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Synopsis

The air quality, health and economic costs and benefits of a zero carbon UK: a comprehensive synopsis

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Abstract

Background: Net Zero policies rarely consider air quality and physical activity health cobenefits, cost–benefit analysis, exposure indoors and exposure inequalities.

Objectives To calculate the air quality, health and economic costs and benefits of United Kingdom Net Zero policy, impacts on inequalities and consult the public on the acceptance of Net Zero policy.

Design and methods: We used sophisticated emissions and air quality models, Life Table health impact analysis, United Kingdom Government cost–benefit methods and estimated exposure inequalities. We compared 2030 and 2040 United Kingdom PM_{10}, $PM_{2.5}$, nitrogen dioxide and ozone predictions using existing air quality policy, or Business as Usual, with Net Zero policy. We predicted Net Zero 2050 pollutant concentrations.

Interventions: Business as Usual scenarios were from United Kingdom Government projections and Net Zero scenarios were from the Climate Change Committee's sixth Carbon Budget. We used the Balanced Net Zero and Widespread Innovation Pathways for road transport, building heating and active travel.

Main outcome measures: United Kingdom air pollution, including exposure inequalities, mortality, morbidity and economic costs and benefits.

Results: *Air quality:* Under Business as Usual, nitrogen dioxide and particulate matter reduced by 2030 due to new vehicles. The 2040 Balanced Net Zero Pathway and Widespread Innovation scenarios showed further reductions, driven by electric vehicle uptake, reduced vehicle kilometre travelled compared with Business as Usual, and low-carbon building heating. Particulate matter reductions from buildings was two and three times greater than from road transport, for Widespread Innovation and Balanced Net Zero Pathways, respectively. Balanced Net Zero Pathway+ 2050 predictions showed additional air pollution benefits.

Exposure inequalities analysis: In 2019, *urban central professionals* experienced 14 $\mu g\ m^{-3}$ higher nitrogen dioxide concentrations than *rural elderly*. At 1.5 $\mu g\ m^{-3}$, $PM_{2.5}$ concentrations varied less across geodemographic groups. Despite future improvements in nitrogen dioxide, inequalities persisted, but were less pronounced, due in part to Net Zero policies.

Indoor air pollution: Removing gas cooking at home for Net Zero may result in greater nitrogen dioxide reductions than changes in outdoor air pollution.
Health and active travel impacts: Compared with Business as Usual, Balanced Net Zero Pathway gave 4.9 (95% confidence interval 1.0 to 9.0) million life-years gained across the United Kingdom, to 2154, including 1.1 (95% confidence interval 0.7 to 1.6) million life-years gained from active travel. Avoided chronic obstructive pulmonary disease and childhood asthma cases were 201,000 (95% confidence interval 150,000 to 250,000) and 192,000 (95% confidence interval 64,600 to 311,000). Monetised morbidity benefits of £52.1B (95% confidence interval 36.4 to 67.8) added significantly to mortality benefits of £77.9B (95% confidence interval 42.9 to 90.8). Total yearly air pollution and active travel benefits were £153B (95% confidence interval 122 to 184), rising to £278B (95% confidence interval 228 to 334), including outcomes with weaker evidence.
Costs/benefits: Building sector Balanced Net Zero Pathway air quality health benefits were £21.3B (95% confidence interval 16.4 to 26.2) by 2050 and were £98.4B (95% confidence interval 75.7 to 121.1) by 2154. Transport benefits were £9.1B (95% confidence interval 7.0 to 11.2) by 2050 and were £36.5B (95% confidence interval 28.1 to 44.9) by 2154. Balanced Net Zero Pathway building sector operating costs alone did not achieve break-even, but with greenhouse gases reductions (lower benefits) break-even was achieved by 2052. Air pollution health benefits reduced the building sector time to break-even by between 3.1 (95% confidence interval 2.5 to 4.7) and 6.3 (95% confidence interval 4.7 to 7.6) years.
Public engagement: Conversations reflected an intergenerational commitment to Net Zero policies, although there was uncertainty about an individual's impact.
Limitations: Uncertainties in future air quality and meteorological conditions; through lack of evidence, being unable to use multipollutant models and indoor air pollution, missing indoor health and monetised benefits; some health outcomes with weaker health evidence strongly influenced the results. The COVID pandemic prevented us from exploring social acceptance as planned.
Conclusions: This study identified health and economic cobenefits through reductions in greenhouse gases, air pollution, inequalities and increased exercise.
Future work: To separately evaluate the health and monetary impacts of indoor and outdoor air pollution; to understand the overlapping effects of $PM_{2.5}$ and nitrogen dioxide health impacts; to develop effective ways of communicating the health and economic benefits and to increase the social acceptability of Net Zero.
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Introduction

Background and rationale

Globally, air pollution is considered on a par with risk factors, such as tobacco smoking and unhealthy diets, and is the largest environmental risk to human health in the UK, contributing to 29,000–43,000 premature deaths annually.[5,6] Air pollution has detrimental effects on heart disease, stroke, cancer, asthma exacerbation, mortality and children's lung development, and while outdoor air pollution is improving, health risks remain.[5,7,8] However, the recent Chief Medical Officer's report stated that people spend more than 90% of their time indoors and that the contribution from indoor sources is increasingly important for public health.[9]

There is a simultaneous global need to mitigate climate change through reductions in greenhouse gas (GHG) emissions, as highlighted by the Intergovernmental Panel on Climate Change (IPCC) Synthesis Report,[10] with the UK committing to achieving Net Zero (NZ) GHG emissions by 2050, and with legally binding targets in line with the Paris agreement and ratified at the Conference of the Parties (COP21) in 2015.[11] The independent Climate Change Committee (CCC) provides advice to the UK government on how to achieve NZ targets, with the most recent being the Sixth Carbon Budget.[12]

Given the numerous common sources being targeted, policies aimed at tackling climate change and attaining NZ emissions could have substantial benefits on air pollution, offering one of the greatest global public health opportunities of the twenty-first century.

