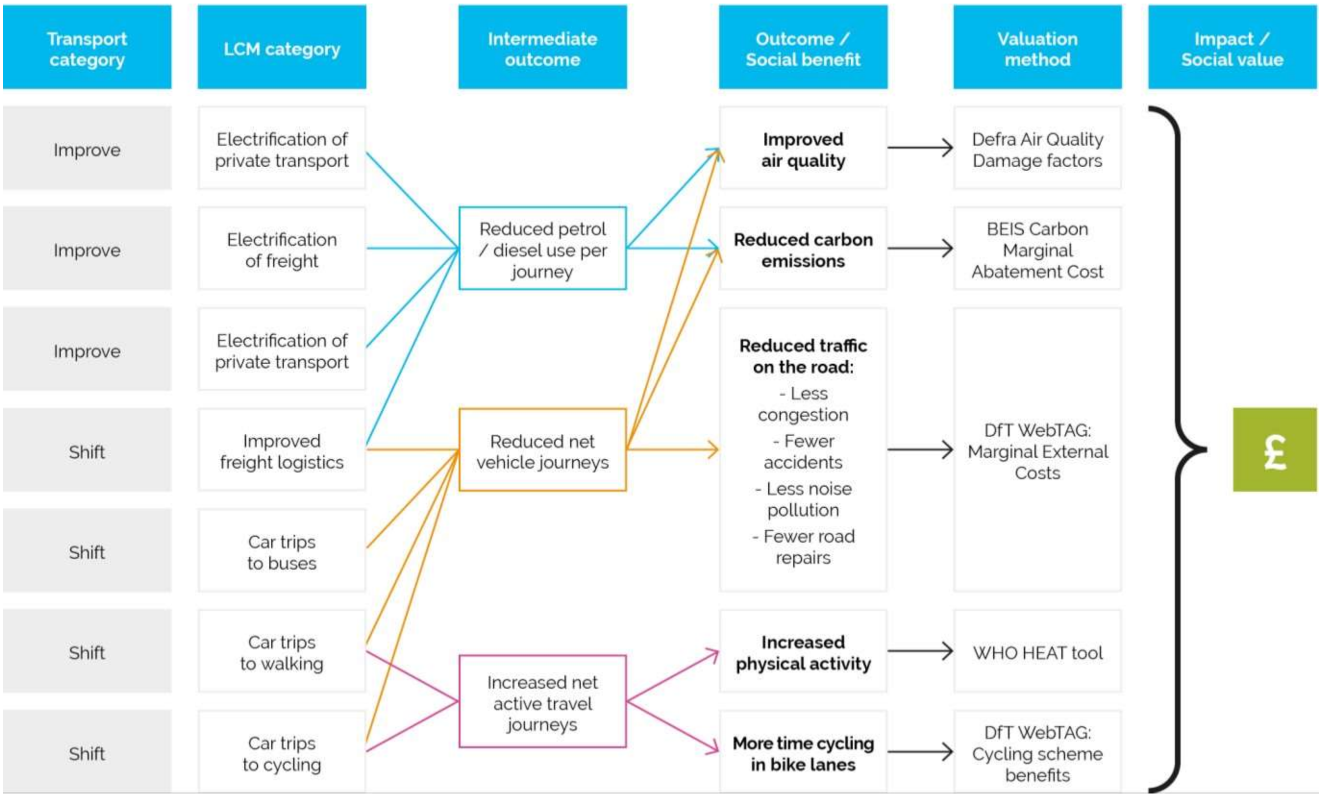
Assumption	Description	Source
Rebound effect	For some domestic LCMs, an increase in energy efficiency leads to increased use of energy to provide more comfort. We have assumed a rate of 15% rebound for certain measures and valued this using BEIS guidance - see 'Home Comfort' on pg 25	Committee for Climate Change (2013) - discussion of how the energy savings potential of low carbon measures is rarely reached because of in-use, comfort and inaccessibility factors. This analysis only considers comfort factors, but the context may be useful for further analysis UK Energy Research Council (2007) - extensive evidence of the size of the rebound effect in different settings, concluding that "The direct rebound effects were estimated to reduce overall energy savings by 15%"

3. Social costs and benefits

Besides their financial costs and benefits, each low carbon measure creates various wider social costs and benefits. These have been identified and defined using impact pathways and drawing on the extensive existing literature that has considered the potential impacts of urban decarbonisation[5]. Taken together, the financial costs and benefits plus the wider social costs and benefits provide our estimates of the net present social value (NPSV) of each low carbon measure.

