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Health and associated economic benefits of reduced air pollution and increased physical activity from climate change policies in the UK

Heather Walton [a,b,c,*], David Dajnak [a,b,c], Mike Holland [d], Dimitris Evangelopoulos [a,b,c], Dylan Wood [a,b,c], Christian Brand [e], Nosha Assareh [a,b], Gregor Stewart [a,b], Andrew Beddows [a,b], Shawn YC Lee [a,c], Daniela Fecht [b,f], Yunzhe Liu [b], Bethan Davies [b,f], Anna Goodman [g], Tuan Vu [a,b], Sean Beevers [a,b,c]

[a] Environmental Research Group, School of Public Health, Faculty of Medicine, Imperial College London, UK
[b] MRC Centre for Environment and Health, School of Public Health, Faculty of Medicine, Imperial College London, UK
[c] NIHR Health Protection Research Unit in Environmental Exposures and Health, Imperial College London, UK
[d] Ecometrics Research and Consulting, Reading, UK
[e] Transport Studies Unit, University of Oxford, Oxford, UK
[f] NIHR Health Protection Research Unit in Chemical and Radiation Threats and Hazards, School of Public Health, Imperial College London, UK
[g] Faculty of Epidemiology and Population Health, London School of Hygiene and Tropical Medicine, London, UK

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ABSTRACT

Climate change policies do not always include analysis of air quality and physical activity co-benefits. We compared business as usual (BAU) UK policy with Net Zero scenarios from the UK Climate Change Committee for road transport and building sectors. We quantified and monetised the health benefits of the Balanced Net Zero (BNZP) and Widespread Innovation (WI) Pathways.

Air pollution concentrations were predicted using Chemical Transport Models and population-weighted. Shifts from car to walking and cycling for transport were converted to METhrs/week. Literature concentration–response functions were combined with baseline rates from routine statistics/other sources. Mortality and multi-morbidity impacts were calculated using lifetable analysis, and an incidence/prevalence model from 2019 to 2154 (a lifetime after 2050). Monetary values were applied to the results.

The BNZP policy compared with BAU gave 4.9 (95 % confidence interval 1.0–9.0) million life-years gained (LYG) (UK population, to 2154), including 1.1 (0.7–1.6) million LYG from active travel improvements. Avoided COPD and childhood asthma cases were 201,000 (150,000 – 250,000) and 192,000 (64,600–311,000). The monetised air quality morbidity benefits (£52.1 (36.4 – 67.8) billion) substantially added to the air quality mortality benefits (£77.9 (42.9 to 90.8) billion). Total yearly monetised benefits for BNZP vs BAU summed to 2154 (air pollution/active travel) were £153 (122 to 184) billion (core); 278 (228 to 334) billion (+outcomes with weaker evidence).

Adding the effects of air pollution reductions on disease incidence, with effects of air pollution and physical activity on mortality, increases the monetised benefits that may justify Net Zero policies in cost-benefit analysis.

1. Introduction

Climate change will have widespread major adverse impacts on human health both in the UK (UK Health Security Agency (UKHSA), 2023) and globally (Romanello et al., 2024). While some of these impacts are already apparent, even larger impacts are forecast in the years ahead, ranging from heat-related mortality (already 167 % higher than the 1990 s in the over 65 s), wildfires and life-threatening extreme

Abbreviations: BAU, business as usual; BNZP, Balanced Net Zero Pathway; CCC, UK Climate Change Committee; PWAC, population-weighted average concentration; WI, Widespread Innovation.

* Corresponding author at: Environmental Research Group, Imperial College London, 10th Floor, Sir Michael Uren Building, White City Campus, London W12 7TA, UK.

E-mail address: h.walton@imperial.ac.uk (H. Walton).

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weather events to increased infectious disease transmission (Romanello et al., 2024). Air pollution also has extensive impacts on health, (World Health Organization, 2021) but these are more immediate (days to a few years), (US Environmental Protection Agency (USEPA), 2021) and more local/regional. Several climate change policies reducing greenhouse gas emissions reduce air pollution emissions too, yet air pollution impacts are not necessarily included in cost-benefit analyses of those policies. Inclusion of as many co-benefits (and trade-offs) as possible is important for efficient policymaking. In addition, it can be difficult to encourage the public to support climate mitigation policies when the benefits are greater for the next generation rather than this one and many of the benefits will occur in other parts of the world. In contrast, air quality benefits (and physical activity benefits) occur in this generation and local to the population undertaking the necessary actions. In 2020, the UK Government committed to implement policies to achieve net-zero emissions by 2050, as set out by the Climate Change Committee's (CCC) Sixth Carbon Budget (Committee on Climate Change (CCC), 2020).

Previous studies have estimated the health or economic impacts of air pollution reductions from climate change policies. We conducted a literature review of these studies since 2018 – most previous analyses focused on earlier UK or global climate change policies, (Supp A1). Milner et al. assessed two CCC scenarios in the UK but focused only on mortality and used simple air pollution modelling (Milner et al., 2023a).

Previously, reductions in mortality benefits exceeded the monetised morbidity benefits of air pollution control as shown in our study of the UK achievement of the World Health Organisation (WHO) interim target of 10 μg/m^3 $PM_{2.5}$, up to 2030 (Dajnak et al., 2022) However, evidence for effects on incidence of disease, (Forastiere et al., 2024) has strengthened in recent years.

Here we examined the health and economic mortality and morbidity benefits due to air pollution reductions related to the roads (largest source of NO_x) and buildings (largest source of $PM_{2.5}$) sectors in CCC's Sixth Carbon Budget Balanced Net Zero (BNZP) and the roads sector Widespread Innovation (WI) Pathways (Committee on Climate Change (CCC), 2020). We have included impacts up to 2154, i.e. a lifetime after the proposed policies in 2050, to ensure capture of the full benefits of the air pollution reductions and to see how the new evidence increases the benefits. Similarly, we have included the health benefits from increased active travel (i.e. walking and cycling for transport) in these policies. Active travel has been shown to contribute significantly to reducing the burden of chronic diseases, including cardiovascular disease, type 2 diabetes, and some cancers, while also enhancing mental well-being and quality of life (Kelly et al., 2014; Patterson et al., 2020). It is also helpful to consider physical activity and air quality benefits together because there is an interplay between reductions in vehicle km and increases in active travel. Finally, we assessed impact modification by socio-economic status (SES) and estimated the monetised benefits for use in cost-benefit analysis.

2. Methods

2.1. Scenario definitions

Scenarios were developed through detailed discussions with CCC and government departments. Predictions in 2030 and 2040 were made using Business as Usual (BAU) European and UK Government's emissions forecasts and adding Net Zero scenarios for transport and buildings from the CCC's 6th Carbon Budget (2020). Details are in Supp A2 but briefly, we included scenarios:

1. Balanced Net Zero Pathway (BNZP), including road transport and a rapid uptake of electric vehicles, together with changes in buildings and a rapid uptake of energy efficiency measures, deployment of heat pumps, low-carbon district heat networks and people's behavioural change in saving energy in the home.
2. Widespread Innovation (WI) with greater levels of active travel, accelerated uptake, and more affordable battery technology for EVs, resulting in small increases in EVs and a two-fold increase in e-biking compared with BNZP.
3. 'Combined' BNZP + up to 2050, combining road transport and buildings from BNZP 2050 with the European Commission's Second Clean Air Outlook v2021 projections for all other sources (European Commission, 2021).