Aims and objectives

This project compared the impacts of existing UK Air Quality Policy or Business as Usual (BAU), with BAU plus the CCC's Balanced Net Zero Pathway (BNZP) and Widespread Innovation (WI) pathway in 2030 and 2040, focusing on road transport, building heating and active travel. BNZP and WI encourage larger uptake of electric vehicles (EVs) into the vehicle fleet, with less vehicle km travelled and more active travel than BAU. The WI scenario has greater emphasis on active travel, with over six times the bike use compared with BAU (albeit from a small base). BNZP requires a switch to electricity to heat buildings and removal of fossil fuel burning at home, such as using gas for cooking. We also predicted for 2050 using BNZP predictions for roads, buildings and active travel, plus changes to other air pollution sources from the UK and Europe. We assessed the changes to $PM_{2.5}$, PM_{10}, ozone (O_3) and nitrogen dioxide (NO_2) and their public health impacts, economic costs and benefits and exposure inequalities. We addressed the following aims and research questions:

1. To provide a comprehensive assessment of emissions, air quality, health and economic costs and benefits for each scenario to help answer the question:
    a. How can the UK's public health and economic burden from air pollution in 2030–40 and 2050 be reduced by the introduction of the NZ climate policies?
2. To engage with a large range of stakeholders to assess:
    a. What is the social acceptance of these policies across demographic and socioeconomically different parts of society?

    Note: Due to the COVID pandemic, we were unable to consult with a large range of stakeholders as originally planned and, with National Institute for Health and Care Research (NIHR) agreement, amended this aim, including creating a film with students from inner-city London and rural Scotland on the uneven impacts of air pollution and NZ policies – see the work described in *Patient and public involvement*.
3. Provide a comprehensive assessment of impacts of different urban, rural socioeconomic and ethnic groups to answer:
    a. Is the burden/benefit of climate policies equally distributed across the population or do policies favour/disadvantage certain parts of the population?
4. To what extent do the additional health benefits of UK climate action, studied in this project, change the benefit/cost ratios and does this increase the acceptability for policy-makers and improve the likelihood of early adoption of these policies?
5. From one above to answer, what impact do individual actions have on air pollution and what can people do to reduce their contribution and exposure to it?

Throughout the project, we engaged with patients, the public and school children in understanding their knowledge, perceptions and acceptance of NZ policies, details of which are given in *Patient and public involvement*. Early in the project, we defined the present and future emissions for 2019, 2030 (BAU/BNZP/WI), 2040 (BAU/BNZP/WI) and 2050 (BNZP+) and then predicted UK air pollution concentrations for each – see Assareh *et al.*[1] in *Table 1*. The air pollution concentrations were then used in the health impact modelling of mortality, multiple morbidity outcomes and active travel, and including monetary benefits – see Walton *et al.*[2] in *Table 1*. The air pollution scenarios were also used to assess present and future changes in exposure inequalities, as well as developing new socioeconomic groupings – see Liu *et al.*[3] in *Table 1*. Finally, a cost–benefit analysis (CBA), indoor air pollution analysis and socioeconomic impacts analysis was undertaken – see Beevers *et al.*[4] in *Table 1*.

Discussion/interpretation

The following section provides the principal results relating to each of the four papers described in *Table 1*.

Principal results 1: Net Zero impacts on air pollution

Results of the air pollution modelling are based upon the Assareh *et al.*[1] paper 'What Impact Does Net Zero Action on Road Transport and Building Heating Have on Exposure to Air Pollution?'. The following findings come from the abstract of Assareh *et al.*[1]

This study explores the cobenefits of reduced NO_2, O_3 and particulate matter (PM) through NZ climate policy in the UK. Under UK existing policy, BAU, reductions in NO_2 and PM were predicted by 2030 due to new vehicle technologies, but plateau by 2040. The BNZP and

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TABLE 1 Publication outputs

Paper title	Journal	Lead author	Link to publication	Reference number
What impact does Net Zero action on road transport and building heating have on exposure to UK air pollution?	*Environmental Science and Technology*	Nosha Assareh	https://doi.org/10.1021/acs.est.4c05601	
Health and associated economic benefits of reduced air pollution and increased physical activity from climate change policies	*Environment International*	Heather Walton	https://doi.org/10.1016/j.envint.2025.109283	
Impact of net zero policy scenarios on air pollution inequalities in England and Wales	*Environment International*	Yunzhe Liu	https://doi.org/10.1016/j.envint.2024.109065	
Climate change policies reduce air pollution and increase physical activity: benefits, costs, inequalities, and indoor exposures	*Environment International*	Sean Beevers	https://doi.org/10.1016/j.envint.2024.109164	Beevers *et al.*[4]

WI scenarios predict further reductions particularly by 2040, driven by accelerated EV uptake and low-carbon heating in buildings, with the building contribution to PM reduction being two and three times greater than road transport, for WI and BNZP, respectively. The results demonstrate that the NZ transition to EVs (cars and vans) reduces both exhaust and non-exhaust emissions, as well as reducing traffic volumes, compared with the BAU scenarios. O_3 trends are complex, with a small overall increase by 2030 and a decrease by 2040. Although uncertain, 2050 predictions of BNZP showed important additional air pollution benefits. Our findings highlight the efficacy of NZ strategies, providing insights for UK and international policy-makers interested in the air pollution cobenefits of climate policy.