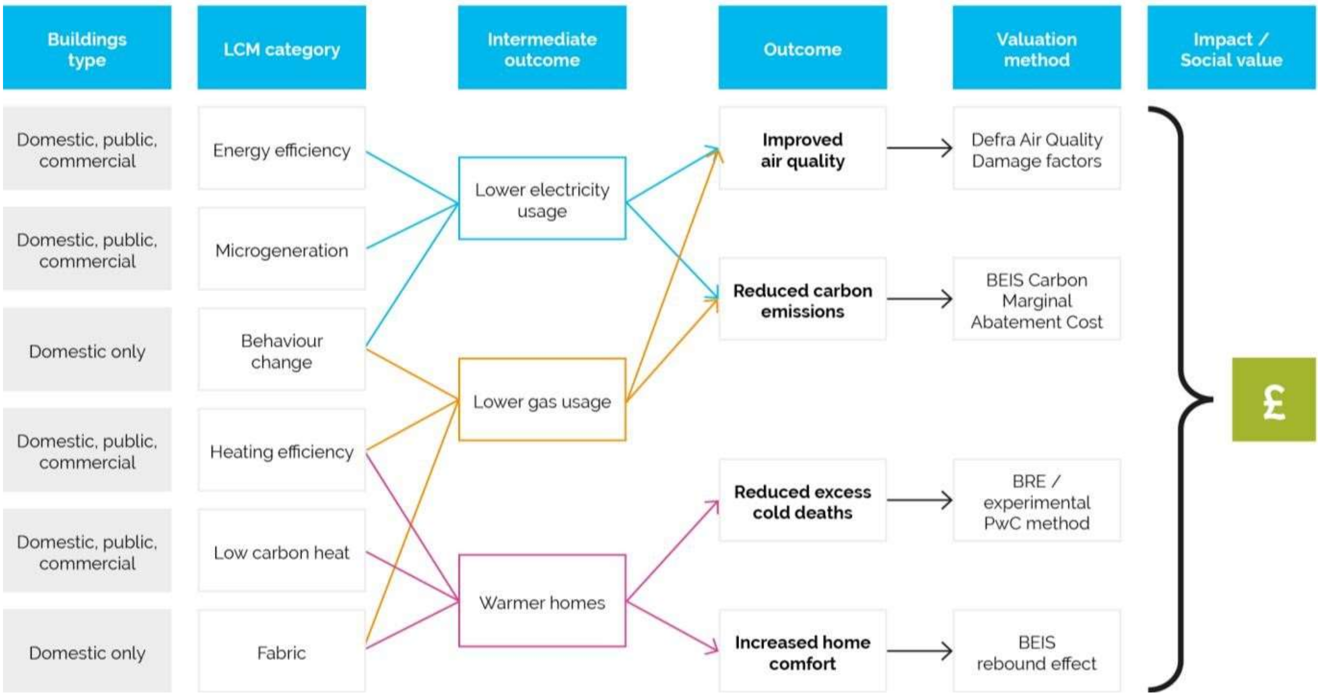
Figure 6 summarizes the key impact pathways identified in relation to the low carbon measures relevant to surface transport and Figure 7 does the same for heat and buildings.

Figure 6: Simplified impact pathway for surface transport low carbon measures, by category



All social benefits are presented as positive benefits ('Improved air quality'). In aggregate, net benefits are generated under all scenarios but they comprise both costs and benefits. For example, switching car trips to buses results in a benefit of fewer cars on the road → *reduced* carbon emissions, congestion, accidents
... but a cost of more buses on the road → *increased* carbon emissions, congestion, accidents.