These BNZP and WI scenarios were compared with 2019 concentrations remaining unchanged and the BAU scenario over 2019–2154. No 2050 BAU scenario exists so the BNZP + scenario was compared with BNZP.

2.2. Population

Population data by sex and single year of age (2019) for England and Wales (E&W) and Scotland were obtained at Ward level from national statistics. We collected 2019 data from Northern Ireland Statistics and Research Agency (NISRA) by sex and 4 broad age bands at Ward level adjusted to single year of age using data from Administrative Areas. Subsequent population data were derived from the lifetables. Supp A6 gives the data sources and processing in detail.

2.3. Emissions and concentrations

Emissions changes relating to the policy scenarios described above were obtained from emission inventories and incorporated into the CMAQ-urban atmospheric model to derive air pollutant concentrations as described in Supp A2 and Dajnak et al (Dajnak et al., 2022). Modelled annual mean concentrations for $PM_{2.5}$ and NO_2 for 2019, 2030 (BAU/BNZP/WI), 2040 (BAU/BNZP/WI) and 2050 (BNZP +) were linearly interpolated between years and maintained beyond 2040 (2050 BNZP +) until 2154. More complex metrics for long-term and short-term exposure to ozone were also predicted (Supp A2). The CMAQ urban model outputs were averaged by Ward.

Population-weighted average concentrations (PWAC) were produced by local authority (LA) for each scenario for the mortality analyses, using the population aged 30 + . For morbidity calculations, LA data were population-weighted by the relevant age group to country level.

2.4. Physical activity

To assess the mortality effects from a switch to active travel we modelled changes in trip numbers, distance travelled and activity intensities in E&W to derive changes in physical activity (in METh/week) by mode, age, gender, and year (2030, 2040, 2050) at Lower Super Output Area level, aggregated to LA. Active travel inputs from BNZP and WI scenarios were adapted and mapped onto the 'government target, near market', 'e-bike' and 'Go Dutch/e-bike+' scenarios of the DfT's Propensity to Cycling Tool (PCT) (Woodcock et al., 2021). We estimated (probabilistically) the potential for change for those who were inactive or already active, based on trip distance, hilliness, mean trips per cyclist or pedestrian per week, (Department for Transport (DfT), 2022) marginal METs per hour, (Costa et al., 2015) and mean travel speed (Kahlmeier et al., 2017). Supp A3 describes this in detail.

2.5. Baseline rates

Baseline mortality data were obtained by LA and single year of age as a 3-year average (2017/2018/2019 NI and Scotland; 2016/2017/2018 for E&W). (Details in Supp A6).

Incidence, prevalence, and other baseline morbidity rates for 2019 were often not available from routine statistics and were estimated from alternative sources (Supp A6). For serious outcomes, such as acute myocardial infarction (AMI), stroke and ischaemic heart disease (IHD), first admission or death from the relevant cause without previous hospital admissions were used as an incidence proxy. Where data were not available for the desired country, year, or age group, it was inferred from rates in other areas, years, or ages.

2.6. Exposure-response functions

For air pollution, the concentration–response functions (CRFs) were based on *meta*-analyses considered scientifically robust by the Committee on the Medical Effects of Air Pollutants (COMEAP) (Committee on the Medical Effects of Air Pollutants (COMEAP), 2023a) and/or WHO (Forastiere et al., 2024).

Physical activity calculations were based on the associations for all-cause mortality (Kelly et al., 2014). Supp A4 contains more details of CRFs for core and sensitivity analyses.

2.7. Health impact calculations

Mortality impact calculations used the lifetable method of Miller and Hurley projecting from 2019 to avoid atypical pandemic mortality influencing the projections (Miller and Hurley, 2003). Birth projections, neonatal deaths, baseline mortality rates and mortality improvements were incorporated. Mortality impacts are expressed as life-years gained/ lost (LYG/LYL) when comparing different scenarios. The impacts were calculated assuming effects with or without a ‘cut-off’ concentration, which for mortality was 0 ($PM_{2.5}$) and 0 or 5 $\mu g/m^3$ (NO_2), (Committee on the Medical Effects of Air Pollutants (COMEAP), 2018) and for morbidity was 5 $\mu g/m^3$ ($PM_{2.5}$) and 10 $\mu g/m^3$ (NO_2), (World Health Organization, 2021; Forastiere et al., 2024) due to sparse data in the epidemiological studies underlying the CRF. If the difference between PWAC and cut-off was negative, we set it to zero.

Health impact calculations at LA level were then summed to country and UK level. Results by LA were also summed by Carstairs index to compare differences by socio-economic status.

The number of morbidity cases were estimated as the attributable fraction for the relevant population, with or without cut-offs, for 2019–2154. For incident cases, the population at risk was derived from the relevant age group population from the lifetables minus the baseline prevalent cases (as those with the disease cannot become an incident case). Baseline incidence was calculated from the incidence rate in those without disease from the year before and air pollution attributable incident cases derived from this. The latter cases were then added to the baseline incidence and baseline prevalence to provide new inputs for the following year.

For short-term exposure to pollution, we estimated the attributable fraction for the pollutant of interest without using information on prevalence.

Cessation lags between reductions in exposure and effects were used for mortality, (US Environmental Protection Agency (USEPA), 2021) and for morbidity, lags were based on analogy with the smoking cessation literature (Supp A5).

More methodological details are given in Supp A8.

2.8. Economic valuation

General guidance for quantification of health impacts of air pollution in UK policy assessments has been taken from DEFRA, (Department for Environment and Affairs, 2023) HM Treasury, (HM Treasury, 2022) and Ricardo (Ricardo, 2023). The approach adopted quantifies the full consequences linked to LYL and disease incidence, covering health care costs (primary, secondary, social, and at-home care), productivity and utility. The valuations adopted here are listed in Table 1 with full details in Supp A7. The potential for double counting economic impacts when combining results for different morbidities was considered. Economic results presented here match the extended 2019–2154 period used for the health impact assessment, reflecting that measures adopted now will have long-term consequences. Increased uncertainty in estimates over longer time periods is acknowledged for both costs and benefits (Beevers et al., 2025).

2.9. Uncertainty estimation and sensitivity analysis

To minimise biases from double counting between $PM_{2.5}$ and NO_2, we followed recommendations from COMEAP and reported the results from the pollutant which gave the largest effects for the baseline 2019 scenario (Committee on the Medical Effects of Air Pollutants (COMEAP), 2018). The other pollutant results were used in sensitivity analyses.

We estimated uncertainty in the health and economic impact calculations using the 95 % confidence interval (CI) limits from the corresponding CRF and monetary values and combined them analytically (Supp A7).

Sensitivity analyses were performed to test various assumptions, such as the inclusion of a cut-off and the choice of pollutant to represent the air pollution mixture. Long-term exposure to ozone was included as a sensitivity analysis in the mortality calculations. Additional calculations were also conducted on health outcomes not included in the core analysis for reasons ranging from uncertainties in the CRF, uncertainties in the baseline rates and plausibility of the size of the impact compared with other related outcomes (Supp A8).

3. Results

3.1. Descriptive statistics for inputs

Both BNZP and WI showed similar reductions in UK-wide PWAC from 2019 to 2040 (larger for NO_2 than $PM_{2.5}$). For the BNZP + scenario, the reductions are greater, but the policies are more uncertain/ include other sources than buildings/transport (Fig. 1a). The differences between BNZP and BAU in PWAC $PM_{2.5}$ at LA level used in the mortality calculations varied spatially (Fig. 1b). UK nation values; the slightly different spatial patterns for NO_2; the similar PWACs by age groups other than aged 30 or above and the increase and decrease in the daily 8-hour maximum ozone long-term exposure metric (summer mean above 60 $\mu g/m^3$) and the short-term exposure metrics (annual mean) respectively are given in Supp A2.