Principal results 2: health and economic benefits resulting from Net Zero policies

The outputs of the air pollution modelling work were incorporated into the Walton *et al.*[2] paper entitled 'Health and associated economic benefits of reduced air pollution and increased physical activity from climate change policies'. The following findings come from the abstract and results section of Walton *et al.*[2]

The BNZP policy compared with BAU gave 4.9 [95% confidence interval (CI) 1.0 to 9.0] million life-years gained (LYG) for the UK population to 2154, including 1.1 (95% CI 0.7 to 1.6) million LYG from active travel improvements. Avoided chronic obstructive pulmonary disease and childhood asthma cases were 201,000 (95% CI 150,000 to 250,000) and 192,000 (95% CI 64,600 to 311,000). Avoided cases in a wide range of other outcomes were also quantified, including incidence of other respiratory diseases {asthma in adults [110,000 (95% CI 11,600 to 218,000)] and lung cancer [51,000 (95% CI 33,100 to 70,400)] and cardiovascular disease such as stroke [110,000 (95% CI 84,400 to 134,000)], acute myocardial infarction [81,300 (95% CI 32,900 to 130,000)]}. Some outcomes with weaker evidence for the health effect (e.g. dementia and diabetes) or for the baseline rates (acute lower respiratory infections in children) were included in the sensitivity analysis. The total (i.e. core and sensitivity analysis) monetised air quality morbidity benefits of £52.1B (95% CI 36.4 to 67.8) were comparable with the air quality mortality benefits of £77.9B (95% CI 42.9 to 90.8). Total yearly monetised benefits for BNZP versus BAU summed to 2154 for air pollution and active travel were from £153B (95% CI 122 to 184) up to 278 (95% CI 228 to 334), including outcomes with weaker evidence. There were higher physical activity benefits for WI than BNZP.

Principal results 3: impact of Net Zero policies on inequalities

Through the creation of new geodemographic groups, novel socioeconomic analysis was developed in the Liu *et al.*[3] paper entitled 'Impact of net zero policy scenarios on air pollution inequalities in England and Wales'. The following findings come from the abstract of Liu *et al.*[3]:

> Urban central professionals experienced 14 µg/m^3 higher average NO_2 concentrations compared with rural elderly in 2019. Despite substantial improvements to air quality in 2030 and 2040 of up to 6.3 µg/m^3 for NO_2 based on BAU, and further reductions of up to 2.4 µg/m^3 NO_2 under NZ policies, the overall pattern of inequality persists, but it is predicted to be less pronounced.
> Our findings demonstrate the effectiveness of targeted policies and innovations in reducing both air quality and GHG emissions and in bridging the environmental inequality gap. They are also essential to develop targeted communication campaigns to secure acceptance and willingness across the sociodemographic spectrum to support the significant behavioural changes needed to achieve NZ, by highlighting the wider cobenefits to the environment and health of such policies.

Principal results 4: cost–benefit analysis, indoor air quality and further assessment of inequalities

We combined the monetised health benefits from the Walton paper[2] with costs associated with implementing the policies to produce a CBA, plus an assessment of indoor air quality and exposure inequalities. All of these were summarised in the Beevers *et al.*[4] paper entitled 'Climate change policies reduce air pollution and increase physical activity: benefits, costs, inequalities, and indoor exposures'. The following findings come from the abstract of Beevers *et al.*[4]

Compared to BAU predictions, BNZP assumptions lead to more EVs, reduced vehicle kilometers, more low-carbon building heating and reduced emissions of NO_2 and $PM_{2.5}$. By 2040 under BNZP, relative to BAU, the building sector was predicted to be three times more effective at reducing $PM_{2.5}$ than road transport. To help reduce the inequality gap, the NZ building transition was tailored towards those most in need. Outdoor air pollution exposure inequalities prevailed across the socioeconomic spectrum, especially for NO_2, but were less pronounced due in part to NZ policies. Core air quality health benefits for the BNZP building sector were £21.3B (16.4 to 26.2) by 2050 and £98.4B (75.7 to 121.1) by 2154. For the transport sector, the health benefits were £9.1B (7.0 to 11.2) by 2050 and £36.5B (28.1 to 44.9) by 2154. NZ building sector operating costs did not achieve break-even via efficiency savings, but with GHG reductions (lower benefits), break-even was achieved in 2052. With additional air pollution health benefits, the building sector time to break-even improved by between 3.1 (2.5 to 4.7) and 6.3 (4.7 to 7.6) years, between 2046 and 2049.

Analysis found that removing gas cooking at home, for NZ, may result in greater concentration reductions than outdoor air pollution for NO_2. NZ health and economic cobenefits are large, as are the changes needed. Our findings are relevant to other countries facing the NZ transition.

Contribution to existing knowledge

There have been relatively few studies published on NZ and air pollution cobenefits in the UK, and none of these compare existing air quality policy (BAU) and NZ alternatives. This report and associated papers are therefore highly relevant to policy-makers and should support those who advocate for the transition to NZ, both in the UK and internationally. Through our analyses, we have added the following important findings to existing knowledge.

1. NZ has additional benefits of reducing air pollution and improving people's health beyond BAU. NZ policy may therefore serve as a potential 'back-up' if BAU does not achieve all its intended goals, for example, if vehicle-related NO*x* emissions do not fall as predicted in the BAU plan.
2. EV uptake among light-duty vehicles will be beneficial for air pollution, even for non-exhaust PM emissions. This was established having made use of new measurement data.[13,14]
3. PM emissions reductions from households in 2040 is a factor of two or three times more important than road transport for reducing $PM_{2.5}$ outdoor concentrations, for the WI and BNZP scenarios, respectively.
4. Future exposure inequalities across the full range of socioeconomic groups reduces over time, and that this is in part because of NZ policies.
5. The monetary benefits of air pollution reductions are large and make an important contribution to achieving break-even, particularly in the building sector.
6. The monetary benefits of reducing air pollution-related morbidity constitute a substantial proportion of the mortality benefits, because of new evidence related to air pollution effects over a wider range of morbidity health outcomes.
7. That the air pollution mortality benefits of $PM_{2.5}$ changes are greater than for active travel, due to everyone benefiting from clean air, compared with the relatively small numbers of people who increase their active travel through NZ policy. There is also a lack of ambition for walking in the NZ scenario projections.
8. That indoor air pollution can be reduced by removing fossil fuel use, such as gas for cooking, and that these changes can be larger than the changes in outdoor air pollution alone, especially for NO_2.
9. That health, economic and inequality benefits from air pollution reduction and active travel can help justify NZ policy, demonstrating the value of the transition despite concerns around uncertainty and unaffordability, especially in light of recent cost-of-living issues.