Figure 7: Simplified impact pathway for buildings low carbon measures by buildings type and category



Scale and scope low carbon measures are not shown; not all individual pathways shown e.g. some heating efficiency low carbon measures also reduce electricity usage, but they reduce gas usage far more as most UK homes have gas boilers

3.1 GHGemissions

As per BEIS guidance: "Greenhouse gas emissions values ("carbon values") are used across government for valuing impacts on GHG emissions resulting from policy interventions. Carbon values represent a monetary value that society place on carbon dioxide equivalent(£/tCO2e).They differ from carbon prices, which represent the observed price of carbon in a relevant market (such as the UK Emissions Trading Scheme).The government uses these values to estimate a monetary value of the greenhouse gas impact of policy proposals during policy design, and after delivery." BEIS Valuation of greenhouse gas emissions: for policy appraisal and evaluation, updated Sep 2021, Annex 1, is the key source for this analysis.

3.1.1 Valuation methodology

- Step 1: The annual net GHG emissions savings from the transport and buildings models
- Step 2: These are multiplied by the carbon price for the appropriate year
- Step 3: The estimated benefits are discounted at 3.5% to derive their net present value.

By considering the change in use of different types of energy because of low carbon measures, it is possible to split the carbon values into traded and non-traded values. For example, as per BEIS guidance, electricity forms part of the traded sector, but domestic gas use is in the non- traded sector.

We do not present this analysis in our main findings or supplementary evidence. This is because reading of the updated guidance and further correspondence with BEIS GHG appraisal team suggests that (1) the usefulness of this disaggregation in a broad, hypothetical appraisal such as this study is limited and (2) the methodologyis subject to change pending consultation on design of the UK ETS.

3.2 De-congestion benefits

Our assessment of the potential benefits of reduced congestion follows the approach recommended in the Department for Transport's WebTAG relating to Marginal External Costs, which builds on an academic paper from Samson et al(2001)[1]

MECs measure the change in social value in having one less car on the road because of different factors:7

1. Lesscongestion → Improvedjourneytime andquality, lowervehicleoperatingcosts
2. Fewer accidents → lower mortality and morbidity
3. Fewer road repairs required → lower cost to the Exchequer
4. Lower levels of noise pollution → lower health and productivity burden
5. Fewer GHG emissions
6. Lowerair pollution
7. Lower road / fuel duty to the Exchequer

Note that 5 and 6 are valued elsewhere in our analysis (so not used here) and 7 is a transfer from one group to another.

3.2.3 Valuation methodology

We use two sheets from the Tag MEC data - A5.4.1 (traffic data) and A5.4.2 (cost data)

3.2.3.1 Traffic data

The output from the transport models is vkms for different vehicle types, per year, but these are not split by region or road type. Therefore, the first step required is to:

Step 1: Split total vkms in each city-region into different region and road type

This is done using DfT WebTAG Sheet 5.4.1: "Traffic by region, congestion band, area type & road type"

- Assumption: Regions are at the International Territorial (NUTS-1, i.e. Scotland, North-East, London); it is assumed that

[1] Sansom T, Nash CA, Mackie PJ, Shires J, Watkiss P (2001) Surface Transport Costs and Charges: Final Report. For the Department of the Environment, Transport and the Regions. Institute for Transport Studies, University of Leeds

each city-region has the same transport road usage as the region it is located in. So, for example, Manchester and Liverpool both use North- West

- Assumption: There is no regional split for Northern Ireland, so Wales is used instead as Swansea-Bay and Belfast city-regions have similar levels of density
- Assumption: DfT's regional road-usage splits (5.4.1) change every 5 years but stay constant between them[8]

This allows us to say that, for example, if 100km is driven by a car in Glasgow city-region, X% of it will be on an A road in an Inner conurbation. So if 100km *less* is driven, it will disappear from this same road/regio

3.2.3.2 Cost Data

DfT gives values in pence per vehicle kilometre (vkm) avoided, split by the mode, place and time the vkm is avoided, by:

1. -Vehicle type (Cars, LGVs, OGV, HGV and PSV)
2. Year (2015-2050)
3. Region (London, Inner and Outer Conurbations, Other Urban, Rural)
4. Road type (Motorways, A roads, Other Roads)
5. Congestion band (1 to 5; this describes what % of the time each road is expected to be in free-flowing traffic (band 1) or standstill (band 5))

1 and 2 are outputs from the transport model and 3, 4 and 5 are calculated using webtag A5.4.1 above.