For active travel our modelling showed a 4.8-fold and 6.6-fold increase in physical activity (METh/week) from cycling and e-biking in 2040 for the BNZP and WI scenarios respectively, when compared with baseline 2019 levels, while physical activity from walking did not increase as much, only 7.4 % on average for both scenarios (Supp A3: table S3.5). These estimates were then used in the mortality calculations.

Other inputs for the health and economic impact analysis are presented in Table 1.

3.2. Mortality impacts

The adverse impacts of $PM_{2.5}$ on mortality for 2019 gave larger results compared with NO_2 and O_3 (Supp A9), and therefore was chosen to represent the air pollution mixture across all scenarios.

Benefits of 3.8 (95 % CI: 2.9–4.3) million LYG related to reductions in air pollution were estimated for BNZP compared with BAU, with an additional 1.1 (0.7–1.6) million LYG for changes in active travel for 2019–2154 (Table 2). The associated combined discounted monetary benefits were estimated at £101 (73–127) billion pounds. These benefits can be put into the context of 59.6 (45.2–66.7) and 46.0 (34.8–51.4) million LYL across the UK 2019–2154 for 2019 concentrations remaining unchanged and BAU, respectively (Supp A9).

The corresponding estimates for WI are very similar to BNZP, except for changes in cycling, which would save a further 0.6 (0.4–0.9) million life-years up to 2154 compared with BNZP. This is relatively small, not because physical activity is not important (see air pollution and physical activity life-expectancy for 2019 in Supp A9) but because the benefits of

Table 1
Input data for benefits analysis.

Health outcome (ICD-10 codes)	Risk factor[1]	ERF (95 % CI) per 10-unit increase (Health risk metric)[2]	Age group (Baseline population at risk)	Lags applied	Baseline incidence (Prevalence if applicable) (numbers of cases per year in age group)	Combined total undiscounted valuations per case in £000[3] (95 % CI)
Mortality analysis						
All-cause mortality (A00-Y89)	$PM_{2.5}$	1.08 (1.06–1.09) (HR)	30+:42,484,372	30 % of effect in year 1, 12.5 % in each of years 2–5 and 20 % spread over years 5–20 (US EPA lag)	571,027	51 (38–63)
All-cause mortality (A00-Y89)	NO_2	1.023 (1.008–1.037) (HR)	30+:42,484,372	US EPA lag	571,027	51 (38–63)
All-cause mortality (A00-Y89)	O_3	1.013 (1.002–1.023) (HR)	30+:42,484,372	US EPA lag	571,027	51 (38–63)
All-natural-cause mortality (A00-R99)	O_3	1.0034 (1.0012–1.0056). (RR)	All ages: 66,753,043	No lag (short-term)	581,586	51 (38-63) (1 LY per death)
All-cause mortality (A00-Y89)	Cycling	0.90 (0.89–0.94) (HR)[2]	20+:45,454,996	US EPA lag	506,120 [4]	51 (38–63)
All-cause mortality (A00-Y89)	Walking	0.90 (0.85–0.95) (HR)[2]	20+: 45,454,996	US EPA lag	506,120 [4]	51 (38–63)
Core morbidity analysis						
COPD incidence (J41-J44)	$PM_{2.5}$	1.18 (1.13–1.23) (HR)	30+: 42,484,372	5–10 years evenly spread	160,964 (1,668,968)	80 (60–101)
Asthma incidence in children (J45)	$PM_{2.5}$	1.34 (1.10–1.63) (HR)	0–18: 14,846,358	No lag	91,024 (1,407,455)	226 (167–283)
Asthma incidence in adults (J45)	NO_2	1.10 (1.01–1.21) (HR)	19+:51,906,685	No lag	92,113 (7,167,002)	169 (124–213)
Stroke incidence[5] (I60-I64)	$PM_{2.5}$	1.16 (1.12–1.20) (HR)	30+: 42,484,372	30 % Year 1; 12.5 % each of years 2–5	95,658 (1,278,294)	449 (358–544)
Lung cancer incidence (C34)	$PM_{2.5}$	1.16 (1.10–1.23) (HR)	30+:42,484,372	6–20 years evenly spread	48,129 (67,554)	186 (124–249)
Acute myocardial infarction incidence[6] (I21-I22)	$PM_{2.5}$	1.13 (1.05–1.22) (HR)	30+:42,484,372	30 % Year 1; 12.5 % each of years 2–5	84,507 (1,669,242)	147 (111–184)
Respiratory hospital admissions[7] (J00-J99)	NO_2	1.0057 (1.0033–1.0082) (RR)	All ages: 66,753,043	No lag	1,084,256	15 (4–25)
Respiratory hospital admissions[7] (J00-J99)	O_3	1.0075 (1.0030–1.0119) (RR)	All ages: 66,753,043	No lag	1,084,256	15 (4–25)
Cardiovascular hospital admissions[7] (I00-I99)	NO_2	1.0066 (1.0032–1.0101) (RR)	All ages: 66,753,043	No lag	689,322	7 (2–12)
Sensitivity morbidity analysis (additional outcomes)[8]						
Dementia incidence (F00-F03, G30)	$PM_{2.5}$	1.48 (1.23–1.78) (HR)	60+:16,120,484	4–8 years evenly spread	50,580 (543,594)	453 (351–563)
ALRI in children (J12-J18, J20-J22)	NO_2	1.09 (1.03–1.16) (OR)	0–12: 8,897,119	No lag	2,289,468	0.5 (0.2–0.8)
School absences[9] (n/a)	$PM_{2.5}$	1.0173 (1.0056–1.0290) (RR)	Primary school age children (5–12): 6,572,921	No lag	51,199,876	0.10 (0.06–0.15)
Diabetes incidence (E11-E14)	$PM_{2.5}$	1.10 (1.03–1.18) (HR)	30+:42,484,372	5–10 years evenly spread	424,843 (3,727,299)	255 (190–320)
Chronic phlegm (n/a)	PM_{10}	1.32 (1.02–1.71) (OR)	16+:54,063,466	No lag	2,685,006	80 (60–101)
Cardiovascular hospital admissions (I00-I99)	O_3	1.0011 (0.9973–1.0027) (RR)	All ages: 66,753,043	No lag	689,322	7 (2–12)

[1] Risk factor units: Annual average (μg/m^3) for PM_{10}, $PM_{2.5}$, and NO_2; April to September average of daily 8 h maximum above 60 μg/m^3 for O_3 long-term exposure (HR); annual average of daily 8 h maximum (μg/m^3) for O_3 short-term exposure (RR); MET hours per week for walking and cycling.

[2] Health risks metrics as reported in the epidemiological studies: hazard ratio (HR), odds ratio (OR) or relative risk (RR). For walking and cycling, ERFs are reported per 11.25 MET hours per week.

[3] The total morbidity valuation combines utility, health, and productivity costs. Mortality is utility only per life year lost. http://ec.europa.eu/environment/archives/cafe/pdf/cba_methodology_vol2.pdf.

[4] The effect of active travel policies on physical activity was only done for England and Wales not the UK as for air pollution

[5] First hospital admission for stroke and/or stroke death with no preceding admission used as a proxy for incidence. Could only find prevalence with TIA as well.

[6] First hospital admission for MI and/or MI death with no preceding admission used as a proxy for incidence.