Recommendations for future research

There are several areas deserving of future research, including:

1. To develop methods to separately evaluate the health and monetary impacts of indoor and outdoor air pollution, which is limited because of the complexity and heterogeneity of indoor exposure as well as the lack of health evidence from epidemiological research into indoor air. This is despite us demonstrating that indoor air benefits of NZ policies may be significant.

2. Assessing the impacts of a targeted NZ transition in the home for those most in need, such as the fuel-poor or those in social housing, addressing issues such as the affordability of home heating, cold, damp and mouldy homes.
3. To quantify and reduce the uncertainties in future emissions and air pollution model predictions, incorporating more robust assumptions and assessing the impacts of uncertainty on policy outcomes and advice.
4. To improve research on baseline rates for incidence of disease, as these often had to be inferred indirectly for use in the health impact calculations. This would have advantages for many other fields as well.
5. To understand the extent to which the addition of effects for $PM_{2.5}$ and NO_2 double counts impacts. The approach used here, where results for these pollutants were not combined for the same impact (e.g. mortality) avoids double counting but may lead to underestimation of health benefits. From our results, this was particularly important for transport benefits.
6. To develop and model more comprehensive NZ + Air Quality (AQ) + Active Travel (AT) scenarios that include a wider range of policies and measures, including societal and behaviour change strategies[15] that target the highest polluters (older diesel cars and vans, frequent fliers/drivers, etc.) and walking for transport.[16]
7. Finally, more thought is needed to develop effective ways of communicating the health and economic benefits of NZ, tackling strongly held views that often oppose environmental change, and to provide a narrative to the population, fostering support for this important transition.

Strengths and weaknesses

Since the health impacts of NZ policy were primarily driven by $PM_{2.5}$, we used a state-of-the-science chemical transport model (CTM) discussed elsewhere.[1] $PM_{2.5}$ is a spatially and temporally complex mixture with both primary (e.g. vehicle exhaust) and secondary (created from gaseous pollutants through atmospheric chemistry) sources, is both anthropogenic and biogenic in origin, and is emitted locally, across the UK and in Europe. Our model provided pollutant concentrations every 20 m, including close to roads, which is particularly important for highly spatially variable pollutants such as NO_2, and hourly O_3 predictions, required for health impact assessment. The complex interplay of sources and atmospheric processes is challenging to replicate in a CTM and the results presented here should be considered with model uncertainty in mind.

Our detailed emissions modelling approach allowed the NZ scenarios to be implemented geographically and with consideration of socioeconomic factors. In our scenarios, the installation of low-carbon heating prioritised homes with poor energy efficiency, the fuel-poor, those least able to pay and those in the private rented sector, working towards the wealthiest owner-occupiers. This enabled us to better reflect an equitable policy whereby those most in need are helped earlier to make the transition towards NZ.

Our findings are impacted by several sources of uncertainty, including representing highly complex atmospheric chemistry and physics in a model, emissions data and meteorological conditions. Furthermore, there are uncertainties in the assumptions underpinning emissions forecasts and scenario projections, such as the adoption rates of EVs and advancements in renewable energy technologies. These factors, coupled with changes in policy implementation and behaviour, also influence the accuracy of our predictions. The comparison between existing BAU and BNZP/WI is a strength but assumes that future BAU target emissions reductions would be achieved, which, from experience over previous decades, may not be the case.

A key strength of the health impacts 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.*[17] We included birth projections and mortality rate improvements in the lifetables and incorporated population changes over time in morbidity calculations. We included air pollution and physical activity mortality impacts within the same study, allowing for mortality rate variations by local authority and examining the relationship with the Carstairs index.

The extension of CBA and health analysis to the very long periods (to 2154) considered here is unusual, with the period for analysis for most climate policies being to 2050. However, a long follow-up period is not unusual in health impact assessment,[18] and shorter periods bias the analysis, given that they do not capture the full benefits of actions that have long-term consequences, such as changes to the buildings and transport sectors considered here. Increased uncertainty over longer time periods is acknowledged. For example, future health impacts may decline as new treatment options become available, but similarly, future technologies may be expected to bring down costs as more efficient methods are developed.

Sensitivity results demonstrate that we have taken a conservative approach, with potential for significant additional benefits to be included. For example, impacts on dementia and diabetes are included in sensitivity rather than core analysis. Further to this, mortality is only included for exposure to $PM_{2.5}$ as a compromise to avoid double counting.[18]

There is evidence for additional effects of other pollutants, particularly NO_2, but the extent to which $PM_{2.5}$ functions account for NO_2 effects and vice-versa is unknown. We followed a similar principle of avoiding double counting by using one of the two pollutants for morbidity as well, where there were concentration–response functions for each pollutant for the same outcome. We did not use multipollutant model results that control one pollutant for the other, because meta-analyses tend to use single-pollutant model results and there are statistical complexities in interpreting the multipollutant model results.[19]

Analysis also points to the fact that there are potentially considerable additional benefits of removing indoor gaseous and particulate sources. While we acknowledge that available response functions for outdoor air from the epidemiological literature will include some effects of indoor exposure, these cannot be applied directly to changes in indoor concentrations, because outdoor and indoor concentrations act differently as a proxy for personal exposure, and adjusting for this, for example as done by Milner *et al.*,[20] has substantial caveats, which have been highlighted by the Committee on the Medical Effects of Air Pollutants (COMEAP).[21] Consequently, we are unable to monetise these benefits, limiting our ability to make a more convincing economic case for NZ in the home and pointing to the need for future research in this area.

Our predictions in 2030 and 2040 do not cover a complete transition to NZ; although we have included the most important sectors of road transport, building heating and active travel, we have not addressed important and difficult sectors to decarbonise, such as industrial processes, shipping and aviation. However, predictions in 2050 did include a full range of changes to all sources with this scenario, showing the significant additional benefits of further NZ action.