Step 2. Multiply the avoided vkms per mode, place and time by the pence/vkm value for the corresponding mode, place and time

Step 3. These benefits are discounted at 3.5%

3.3 Air Quality

We assess the value of the impacts on air quality using the damage cost guidance prepared by the Department for Environment, Food and Rural Affairs (Defra). The Defra approach considers different health impacts based on the latest advice from Public Health England and the Committee on the Medical Effects of Air Pollution (COMEAP). Three impact pathways are included in this valuation:

- public health
- the natural environment
- the economy

Detailed information on derivation of this methodology is available here

3.3.1 Valuation methodology

There are two Defra tables - one for air quality damage from transport emissions and one for fuel combustion from buildings. Both assume that damage is higher when fuel is consumed in more densely populated areas. They also require the user to calculate where each unit of fuel is used. However, the two tables use different "density areas", as show

Table 10: Density areas used to assess air quality damage in buildings and transport

Buildings
National Average
Domestic: Inner Conurbation
Domestic: Urban Big
Domestic: Urban Medium
Domestic: Urban Small
Domestic: Rural

Transport
Transport Average
Central London
Inner London
Outer London
Inner Conurbation
Outer Conurbation
Urban Big
Urban Large
Urban Medium
Urban Small
Transport Rural

Step 1: Split each local authority in each city- region into a transport and buildings density-area type.

Assumption: This is done, using either (depending on data availability):

- For buildings - The density of the LA is matched to ONS population stats, with each buildings density area being assigned to a different density quintile
- For transport - allocations from Table 6 of the National Transport model - and where these were not present for a place, ONS density is used as per (a)

* Note that neither of these methods have any relations to the splitting of vkms into road types in the section above

Step 2. Multiply the damage factors per fuel type, per year, per density area by the change in energy usage by fuel type per low carbon measure per year. For transport, vehicle type split is also required.

Step 3: These benefits are discounted at 3.5%. In addition, there is no annual data series for transport air quality damage, so damage costs are inflated to 2022 prices and then 2% p.a. as per the Defra guidance.

- Assumption: AQ damage includes both health benefits and non-health benefits (i.e. changes to productivity), therefore we use the discount rate of 3.5% and not the pure health benefits - rate of 1.5%

3.4 Physical activity

Our estimate of the health benefits associated with the change in levels of physical activity associated with adoption of different low carbon measures is based on the World Health Organisation's health economic assessment tool (HEAT). World Health Organisation - online Health Economic Assessment Tool (HEAT) for walking and cycling. Methodology was improved following correspondence with the authors, based on the academic paper that informs the methodology[2]

3.4.1 Valuation methodology

Assumption: The academic paper (Kahlmeier et al., 2011) that underpins the methodology assumes that health benefits only accrue to people between 20-74 for walking and 20-64 for cycling since there is no evidence otherwise. We assume that all extra vkms travelled by active travel are completed by this age group. This is viewed as reasonable since:

- loss of life due to lack of physical exercise is very unlikely before 20
- frequency of exercise drops for those over 75, who are half as likely to walk regularly and for the over 65 who are three times less likely to cycle regularly than the population aged between 20 and 64/74 population10
- In addition, these age-groups are broken down further because the younger group (20-44) has a much lower risk of mortality - see step 5

Step 1: Our transport model estimates the extra vkms being walked and cycled per year

Step 2: Divide by the 20-64/74 populations, average walking/cycling speed (from HEAT; 14km/h) and 365 to give hours of exercise per person per year - assuming all people split the exercise evenly.

[2] Götschi, T et al (2020) Integrated Impact Assessment of Active Travel: Expanding the Scope of the Health Economic Assessment Tool (HEAT) for Walking and Cycling. Int J. Environ. Res. Public Health

Step 3: Use HEAT calculation: Divide the extra exercise per person in each age group by the reference range given by HEAT, and then multiply by the total reduction in risk that is associated with the reference range (see HEAT tool).