[7] Emergency admissions.

[8] Further CRFs for sensitivity analyses that involve replacing one CRF with another are given in Supp. A4.

[9] School absences in general not absence for illness or absence for respiratory illness. The most dominant studies in the *meta*-analysis used school absences in general.

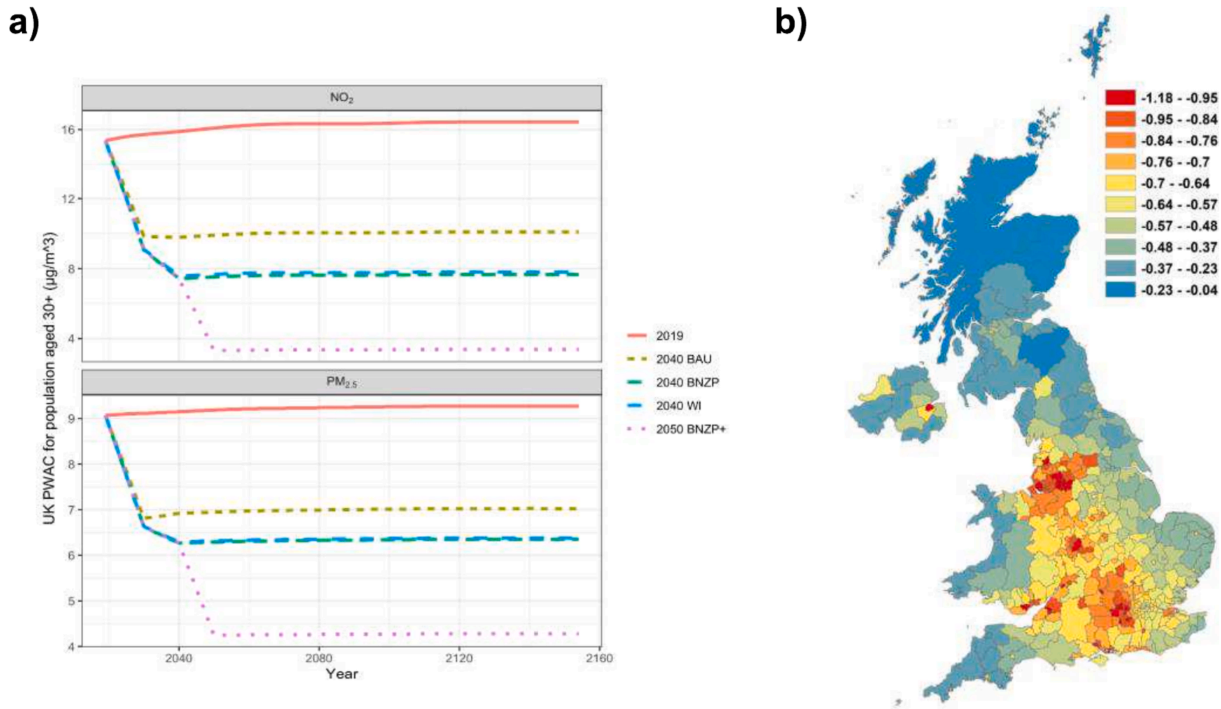

Fig. 1. a) $PM_{2.5}$ and NO_2 population-weighted mean concentrations (PWAC) age 30 + by year for the different scenarios b) $PM_{2.5}$ population-weighted mean concentrations age 30 + by local authority – difference between the balanced Net Zero pathway and business as usual in 2040. Note that smaller differences do not necessarily mean more should be done – sparsely populated areas may have low emissions already or policies may have already been implemented at an earlier date e.g. London. Concentrations remained consistent after the relevant years per scenario, however population changes year on year resulted in slight variation in PWAC across years projected into the future. Note that NO_2 and $PM_{2.5}$ are on different scales in a).

increased activity only accrue to those that do it. The number of people projected to be cycling for transport in 2040 in E&W were 81,400 for WI and 60,500 for BNZP compared with 10,700 in 2019, all gaining around 5.4 – 5.7 months life-expectancy if walking/cycling for transport from age 20 (Supp A9). In contrast, everyone in the population is exposed to air pollution. This comparison is specific to the policy scenarios investigated – more ambitious active travel policies and promoting walking as well as cycling would increase the physical activity benefits (Hobbs and Frost, 2024).

The more extensive emission cuts under the BNZP + scenario resulted in an extra 10.4 (8.6–12.2) million LYG compared with BNZP and the discounted costs were estimated at £193 (144–241) billion pounds.

Sensitivities with cut-offs and for other pollutants are given in Supp A9. Of these, only ozone would be an addition rather than an alternative to the results above. However, the total LYG for ozone would only increase the result for BNZP vs BAU by approximately 4 %. This is policy specific: overall adverse impacts for 2019 concentrations of ozone are 45 % of those for $PM_{2.5}$ (Supp A9).

All UK results above were summed across LAs and then country – results by country and maps by LA are shown in Supp A9. We also investigated how LA results varied by Carstairs Index – the proportion of LYL/LYG was greater in the most deprived areas but this was primarily driven by the greater population (deprived areas tend to be in city centres with a high population density; Supp A9).

3.3. Morbidity impacts

The adverse impacts of the concentrations remaining after the scenarios are given in Supp A10. Where outcomes had CRFs for both $PM_{2,5}$ and NO_2, the largest impact for the 2019 baseline scenario was for NO_2 for respiratory and cardiovascular hospital admissions and $PM_{2.5}$ for asthma in children. Therefore, these pollutants were used in the core analysis for these outcomes.

For morbidity analysis, $PM_{2.5}$ contributed the most to the results (Fig. 2). Cardiovascular outcomes gave larger benefits (due to the higher baseline rates; Table 1), but benefits from avoiding respiratory outcomes were also substantial. COPD and asthma in children resulted in the largest numbers of attributable cases saved for BNZP compared with BAU (201,000 [150,000-250,000] and 192,000 [64,600–311,000], respectively), with the associated discounted costs being £5.2 [3.6 to 6.8]) and £17.4 [5.3 to 29.5] billions, respectively up to 2154. Asthma in children was highest in the economic valuations (£17.4 (£4.5 to 30.3) billion) with stroke second ((£15.4 (£11.3 to 19.5) billion) and asthma in adults (£7.3 (£0.36 to 14.3) billion) third. Attributable cases for ozone increased but not by as much as the avoided cases from reductions in cases for other pollutants.

The air pollution benefits were lower for WI but the ranking by health outcome was similar (Table 3). Further large benefits beyond BNZP were found for the BNZP + scenario, (Table 3, Supp A11).

The evidence behind the inputs to the calculations are more uncertain for some outcomes than others. These made a large difference to the result when added to the core analysis as a sensitivity (Table 3), including some large numbers for outcomes that can occur more than once such as ALRI and school absences. Dementia cases gave the largest numbers amongst the disease incidence outcomes. As this is a more serious outcome, dementia made the largest difference to the monetised benefits (Supp A11). The remaining sensitivities (with or without a cut-off; COMEAP recommendations for IHD and stroke, substituting $PM_{2.5}$ for NO_2 or *vice versa*) are shown in Supp A10/11.

3.4. Overall monetised benefits

The overall monetised benefits from reductions in air pollution and improvements in active travel for the policy scenarios are shown in Table 4. This shows substantial benefits for the BNZP scenario compared with BAU of £153 (122 to 184) billion for the core analysis to 2154, rising to £286 (231 to 341) billion with sensitivity functions added.