Project reflections

This project has been a considerable undertaking and has created very large and rich data sets, which we have only begun to understand and to use in support of those advocating NZ and air pollution policy.

Running a project during a global pandemic was not without its problems and set our initial progress back by around 6 months, a period we were unable to gain back during the project. It also meant that our patient and public involvement and engagement strategy significantly changed and we adapted our activities to reflect a shift towards remote working (two focus groups held online rather than in person). In particular, the plans for citizen panels towards the beginning of the project and those for the art installation were significantly impacted. Although different from what was first envisaged, the creation of the film 'Air Quotes' with students in London and Scotland was very satisfying. The film represents a significant engagement resource and is already being used as an engagement tool as part of the NERC WellHome study.

During the project, there were other changes. A significant one was the switch from a shipping NZ scenario, which had small benefits compared with the existing UK BAU forecasts, to using BNZP and WI pathways to look at the important effects on active travel. We also used a more recent year, 2019, on which to base the project, making it more relevant to policy-makers.

We capitalised on links with a World Health Organization (WHO) project, Estimation of Morbidity from Air Pollution and its Economic Costs (EMAPEC), doing a quality assessment of the available meta-analyses in order to select concentration–response functions.[17] This project will form a case study within that project, increasing dissemination of our work internationally. We were not expecting to calculate as many morbidity outcomes as we did, but it is important that as soon as there is sufficient evidence, this should be incorporated so that CBA includes the full range of costs and benefits. This was particularly important because it demonstrated that morbidity benefits were similar to mortality benefits but did lead to substantially more work. In addition to expanding the number of calculations, it increased the number of outcomes for which to derive baseline rates, a particularly challenging aspect of this work. It also increased the number of outcomes for which to derive monetary values.

We have strengthened our links with several government departments, including Department for Environment, Food and Rural Affairs (Defra), Department for Energy Security and Net Zero (DESNZ), Department for Transport (DfT) and with UK Health Security Agency (UKHSA) and the CCC. We are actively presenting results nationally and internationally (in Europe, Asia and, in 2024, in South America) to academics and the public as well as to groups such as COMEAP.

We have built significant capacity in several areas, including modelling methods; emissions inventory development, especially for EVs; health impacts methods for a wide range of morbidity outcomes; and linking these to costs and benefits. As part of our inequalities research, we have developed new and interesting ways of understanding air pollution exposure for different population subgroups.

Challenges

Data collection and analysis were challenging since we relied upon Defra, DfT, DESNZ, Transport for London (TfL) and the CCC for much of the information needed to create emissions and air pollution model projections of NZ and BAU. This entailed a comprehensive and lengthy engagement as well as waiting for newly updated data to ensure that the outcomes remained relevant beyond the end of the project.

The emissions data creation was novel and complex, with numerous assumptions required for its completion. The need for computing resources, which proved to be very large, presented a problem for existing high performance computing access and speed. In all, 1.6 PB of modelled air pollution data was created.

Previous health impact assessment work has been able to use baseline rates from routine mortality or Hospital Episode Statistics and from baseline rates recommended by others.[22] Expanding into quantification of effects of air pollution on incidence of disease is an important step, but the baseline rates for incidence of disease are not routinely available and were difficult to find, entailing unexpected additional work. Similarly, identifying consistent sources of valuation data for an expanded set of impacts that were relevant to the UK economic situation required further work. The project risk was heightened by the fact that tasks were largely scheduled sequentially, creating pressure towards the latter stages of the project. This was exacerbated by progress with some of the tasks during the project as well as changes in circumstances.

Patient and public involvement

Our project included both a patient and public involvement (PPI) and a community engagement and involvement (CEI) component. The aim of the PPI was to seek input and receive feedback on our study design to ensure the interpretability and relevance of our findings to the public. The CEI aimed to explore public perception of the assessed NZ policies and to understand their acceptance across society, including young people.

For the PPI component, we recruited two public representatives onto our study Steering Committee via the VOICE platform (https://voice-global.org/) to provide continuous input throughout the research cycle. We also established a focus group consisting of 13 members of the public aged between 18 and 75 years from London, the Northeast and Southwest of England via VOICE. We discussed the relevance of the proposed scenarios, the importance of the proposed health outcomes and our overall PPI and CEI strategy. The focus group deemed the selected policy scenarios as important but highlighted that their relevance might differ by individual circumstances. Their input also shaped decisions around the health outcomes included in the health impact assessment, in particular the recommendation to report on specific health outcomes, complementing our previously planned life-course approach. They also encouraged us to focus future PPI and CEI activities predominantly on children and young people as the group most affected by the effects of climate change; this informed the dissemination activities around the film ‘Air Quotes’, which has been widely shared with young people.

To support the CEI component, we recruited a Public Engagement Co-ordinator (PEC) and a Public Engagement Evaluator (PEE) to help facilitate citizen panels and to lead and evaluate the coproduction of a piece of art reflecting young people’s voices on air pollution and climate change.

Citizen panels were held as part of the Great Exhibition Road Festival on 18 June 2022 in South Kensington, London (www.greatexhibitionroadfestival.co.uk/media/documents/greatexhibitionroadfestival2022_programme_web.pdf; ~50 participants), and on 1 November 2022 in Glasgow, Centre for Contemporary Arts (www.cca-glasgow.com/programme/net-zero-citizens-panel; 15 participants). Both events were facilitated by principal investigator (PI) Beevers and coinvestigator Fecht with support from the PEC. Common issues raised in these discussions related to the responsibility of actions and if these lie with individual members of the public or the government and policy-makers. The need for clear messages and guidelines on the most impactful changes were also raised. Members of the public highlighted that they are more likely to listen to individuals such as Jamie Oliver or Martin Lewis than government figures. These discussions have shaped our communication strategy with stakeholders, including Defra and CCC.