Step 4: If volume of exercise exceeds the capped amount, cap. NB: this does not happen in any of the modelled scenarios, as it is equivalent to 450 minutes per week of cycling or walking

Step 5: Multiply the reduction in risk for each age group by the total all-cause mortality for each age group in a given city-region - *this gives the total number of mortalities per city-region per year that would be avoided by increased physical activity*

Step 6: Calculate the average number of life years remaining for each age group - e.g., older age groups are likely to live less long

Step 7: Multiply this by the number of expected mortalities (5) and the VOLY to give a total value of life lost per year

Step 8: Create a lag so that it takes 5 years to accrue total benefits, with 20% created in the first year, 40% in the second etc.

Step 9: Discount by 1.5%: we use the Green Book recommended discount rate for health benefits as they are pure health benefits.

3.5 Excess cold

Our estimates of the social costs and benefits associated with the avoidance of excess cold follow an experimental method based on evidence from Building Research Establishment and Cambridgeshire County Council.[3] BRE estimate the potential NHS savings if 25 different housing hazards were eliminated in the UK. The largest hazard is "excess cold" which was estimated to cost the NHS £848m in 2015 (£1.4bn in 2020 prices). The approach set out below allocates a proportion of these potential savings to the successful deployment of low carbon measures that increase domestic warmth.

This approach is experimental, was designed for this study and should be used with caution as the causal pathway from improved housing measures to lowered likelihood of morbidity or mortality from excess cold is complex and this study does not have sufficient data to draw a direct line from one to the other.

However, the assumptions used are conversative and the resulting benefits are not significant to the overall analysis (excess cold benefits represent ~1-5% of all social benefits in any given city-region/scenario).

- Assumption: The model does not contain information on income distribution so it is assumed that all low carbon measures generate the same level of benefits, even though, insulation in a poorer household would be more likely to eliminate excess cold
- Assumption: Excess cold creates wider social costs through lost productivity and reduced utility (it is unpleasant to live in a cold home). This study does not consider the former at all, which is likely to be significant, but the latter is included in "Home Comfort" benefits (see next section)
- Assumption: This method assumes a direct link between temperature increase and health benefits and makes no provision for other impacts of temperature e.g. (1) increased temperature may also decrease dampness which has health benefits (2) increased insulation may increase the likelihood of excess heat in summer which has health disbenefits not considered in this study

3.6 Valuation methodology

Step 1: Calculate the total value to the NHS of eliminating excess cold Two datasets are combined:

- BRE show that 60% of total NHS costs are due to excess cold (£848m of £1.4bn)
- Cambridge Research Group show that the total cost to the NHS of ALL housing hazards is £2bn p.a13
- Therefore, we assume that a cost to the NHS of £1.2bn p.a. can be associated with cold- related housing hazards that can be tackled by warming low carbon measures (60% x £2bn)
- This is inflated to 2020 prices to give a figure of £1.43bn NHS costs

Step 2: Allocate NHS costs to city-regions. Total NHS costs are split between city-regions on a population basis, but weighted for that city's experience of excess winter deaths in 2018/19 (i.e. pre-COVID)

- Assumption: Weighting NHS costs per city- region by observed excess winter deaths: Excess cold deaths depend on many factors including ambient winter temperature, housing stock and poverty levels of a city. In the absence of an analysis of these factors, it is assumed that observed excess winter deaths in a city-region could be considered indicative of them all
- Assumption: Excess cold baseline: Analysis of long-term trends show that excess winter deaths in the UK are falling by

[3] BRE (2015). Understanding the cost of Poor Housing to Health. Available from <https://www.gov.uk/government/publications/homes-and-ageing-in-england-understanding-the-cost-of-poor-housing-to-health>

approx. 1% p.a. even as the population rises. This may be because of the factors mentioned above (warming temperature, improved housing) and it means that in the absence of low carbon measures, NHS costs would reduce over time. Therefore, this long-term trend is extrapolated and used to reduce the total amount of NHS savings available by ~1% p.a.