Table 2
Total life-years gained (or lost, negative numbers) and associated discounted costs across the UK population from 2019 to 2154 for $PM_{2.5}$ without a cut-off concentration, and across England and Wales for cycling and walking for the difference between BAU and BNZP, WI and between BNZP + and BNZP.

Scenario	Total life-years saved by BNZP/WI compared with BAU	Costs in £billions for life-years saved by BNZP/WI compared with BAU	Total life-years saved by WI/BNZP + compared with BNZP	Costs in £billions for life-years saved WI/ BNZP + compared with BNZP
	Central estimate (95 % Confidence Interval)			
Air Pollution ($PM_{2.5}$)[1]				
BNZP	3,810,000 (2,890,000 to 4,260,000)	77.9 (42.9 to 90.8)	–	–
WI	3,660,000 (2,770,000 to 4,090,000)	74.7 (39.4 to 84.4)	−157,000 (−119,000 to −175,000)	−3.2 (−1.7 to –3.7)
BNZP+	–	–	10,100,000 (7,670,000–11,300,000)	187.3 (117.3 to 213.9)
Cycling for transport				
BNZP	1,210,000 (714,000 to 1,730,000)	25.1 (12.8 to 37.4)	–	–
WI	1,820,000 (1,070,000 to 2,600,000)	38.2 (19.5 to 56.9)	607,000 (358,000 to 865,000)	13.1 (6.71 to 19.5)
BNZP+	–	–	217,000 (128,000 to 309,000)	3.87 (1.98 to 5.76)
Walking for transport (mainly indirect trends with a small effect of mode shift policies)[2]				
BNZP	−85,200 (−40,700 to −134,000)	−2.3 (−0.9 to −3.7)	–	–
WI	−85,200 (−40,700 to −134,000)	−2.3 (−0.9 to −3.7)	0	0
BNZP+	–	–	83,500 (41,100 to 127,000)	1.4 (0.6 to 2.3)
Total				
BNZP	4,940,000 (4,080,000 to 5,800,000)	100.7 (73.1 to 127.4)	–	–
WI	5,390,000 (4,380,000 to 6,400,000)	110.6 (81.4 to 139.7)	450,000 (195,000 to 705,000)	9.9 (3.4 to 16.2)
BNZP+	–	–	10,400,000 (8,590,000–12,200,000)	192.6 (144.2 to 241.0)

[1] $PM_{2.5}$ represents the regional air pollution mixture and some of the local mixture.
[2] Although the total number of people walking increased across an aging population (which differs by scenario due to air pollution and cycling effects), the amount of walking per person decreases giving negative results. – see Supp A9. ('For transport' excludes leisure).

Corresponding figures for 2019 to 2060 are £46.4 (37.0 to 55.9) billion and £94.4 (81.8 to 107) billion. The alternative results for 2019 to 2060, while missing some benefits, are more closely tied to policy analysis focused on the year 2050. These figures are in a discounted form ready to be compared with policy costs and other benefits in the accompanying paper (Beevers et al., 2025). The sensitivity morbidity calculations generate economic benefits that are larger than either mortality or core morbidity for the air pollutants. Supp A11 gives the total economic damage in all scenarios from 2019 to 2154, highlighting both the major benefits between the 2019 and BAU scenarios from air quality improvement policies already adopted and the significant economic and health burden even after full implementation of existing air quality measures and climate actions.

For the core functions, mortality dominates the sum of benefits to 2154. The distinction is smaller for the sum to 2060 because of the lag adopted for $PM_{2.5}$ mortality quantification: several of the core morbidity functions involve no lag or a shorter lag than that used for $PM_{2.5}$ mortality. When sensitivity functions are added in there is a small increase in mortality benefits but a much bigger increase for morbidity, such that the morbidity functions dominate in the sum of core and sensitivity benefits.

Disutility provided the largest contribution (69 %) to the overall monetised benefits for the BNZP scenario relative to BAU, including core and sensitivity functions compared with healthcare costs (26 %) and productivity costs (5 %) (Supp A11).

4. Discussion

Using complex modelling, we have shown that the health benefits from air pollution reductions from Net Zero policies compared with a realistic BAU scenario can be substantial. These are often omitted from traditional assessments of climate change policies, despite affecting the population in the short to medium term and in the area local to emission controls – differentiating them from longer-term and global effects of climate actions. Furthermore, with the increasing evidence on air pollution and incidence of disease, we found morbidity benefits substantially added to the mortality benefits.

Incidence of COPD made the largest contribution to numbers of avoided cases (due to its moderate HR, and high baseline cases), Asthma in children gave the highest monetised morbidity benefits. While the baseline cases were low (as just children), the HR was high and the monetary value was high (partly due to the long duration of disease). Potential much larger contributions were provided by some sensitivity analysis outcomes, such as dementia. Avoided incident dementia cases were unexpectedly high compared with cardiovascular cases given the hypothesis that air pollution associated dementia is secondary to the air pollution effects on cardiovascular disease (Committee on the Medical Effects of Air Pollutants (COMEAP), 2022). The high result was driven by a high CRF. The studies are recent and the outcome difficult to define, (Ford et al., 2019) adding to uncertainties in valuation. The potential size of the dementia contribution and the uncertainties discussed above emphasise the importance of more research in this area.

We also included physical activity benefits on mortality as transport policies often affect both air pollution and physical activity. The LYG across the population for increases in physical activity were modest largely because of limited exposure to physical activity from active travel assumed in the CCC scenarios and a focus on commuting in policy. However, the health benefits of increased physical activity for those who travelled more actively were substantial, showing the potential for greater benefits to new and existing walkers and cyclists by promoting and investing in active travel for all travel purposes, not just commuting. Shopping and leisure trips constitute a significant share of overall cycling and physical activity potential. Focussing on commuting alone may have led to underestimation of total benefits. Indeed, our baseline (but not the policy change) total physical activity was based on commuting and would be 4.2 (walking) and 4.8-fold (cycling) higher for all journey purposes (Supp A3). Furthermore, morbidity benefits from active travel, such as reductions in the risk of type-2 diabetes, breast cancer, and stroke, represent an area of untapped potential (Patterson et al., 2020), particularly if policies promote widespread and sustained engagement in active travel across diverse populations. We did not cover disbenefits from cycling accidents, but these are outweighed by the benefits (Mueller et al., 2015).