Following an initial workshop with Year 12 students from Southbank University Academy in Elephant and Castle, London, to develop an artist brief, recruited film maker Louis Brown from East London Cable continued working with those students and young people from the Eco Committee of Armitage Academy in Helensburgh, Scotland, throughout 2022 to co-design the 1-hour film Air Quotes.[23] Air Quotes explores young people’s views on climate justice and the uneven impacts of air pollution and NZ policies. It is a collection of short segments, vox pops and graphics, including drawings by the young people, and summarises hours of multifaceted discussions. Young people held round-table discussions about NZ policies, interviewed activities, for example Mums for Lungs, and took home portable camera kits to interview adults in their lives. The conversations they recorded reflect an intergenerational commitment to achieving climate targets but with uncertainty about the impact that individuals can make. The film has been screened in Glasgow's Centre of Contemporary arts on 1 November 2022 and in London at Forma HQ on 29 November 2022. Both screenings were attended by around 50 members of the public. The screening was followed by a Q&A session with film maker Louis Brown, PI Sean Beevers and young people participating in the film. The session was facilitated by our PEC.

The activity was evaluated and assessed by our PEE throughout the life cycle via feedback forms, surveys and postcards, immersive evaluation and interviews. The initial workshop to increase literacy around climate change, air pollution and NZ policies was also attended by an artist, Esther McManus, who summarised some of the discussions and reflections in a series of drawings which have since been shared with the public and stakeholders. The most common words on feedback postcards after the initial literacy workshop were 'Inspiring', 'Fun', 'Educational' and 'Informative'. Before-and-after activities to assess the increase in awareness of the knowledge showed a much wider awareness of air pollution and health issues, with over half of the responses (total number = 35) focusing on lung disease, bad health and air quality, as opposed to the exercise which took place at the start of the first workshop, in which there were only two comments on health and disease out of a total of 62.

The evaluation by the PEE also showed a very positive impact of those contributing to the film, the researchers involved in the film and the audience. Interviews conducted after the viewing included comments such as:

> *The film was very good, and I really enjoyed it … .I definitely got a lot from it as well … it was good to hear what everyone else had to say'' and 'So the key message from the film for me were that young people know more than adults would expect; and they [adults] should be listening more to what young people think.*

Researchers were not directly involved in the making of the film, which was a decision by the PEC and film maker to give young people the space to express their voice: '*The artist wanted to focus on what the young people think [rather than the researchers] and … I think from my perspective personally, is one of the biggest successes of the project*' (PEC). Reflections by one of the young participants is highlighted in a blog (https://naee.org.uk/conversations-we-need-to-have-my-experience-of-the-air-quotes-film-project/). The film continues to be shown as part of public engagement and training activities.

Overall, we found very high support from among members of the study. All PPI and CEI aspects were well attended and made for very engaged and fruitful discussions. The vast majority of members of the pubic we have spoken to were in very strong support of NZ actions and willing to make changes to their behaviour as a result. However, any recommendations must take the needs of different sociodemographic groups into consideration to avoid widening inequalities.

We initially planned to interact with the Guy's and St Thomas's BRC Cardiovascular, Respiratory and Young People's Advisory Groups, but, after the move of ERG to Imperial College, we refocused our strategy to work with the Patient Experience Research Centre at Imperial and recruited a dedicated focus group via the VOICE platform. Citizen panels were planned for Year 1, but this was not possible due to the COVID-19 pandemic. Instead, we adopted an opportunistic approach and leveraged other activities to host these panels, namely the Great Exhibition Road Festival and the film screening in Glasgow.

Equality, diversity and inclusion

Our study was at population level, including the total population for the UK, and did not recruit study participants. Our findings are therefore representative of the UK population. The input data used for the health impact assessment and the socioeconomic analysis were obtained mostly from the Office for National Statistics and the Census. The mortality analysis was done by local authority, including exposure inputs and mortality rates. This ensures that the differing health status of local populations is reflected. We analysed the mortality results by Carstairs index and, given the whole population is included and that exposure is modelled at a fine spatial scale, can analyse the mortality data set by other features of diversity available at local authority or ward level in future work. For most of the morbidity outcomes (particularly incidence), there is insufficient local-scale information on baseline morbidity rates to allow this type of analysis.

For our public involvement activities, including focus group and cocreation of a film with young people, we developed a dedicated recruitment strategy which focused on gender balance, ethnic diversity and geographic representativity. Young people involved in the cocreation of the film, for example, included students from a deprived, ethnically diverse inner-city area (Elephant and Castle in London) and a less deprived rural community in Scotland (Helensburgh). Our focus group consisted of 13 members reflecting different demographics. The focus group included nine women and four men, and 46% were of non-White ethnicity. Members of the group were 17–70 years old and came from London (n = 7), the North East (n = 5) and the South West (n = 1).

We are a team of diverse international background (UK/France/Germany/Greece/Vietnam/Iran), with different genders and a range of ages. We follow Imperial's Equality, Diversity and Inclusion strategy.[24] Staff on the project have attended Unconscious Bias training.

Impact and learning

Policy advocacy/health awareness/economics

Policy advocacy stemming from this research has in many ways just begun, although there have been a number of events and publications on the back of this work described below and elsewhere in the document.

In addition to closer ties with Defra and other government departments described above, we also have closer relations with UKHSA and were invited to present our work at the COMEAP in February 2024. We will offer a further talk on methodological aspects to the COMEAP Sub-group on Quantification of Air Pollution Risk, thus contributing to the development of expert Committee advice to government on health impact assessment methods, relevant not only to NZ policies but also to other air pollution reduction policies as well.

Through membership of Defra's Air Quality Expert Group, our model source apportionment analysis has contributed to a Defra report on 'Air pollution arising from Hydrogen combustion', and results for 2019 have contributed to a Defra report on exposure inequalities ('Differentials in UK air pollution emissions and concentrations'), which is in final draft form.

We have presented our work internationally at the International Society of Environmental Epidemiology (Greece and Taiwan) and at the International Society of Exposure Science (Lisbon) – see *Additional outputs*. We have also presented the health impact assessment analysis at the RespiraMi 2024 Conference which focused on 'Recent advances on air pollution and health' (Milan, Italy) – the presentation was entitled 'Net Zero policies in the UK: The air pollution co benefits on mortality and morbidity'.