Step 3: Allocate NHS costs to each low carbon measure deployed

Domestic low carbon measures that increase heat are selected (67 out of 235).

- Assumption: only low carbon measures that increase temperature infer 'anti-excess cold' health benefits - therefore insulation is included, heat pumps are excluded

The temperature increase of each is used to calculate a warming factor per low carbon measure Using data from National Housing Model / SAP scores - See Standard Assessment Procedure - BEIS 2013

- Assumption: there is a direct, linear relationship between the extent to which a measure increases temperature and that measure's reduction in NHS costs
- Assumption: Measures that lower heat - thermostats, behaviour change - are assumed to not be deployed by households that are already cold, therefore there is no excess cold disbenefit applied to those measures

The warming factor is corrected by deployment potential so that 70% of max deployment = 100% of NHS cost savings

- Assumption: an assumption must be made about whether total excess cold is fully eliminated when all possible EPC measures are deployed or at a lower level. This analysis assumes a level of 70%. This is based on evidence showing that 37% of all homes surveyed in England have at least one significant hazard17, which means that the total NHS costs could be avoided if only those 37% of homes received warming low carbon measures. However, it is not possible to disaggregate at the household level so an assumption is made that once deployment reaches 70% of potential, all the at-risk 37% would be covered
- Note: A more means-tested rollout of warming low carbon measures would generate higher NHS savings faster, but a more market-based approach (incentives to install insulation that incentivise richer households first) would likely result in a slower reduction in excess cold

Use the corrected warming factor to assign a total £ value for each low carbon measure in each city. The total NHS costs can now be split between low carbon measures so that for example, in an average bungalow cavity wall insulation installed between 1976-83 is worth £140 p.a. in avoided NHS costs

Multiply these £ values by the number of each low carbon measure deployed in each city- region/scenario each year

Discount benefits at 1.5% (these are pure health benefits so discounted at reduced rate)

3.6 Home comfort

This benefit follows BEIS guidance[4] on how to value the additional comfort that households receive from being able to use domestic appliances (e.g. heating, lighting) more when the energy efficiency of the appliances improves. This benefit values the "rebound effect". This is the extent to which energy efficiency measures result in households saving money on their energy bills enabling them to afford to use these appliances more leading to an improved quality of life (i.e. warmer, more well-lit homes).

From the domestic buildings model: the deployment of those low carbon measures where a reduction in energy usage (and therefore energy bills) may lead to higher usage (148 out of 235). For example a more efficient oven is included, lowering of a thermostat is excluded. Heat pumps are also excluded as they are more likely to increase fuel bills so there would be no rebound effect

- Assumption: in practice, the extent to which the rebound effect is present differs significantly but a central rate of 15% is chosen for all measures
- Assumption: 0% rebound effect is applied for public and commercial usage: the paper gives some evidence that offices, schools, hotels etc. are not constrained by energy prices to the same degree as households
- Assumption: indirect rebound effects are not considered at all - i.e. where money saved on energy is spent in the wider economy, increasing enjoyment
- Assumption: rebound rates remain at 15% throughout the study - there is no reduction over time thanks to exogenous

[4] Valuation of energy use and greenhouse gas: Supplementary guidance to the HM Treasury Green Book on Appraisal and Evaluation in Central Government (October 2021)

changes to buildings standards or energy prices

3.6.1 Valuation methodology

Step 1: Select domestic buildings LCMs that are subject to a rebound effect

Step 2: Select which type of energy usage the rebound would be applied to: For example, triple glazing results in gas savings (boiler usage), but not electricity savings, so the rebound effect applies only to gas; low-energy lighting only affects electricity use; a gas combi-boiler saves both electricity and gas.

Step 3: Calculate 15% of the energy savings for each measure each year in kWhs

Step 4: Multiply this by the number of measures deployed each year and by the retail price of that measure

- Assumption: Analysis of costs in this study always use the long-run variable cost of energy, but the rebound effect uses the retail price. This follows BEIS guidance: because the retail price is the price households pay to increase their heating or lighting it is therefore a revealed preference of their willingness to pay for this experience

Step 5: Benefits are discounted at 3.5%