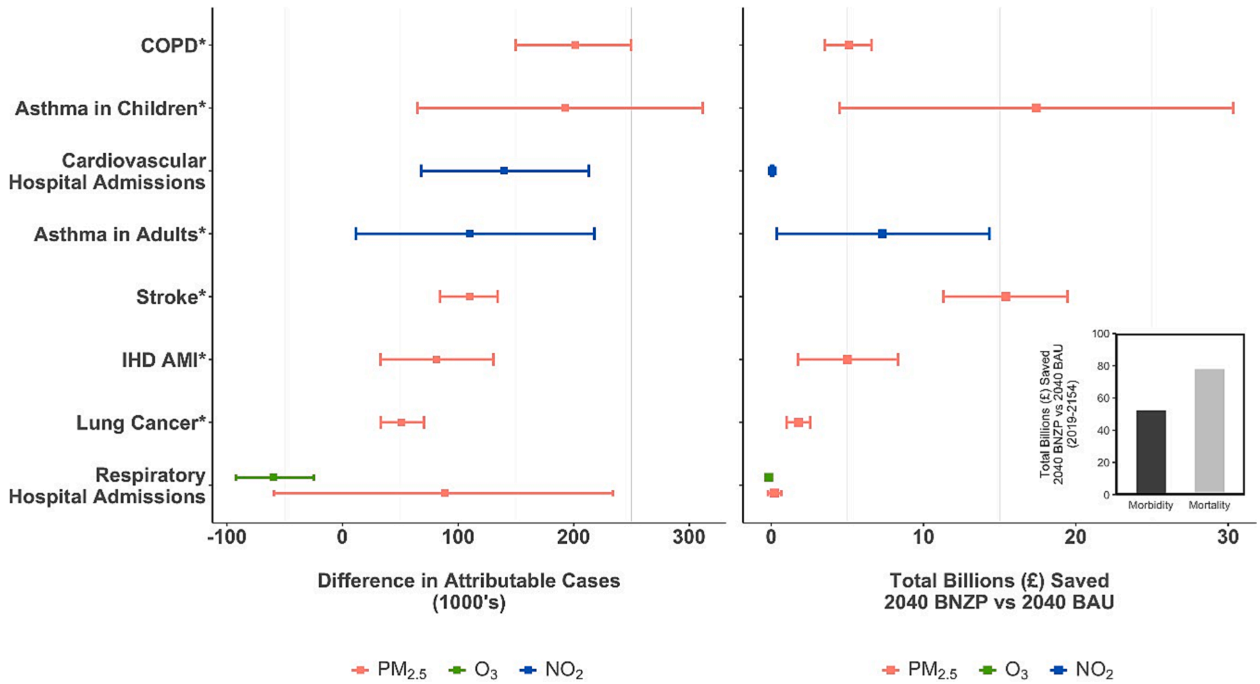

Fig. 2. Forest plot for the difference in attributable cases (in 1000′s) between BNZP and BAU scenarios from 2019 to 2154 from the reductions in $PM_{2.5}$, NO_2 and O_3 (left panel), and the corresponding difference in the monetised benefits [a] between the two scenarios (right panel). Avoided cases are positive (as a benefit).* With cut-off of 5 μg/m^3 for $PM_{2.5}$ and 10 μg/m^3 for NO_2.[a] Values are discounted. Note that using an annual mean does not imply that the mentioned benefits are the same each year – the time profile is shown in the Supplementary Material.

Table 3

Sum of cases and hospital admissions for UK 2019 – 2154 attributed to the changes in $PM_{2.5}$, NO_2 and O_3 from implementing BNZP or WI compared with each other and with BAU, and BNZP + compared with BNZP (negative numbers are cases avoided). (See Supp A11 for the results of combining these numbers of outcomes with monetary values).

Health outcome	Pollutant	BNZP vs BAU	WI vs BAU	WI vs BNZP	BNZP + vs BNZP
Core morbidity analysis					
COPD incidence*	$PM_{2.5}$	−201,000 (−250,000, −150,000)	−193,000 (−239,000, −144,000)	8,320 (6,190, 10,300)	−413,000 (−514,000, −306,000)
Asthma incidence in children*	$PM_{2.5}$	−192,000 (−311,000, −64,600)	−184,000 (−299,000, −62,000)	7,920 (2,650, 12,900)	−397,000 (−654,000, −131,000)
Asthma incidence in adults*	NO_2	−110,000 (−218,000, −11,600)	−106,000 (−209,000, −11,100)	4,240 (445, 8,440)	−61,900 (−123,000, −6,470)
Stroke incidence*	$PM_{2.5}$	−110,000 (−134,000, −84,400)	−105,000 (−129,000, −81,000)	4,450 (3,410, 5,430)	−221,000 (−271,000, −169,000)
Lung cancer incidence*	$PM_{2.5}$	−51,000 (−70,400, −33,100)	−48,900 (−67,500, −31,700)	2,100 (1360, 2,900)	−103,000 (−143,000, −66,600)
Acute myocardial infarction incidence*	$PM_{2.5}$	−81,300 (−130,000, -32,900)	−78,000 (−125,000, −31,500)	3,340 (1,350, 5,380)	−166,000 (−268,000, −66,600)
Respiratory hospital admissions	NO_2	−189,000 (−271,000, −110,000)	−177,000 (−254,000, −103,000)	11,500 (6,690, 16,500)	−299,000 (−429,000, −174,000)
Respiratory hospital admissions	O_3	60,000 (24,700, 92,400)	59,000 (24,300, 90,800)	−1,010 (−1,560, −418)	−312,000 (−481,000, −128,000)
Cardiovascular hospital admissions	NO_2	−140,000 (−213,000, −68,100)	−131,000 (−200,000, −64,000)	8,540 (4,160, 13,000)	−221,000 (−337,000, −108,000)
Sensitivity morbidity analysis[a]					
Dementia incidence*	$PM_{2.5}$	−790,000 (−1,140,000, −421,000)	−757,000 (−1,090,000, −421,000)	32,900 (18,200, 47,700)	−1,680,000 (−2,480,000, −918,000)
ALRI in children*	NO_2	−1,860,000 (−3,190,000, −616,000)	−1,790,000 (−3,060,000, −616,000)	71,600 (24,600, 123,000)	−1,020,000 (−1,760,000, −351,000)
School absences*	$PM_{2.5}$	−6,230,000 (−10,400,000, −1,950,000)	−5,980,000 (−9,940,000, −1,950,000)	255,000 (83,100, 424,000)	−12,600,000 (−20,9000,000, −4,090,000)
Diabetes incidence*	$PM_{2.5}$	−331,000 (−568,000, −99,900)	−318,000 (−545,000, −99,900)	13,200 (4,140, 22,700)	−652,000 (−1,130,000, −203,000)
Chronic phlegm	PM_{10}	−293,000 (−438,000, −26,800)	−279,000 (−417,000, −25,500)	13,900 (1,260, 21,000)	−603,000 (−933,000, −53,400)
Cardiovascular hospital admissions	O_3	5,890 (−14,800, 14,300)	5,790 (−14,600, 14,100)	−100 (−244, 253)	−30,400 (−73,800, 76,400)

* These health outcomes are calculated using a cut-off concentration of 5 μg/m^3 for $PM_{2.5}$ or 10 μg/m^3 for NO_2.

[a] Further sensitivity analyses are given in Supp. A10.

Table 4
UK monetised air quality, cycling and walking[a] benefits in billion £ (95% confidence interval), summed across time and discounted, for selected Net Zero policy scenarios.

	BNZP vs BAU		WI vs BAU		BNZP + vs BNZP[b]	
	2019–2154	2019–2060	2019–2154	2019–2060	2019–2154	2019–2060
	Core analysis					
Mortality	101 (73.1 to 127)	25.9 (19.0 to 32.9)	111 (81.4 to 140)	30.7 (22.5 to 38.9)	193 (144 to 241)	21.7 (15.9 to 27.5)
Morbidity	52.1 (36.4 to 67.8)	20.5 (14.3 to 26.7)	50.0 (34.9 to 65.1)	19.6 (13.7 to 25.5)	84.9 (59.3 to 110.4)	20.3 (14.2 to 26.4)
Total	153 (122 to 184)	46.4 (37.0 to 55.9)	161 (128 to 194)	50.3 (40.1 to 60.6)	277 (221 to 334)	42.0 (33.4 to 50.5)
	Sensitivity analysis for additional health outcomes					
Morbidity and long term ozone mortality	128 (83.6 to 172)	46.2 (30.2 to 62.2)	122 (79.7 to 164)	44.2 (28.9 to 59.5)	288 (188 to 388)	54.4 (35.5 to 73.3)
Total	278 (228 to 334)	92.6 (74.2 to 111)	283 (230 to 336)	94.5 (76.3 to 113)	566 (452 to 679)	96.4 (75.9 to 117)

[a]The walking and cycling portion of the results is for England and Wales not UK.
[b]This column is not directly comparable to the first two because there is no business-as-usual comparator. Instead, it represents the further benefits beyond BNZP.
[c]Further sensitivity analysis results are given in Supp. A11.