In 2024, we presented a paper from the project at the International Society of Environmental Epidemiology in Santiago, Chile, entitled 'Net-Zero policies in the UK: The air pollution co-benefits on mortality and morbidity'.

Our findings have also contributed to the new Royal College of Physicians Air Quality report[25] that includes a section on NZ.

We have contributed to policy debates, including the one at the Public Policy Exchange, Parlicentre on: How to Make Meaningful Progress in Tackling a Public Health Crisis. Our talk was entitled 'The air quality health and economic costs and benefits of a zero carbon UK? – A study of electric vehicles and building heating'

We have also contributed to the Royal Society report[26] – Effects of NZ policies and climate change on air quality.

Through the Grantham Institute, we organised a 'Lunch and Learn' meeting attended by 97 people with representatives from 5 Government departments (DESNZ, DfT, DHSC, Defra, TfL). There were lots of good questions and attendees had relevant plans to use the research insights. We used Menti to ask questions of the audience. Here are the responses:

Q. How might you/your team use today's insights in your work?

- Update University College London's (UCL's) HIDEEM/NBM health model.
- Inform methods for looking at health impacts of other policies.
- Useful for enabling the prioritisation of interventions/policies.
- Internal air quality – ventilation and internal sources like cooking or fossil fuel heating systems.
- Press to have UCL's and DESNZ's TIMES model updated to have better source receptor linkages and health costs.
- Inform future projections of key air pollutants.
- Inform the focus for and impact of innovation (e.g. improving heat pump efficiency).

Q. What next? Please provide any suggestions for future activities related to the insights presented

- Internal air quality – impact of ventilation and internal sources – cooking and heating systems.
- Any work done on extreme temperatures to health or if this may impact air quality factors looked at here would be of great interest.
- A two-page policy-maker's summary.

The WHO are finalising a report on the EMAPEC project. This NIHR project formed the basis for a UK case study, with the project funding, authors and journal papers acknowledged and referenced, demonstrating international impact.

Public awareness and engagement

In addition to *Patient and public involvement* and engagement activities in *Additional outputs*, in 2023, we arranged a seminar at Imperial entitled 'The air quality co-benefits of climate policy and Net Zero',[27] looking at the benefits and disbenefits of the air pollution and health impacts of climate policy and behaviour change. One hundred and forty people attended, including researchers and members of the public.

Industry and business/technological innovation

We have recently talked to the UK Fluids network on aspects of PM emissions, measurement, modelling, mitigation and impact from NZ. The group has a heavy industrial presence, with companies such as Jaguar Land Rover, Johnson Matthey, JCB, Caterpillar and many others taking part, as well as a number of academic members (Birmingham, Nottingham, Loughborough, Coventry, Newcastle).

Educational initiatives

We are developing a MSc module utilising NIHR model data, entitled 'Environmental Data for Public Health Challenges', aimed at public health students. We will use environmental data from this study to address question around significant global public health challenges, including assessing the environmental implications of EVs.

Related work

Through the NIHR project, we were contracted by the Clean Air Fund to undertake a project aimed at achieving the WHO's 2021 Air Quality Guidelines.[1] We investigated alternative air pollution pathways, based upon NZ scenarios, using the additional capacity/capability created by the NIHR project. Superimposed on top of each of these were air pollution-specific policies related to commercial cooking emissions, construction non-road mobile machinery, domestic wood burning and non-exhaust vehicle emissions. This work was published by Dajnak *et al.*[28] and was used within the UK Government's $PM_{2.5}$ target-setting consultation.

PI Beevers has been nominated by the UK (DESNZ) to contribute to an IPCC Special Report on Climate Change and Cities currently being planned. Brand coinvestigator was nominated to serve as expert on 'Clean Our Air' on the Expert Advisory Panel of the Earthshot Prize 2024 and 2025, thus playing a key role in selecting and recommending finalists for the five £1M 'Environmental Nobel Prizes'.

Collaboration, further funding and future work

As a consequence of this project, we have widened our collaboration across disciplines, including online environmental surveying, epidemiology, behavioural psychology and other public engagement activities.

Working with behavioural psychologists at Durham University and public engagement practitioners through the REACT cohort,[29] and funded through the School of Public Health Research consortium,[30] we have begun a PhD project – Learning from the COVID-19 Pandemic to Create a National Narrative and Build Support for population-level Behaviour Change to Achieve Net Zero Sooner.

We have also piloted an environmental survey (n = 50,000 households) through the REACT cohort to test responses and data quality towards a better understanding of domestic environments and how this can be used in indoor air pollution model development for health and NZ applications. We continue to develop our indoor air quality models as part of the NERC WellHome study.

We have presented many important aspects of the data sets produced in the project; however, there are ample opportunities to further capitalise on it, including in collaboration with others. Examples include:

1. To refine and/or explore the air pollution and health data further in a chosen zone(s), possibly in urban areas such as London and Birmingham, and to identify the socioeconomic benefits of NZ policy on the poorest in society, a potentially important benefit, especially for the building scenario.
2. In the mortality analysis, we chose to use $PM_{2.5}$ to represent the air pollution mixture as it gave the largest result in the baseline scenario. However, the pollutant giving the largest result for the change between scenarios could vary, with NO_2 being important in this case. The mortality data could be recompiled, allowing the selected pollutant to differ by scenario, and possibly also split by road and building sources using air pollution source apportionment.
3. The mortality analysis could be further refined to calculate results at Ward level for urban areas and compiled using Carstairs data to understand how mortality and social deprivation varied between wards within local authorities.
4. The morbidity analysis was performed at country level. In collaboration with local partners or devolved administrations, calculations at regional, city

or local authority level could be performed. Such partnerships, for example with Northern Ireland or the Greater London Authority, could improve the calculations with local knowledge on incidence rates of linked mortality and Hospital Episode Statistics.