Our active travel analysis uses fine-scale spatial origin–destination data obtained from the UK Census combined with GIS-based routing algorithms that account for gradients and infrastructure, providing a robust foundation for capturing local commuting patterns and demographic characteristics at the level of LSOAs. This ensures that our estimates are grounded in observed commuting behaviours rather than generalised assumptions.

Direct comparison with results from other studies is difficult because the policy scenarios, counterfactuals and follow-up periods differ. Milner et al. (2023a) found 4.8 million LYG for a different selection of 6th Carbon Budget policies, but the counterfactual for their analysis was maintaining 2020 concentrations unchanged rather than a BAU scenario. So, the most appropriate comparison in our results is with the 17.5 million LYG for BNZP compared with 2019 (Supp A9). Inclusion of changes in indoor $PM_{2.5}$ would increase their results relative to ours, but most other factors would decrease them (E&W vs UK; shorter follow-up (to 2100); and smaller $PM_{2.5}$ concentration changes). The latter could be due either to different policies or the simpler concentration modelling method. It is unclear whether the $PM_{2.5}$ CRF was larger or smaller as they used a non-linear function.

Using the same version of the 6th Carbon Budget as our study but focusing on road transport sources only, Dajnak et al. found a lower 11.5 million LYG (BNZP vs 2018) across a shorter period (2018–2134) (Dajnak et al, 2022). Previously, we found 4.8 million LYG for climate change policies preceding Net Zero, (Williams et al., 2018) using an earlier recommended CRF. The remaining studies (Supp A1) used number of deaths rather than LYG, which is less appropriate for long-term policies.

Most previous studies did not include morbidity. Dajnak et al. (Dajnak et al, 2022) quantified morbidity outcomes using WHO (2013) recommendations, (World Health Organization, 2013) and a constant population at risk. We used population at risk from the lifetable analysis and newer WHO recommendations with more CRFs for incidence of disease (Forastiere et al., 2024). A direct comparison is complex, but our monetised benefits are likely to be larger. Other studies including morbidity were not UK-wide and covered fewer outcomes (Milner et al., 2023b; Baldo et al, 2023).

The relative importance of air quality and active travel benefits compared with other climate effects in terms of cost-benefit analysis is explored in a companion paper (Beevers et al., 2025). This shows that for the purpose of CBA following UK guidelines, general GHG abatement benefits dominate but additional benefits from improved air quality bring forward time to break even of costs and benefits and enhance benefit-cost ratios. The structural change inherent in the policies investigated suggest that the policies will continue to generate benefits into the far future.

5. Strengths and limitations

We used cutting edge regional modelling of air quality, physical activity and realistic business as usual, and Net Zero policies based on discussions with policymakers. The accuracy of the modelling relies on the planned emissions reductions happening, which is not always the case.

A key strength of this study is the inclusion of recent evidence on air pollution and incidence of disease based on systematic reviews assessed for quality by Forastiere et al (Forastiere et al., 2024).

Methodological strengths included baseline birth/mortality projections in the lifetables; dynamic population changes in morbidity calculations; combining air pollution and physical activity mortality impacts; allowing for mortality rate variations by LA and examining the relationship with the Carstairs index.

The end-year was chosen as 2154, a lifetime following the last policy implementation year of 2050, assuming no change in pollution concentrations beyond 2050. This ensured capturing all the benefits and although uncertain, this was mitigated to some extent by discounting, which reduced the influence of very long-term benefits. Alternatively, truncating analysis to 2050, corresponding to the analysis provided by the CCC, (Committee on Climate Change (CCC), 2020) brings its own uncertainties by missing lagged effects of exposures to air pollutants and the long-term benefits of structural change to energy and transport systems. Consideration of effects over a much longer period also gives freedom to investigate the sensitivity of conclusions to different assumptions on end-year.

The approach used for valuation of impacts allows disaggregation to health care costs, productivity change and utility. Basing estimates on recent UK studies for each condition has the strength of relevance to the target population but limits the data on which valuations are based. The largest uncertainty for valuation lies in the correspondence of impact (severity, duration, etc.) defined within air pollution epidemiology and within valuation work, an area where further work is required.

While we modelled concentrations at a fine spatial scale, concentrations were aggregated for the health calculations due to morbidity data availability. However, our population-weighting retained some fine scale information. The SES analysis was conducted by LA although deprivation can vary within this scale.

Despite having new CRFs for disease incidence, sourcing baseline rates is a challenge with a lack of formal or local statistics. Using mortality and hospital admission data as a proxy for AMI and stroke incidence (Supp A6) required checking for no previous admissions to ensure first events, a more complex approach than direct recording of incidence data, if the latter had been available. There was only a single quote for bronchiolitis rates within ALRI in children; using pneumonia in children would be preferable. These challenges are discussed further in Supp A6 and work on providing routine statistics on incidence is required.

Our calculations allowed for incidence and prevalence decreasing due to air pollution reductions, but the population at risk (those without disease) increasing. There was a lack of information on age dependent incidence, but this could potentially be modelled in future work.

Our air pollution concentration–response functions were based on outdoor air epidemiology. These cannot be applied directly to changes in indoor concentrations, which we also modelled, (Beevers et al., 2025) because outdoor and indoor concentrations act differently as a proxy for personal exposure and adjusting for this has substantial caveats (Milner et al., 2023a; Committee on the Medical Effects of Air Pollutants (COMEAP), 2023b).

We only quantified changes in health effects for $PM_{2.5}$, NO_2 and ozone but not other pollutants such as sulphur dioxide and carbon monoxide. CRFs are potentially available (O'Brien et al., 2023; Lee et al., 2020); although some of the effects may already be reflected indirectly through correlation with the pollutants that are included. These omitted pollutants are relatively less studied and the range of health outcomes included would be lower, particularly for CO which is only linked to cardiovascular outcomes. In determining the likely size of omitted health impacts, the likely concentration changes are also important. These were not modelled but emissions changes are set out in Assareh et al (2024), primary SO_2 emissions were incorporated in the modelling of sulphate concentrations within $PM_{2.5}$ (which can be more significant than the effect on SO_2 concentrations) and CO emissions were included within the modelled atmospheric chemistry for e.g. ozone. SO_2 concentrations are already generally low and CO concentrations have also reduced significantly since the adoption of catalytic converters. We also did not include health impacts calculations using CRFs for $PM_{2.5}$ constituents separately but considered these to be covered by the CRFs for $PM_{2.5}$ overall. While it would be useful to incorporate calculations on these omitted pollutants in future work, we do not believe the health impacts would be major compared with those that have already been covered.

Limitations of our active travel analysis include its reliance on somewhat outdated UK Census data, focus on commuting while excluding other travel purposes, and simplified origin–destination estimates that may not capture actual routes. It incorporates limited sociodemographic variables, such as age and gender, while omitting factors like income, health, safety, and cultural preferences that influence travel behaviour. Additionally, its assumptions about future infrastructure improvements and behaviour change may be overly optimistic, reflecting ambitious policy goals rather than guaranteed outcomes.

Despite the above limitations, we performed a sophisticated analysis showing both the advantages of including air pollution (and physical activity) health impacts in assessment of climate change policies and in including results on air pollution and disease incidence. The results are compared with the policy costs in our companion paper (Beevers et al., 2025). Our methods can be followed to provide more complete assessments of climate change policies internationally.

6. Data sharing statement

The base year 2019 emissions (https://naei.beis.gov.uk/) and UK air pollution measurements (https://uk-air.defra.gov.uk/networks/network-info?view = aurn) are freely available, as are the WRF (https://www.mmm.ucar.edu/models/wrf) and CMAQ model code (https://www.epa.gov/cmaq/access-cmaq-source-code). Where population, deaths or health incidence and prevalence data were derived from published statistics e.g. scaled by age, these can be provided by contacting the corresponding author. Maps of results by local authority are also available on request. The Small Area Health Statistics Unit does not have permission to supply data to third parties.

CRediT authorship contribution statement

Heather Walton: Writing – review & editing, Writing – original draft, Software, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **David Dajnak:** Writing – review & editing, Visualization, Supervision, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation. **Mike Holland:** Writing – review & editing, Software, Methodology, Investigation, Formal analysis, Data curation. **Dimitris Evangelopoulos:** Writing – review & editing, Software, Methodology, Investigation, Formal analysis, Data curation. **Dylan Wood:** Writing – review & editing, Software, Methodology, Investigation, Formal analysis, Data curation. **Christian Brand:** Writing – review & editing, Software, Methodology, Investigation, Formal analysis, Data curation. **Nosha Assareh:** Writing – review & editing, Software, Methodology, Investigation, Formal analysis, Data curation. **Gregor Stewart:** Writing – review & editing, Software, Methodology, Investigation, Formal analysis, Data curation. **Andrew Beddows:** Writing – review & editing, Software, Methodology, Investigation, Formal analysis, Data curation. **Shawn YC Lee:** Writing – original draft, Writing – review & editing, Methodology. **Daniela Fecht:** Writing – review & editing, Visualization, Supervision, Project administration, Methodology, Investigation, Formal analysis, Data curation. **Yunzhe Liu:** Investigation, Formal analysis, Data curation. **Bethan Davies:** Writing – review & editing, Methodology, Data curation. **Anna Goodman:** Methodology, Formal analysis, Data curation. **Tuan Vu:** Writing – review & editing, Software, Methodology, Investigation, Formal analysis, Data curation. **Sean Beevers:** Writing – review & editing, Validation, Supervision, Software, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: [Mike Holland reports a relationship with UK Research and Innovation that includes: consulting or advisory. Mike Holland reports a relationship with UK Department for the Environment, Food and Rural Affairs that includes: consulting or advisory. Mike Holland reports a relationship with World Health Organization that includes: travel reimbursement. MH and HW are current and former members of the UK Committee on the Medical Effects of Air Pollutants (COMEAP) (unpaid). DE is a co-opted member of the Quantification of Air Pollution Risk (QUARK) sub-group of COMEAP and an associate member of COMEAP (unpaid). SB is a member of the UK Air Quality Expert Group. MH is also an unpaid member of Member of the Evaluation Council of the Green OAT (Obligations Assimilables du Trésor). MH received payment as a freelance consultant from UKRI (EU Horizon Programme (2023–2025), VALESOR Project); Defra (SNAPCS project; Vice-chair of EMEP under UNECE Convention on Long-range Transboundary Air Pollution) and WHO (Task Force for Health meeting 2023). HW was an unfunded member of the WHO EMAPEC project team. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper].

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The views expressed are those of the author(s) and not necessarily those of the NHS, NIHR, UKHSA, HSE, Department of Health and Social Care, or Imperial College London.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2025.109283.

Data availability

Some data is available on request. Some data cannot be shared e.g. due to risk of personal identification.

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Glossary

Air pollution: Consists of gases such as nitrogen dioxide and ozone and particulate matter.

BAU: Business as usual In this research BAU refers to future emissions projections which include all currently agreed UK air quality policy but exclude the impact of clean air zones.

BNZP: Balanced Net Zero Pathway (BNZP), a 'middle ambition' pathway for compliance with UK Net Zero commitments by 2050, which is predicted to reduce greenhouse gas emissions to 78% below 1990 levels by 2035.

CCC: Climate Change Committee, an independent advisor to UK Government on achieving Net Zero.

CMAQ: Community Multiscale Air Quality model a state of the science chemical transport model used to predict air quality.

COMEAP: Committee on the Medical Effects of Air Pollutants. It is a panel of experts that provides independent advice to the UK government on the health effects of air pollution.

CRF: Concentration-response function. The slope of the relationship between air pollution concentrations and a health effect response. Can be used to calculate changes in numbers of health outcomes for particular concentration differences.

Defra: UK Department for the environment, food and rural affairs. Part of Defra's remit is environmental protection, where it develops policies and enforces regulations aimed at protecting the environment, including air and water quality, waste management, and wildlife conservation.

DESNZ: the Department for Energy Security and Net Zero. It is a UK government department responsible for ensuring energy security and driving the transition to net-zero emissions.

DfT: the Department for Transport. It is a UK government department responsible for overseeing the transportation system across England, including roads, railways, aviation, and maritime transport.

EMAPEC: WHO project on Estimating the morbidity from air pollution and its economic costs

Exposure-response function: definition as for concentration–response function except that it refers to risk factors more widely, including those such as physical activity where exposures are not measured as concentrations.

LYG/LYL: Life-years gained/life-years lost. A life-year is one year lived for one person. Life-years are then summed across the population and over time.

MET: Metabolic equivalent the ratio of the work metabolic rate to the resting metabolic rate. Used as a measure of the intensity of exercise.

Net-zero emissions: The IPCC consider net-zero emissions to be achieved when anthropogenic emissions of GHGs such as CO_2 are balanced by anthropogenic removals over a specified period.

Nitrogen oxides (NOx): NOx (NO and NO_2) are produced in combustion processes, from nitrogen in the fuel, but mostly by direct combination of oxygen and nitrogen in flames. NOx are also produced by lightning and by microbial processes in soils. NOx contributes to environmental effects such as acid rain and eutrophication as well as ozone formation and aerosol effects. NO_2 is associated with adverse effects on human health.

Nitrogen Dioxide (NO_2): See nitrogen oxides

Ozone (O_3): O_3 in the troposphere is formed by photochemical reactions between NOx and VOC compounds. O_3 is a powerful oxidant and causes damage to mucous and respiratory tissues in animals and humans.

Particulate matter (PM): refers to airborne mixtures of small solid particles and liquid droplets. PM is often categorised as PM2.5 (particles with a diameter smaller than 2.5 μm) and PM10 (diameter smaller than 10 μm). Some particles are emitted directly from a source, others as a result of complex reactions of chemicals in the atmosphere. On current evidence PM2.5 particles pose the greatest risk to health.

TfL: Transport for London. It is a local government body responsible for managing the transportation system in Greater London, including public transit, roads, and cycling infrastructure.

UKHSA: UK Health Security Agency. It is a UK government agency responsible for public health protection and health security, including the prevention and response to health threats such as infectious diseases and environmental hazards.

WHO: World Health Organization A specialized agency of the United Nations responsible for international public health.

WI: Widespread Innovation (WI) pathway, which assumes greater success in reducing costs of low-carbon technologies, allowing more widespread electrification, and is important for the effects of active transport.

WRF: Weather Researching and Forecasting model a meteorological model used in this research alongside CMAQ to prediction current and future air pollution