Implications for decision-makers

Evidence from this work suggests:

1. Domestic and commercial heating is a significant contributor to UK $PM_{2.5}$ air pollution. While achieving NZ will require substantial change, and current evidence suggests targets on building heating are unlikely to be met,[31] accelerating the transition from fossil fuels (predominantly gas) to electric heating would yield substantial benefits for both climate and air quality.
2. Switching to EVs from the diesel and petrol equivalent benefits both the climate and air pollution, including reductions in non-exhaust PM emissions. These benefits hold despite concerns that the greater weight of EVs could lead to an increase in non-exhaust PM.
3. An additional benefit of moving away from gas for cooking is the potentially considerable reduction in indoor air pollution exposure, particularly to NO_2, for which gas combustion is a major source.
4. The promotion of active travel (walking and cycling) as part of NZ policy is highly beneficial for people's health, and further ambition regarding walking is needed.
5. There are strong economic arguments for undertaking the NZ transition, and particularly so for the building sector, as shown in the CBA.
6. The efficient development of policies for environmental improvement requires recognition of the cobenefits and trade-offs beyond targeted goals. For example, dealing with air quality and climate change together will enable synergies to be exploited, reducing costs and offering potential for increased environmental ambition.
7. The monetised morbidity impacts are greater than previously assumed and, overall, the economic benefits of NZ are large.

Research recommendations

Outdoor model uncertainty reduction

Emissions' estimation is a source of uncertainty in outdoor air pollution modelling, which can be improved by improving source-specific and dynamic temporal profiles and emission factors. The assumptions underpinning emissions forecasts and scenario projections, such as the adoption rates of EVs and advances in renewable energy technologies, are also uncertain. Meteorology and air quality models are another source of uncertainty in capturing complex atmospheric chemistry and meteorological conditions. Future research must focus on refining these models and emissions assumptions.

Indoor exposure modelling

In common with outdoor modelling, reducing model uncertainty is a priority. However, despite many years of indoor environmental research internationally, the application of indoor models to air pollution exposure and health lags behind that for outdoor models. Despite recent progress, significant 'road blocks' limit what indoor models can do to robustly predict exposure in buildings throughout the UK. Foremost among these is the need for a comprehensive and reliable indoor measurement data set. Establishing such a data set provides many challenges, including: to establish measurements that are representative of UK households; the practicality of making long-term measurements in someone's home; and the ability of small sensors to provide robust measurements. In addition, there is a lack of indoor emissions' estimates in UK buildings of the kind for which we rely on for outdoor modelling; this in turn is hampered by a lack of data on household characteristics and relevant indoor activity (cooking, heating methods/fuel, smoking). These issues are being addressed, including piloting household surveys with Imperial's REACT cohort and deploying new indoor measurement devices.

Indoor air pollution and human exposure modelling for households across all UK houses should be a focal point of future research as should using these data to obtain the health evidence relating to indoor air pollution sources. With exposure indoors playing a significant role in total exposure, there is a need to combine modelling and measurement developments to provide better estimates of 'personal' exposure and to use this in health studies. This should also include exposures not normally considered, such as damp, mould, cold and other air pollutants such as Volatile Organic Compounds (VOCs).

Health effects of air pollution and exposure

Further work to develop the use of multipollutant model results in health impact assessment is needed. Using the largest of the two single-pollutant model results[18] is an approximate compromise. Interpretation of multipollutant model results is complex (measurement error can mean one pollutant appears to be more important than the other when that is not actually the case). This problem is solvable with more data and more understanding about exposure measurement error.[19] This issue was especially important for the transport sector analysis.

As mentioned above, further work is needed to provide better established baseline rates for disease incidence, including more on local variations.

The sensitivity analysis on the health impacts demonstrated that some of the health outcomes with weaker evidence potentially have a strong influence on the results. This was particularly the case for dementia. Studying dementia is challenging due to differences in disease definition, proportion of cases undiagnosed and so on. It is important to resolve this, not least because of the overall importance of dementia as a health and social care issue.

In addition, because we were unable to quantify the health impacts of indoor air pollution, we could not monetise the benefits of the policies outlined. Given the significant impacts on indoor NO_2 from the removal of gas cooking in the 2040 scenarios, development of an indoor health impact model and associated costs' estimates is an important area for future research.

Public engagement, behaviour change and Net Zero

More work is needed to develop and evaluate effective ways of communicating the health and economic benefits of NZ, as well as practical 'use cases' relating to EV ownership and the transition to low-carbon homes. Research into the role and value of citizens' panels, or large cohorts such as REACT, is needed, in terms of the degree to which they could be used to establish use cases, co-design engagement activities and address strongly held environmental views.

Conclusions

Some texts in this section have been reproduced with permission from Beevers *et al.*[4] The text below includes minor additions and formatting changes to the original text.

What is striking from the NZ transition, especially for buildings, is the scale of change required in the coming decades, with millions of homes requiring new insulation and heat pumps. This points to the need for considerable public engagement; to increase awareness of associated issues and benefits; to strengthen environmental policies, technology and incentives; and to create a convincing narrative for, and commitment to, the large scale of change that is needed.

Our results forecast important economic benefits of removing fossil fuel burning while improving energy efficiency in UK homes. While UK targets for both insulation and heat pump installations exist, this research should encourage more ambitious policy, especially targeted to help those most in need in society and to address affordability.

Our analysis did not include the health and monetised benefits of reductions in indoor air pollution that could support domestic decarbonisation policy. There is an urgent need for further health evidence associated with indoor air pollution.

The CBA showed that NZ changes to the vehicle fleets were cost-effective and that air pollution health impacts improved things further. Our core analysis provides a possibly conservative view on air pollution benefits, with a preference for estimates linked to NO_2 rather than $PM_{2.5}$, which would have seen them doubled. This should encourage ambitious policies to ensure that the EV transition continues.

We found that meeting NZ for road transport relies on increasing active travel to reduce future travel demand and improve city congestion. However, while the CCC's scenario projected a significant increase for future cycling, scenario levels of walking barely changed and are deserving of more attention.

Our research showed that while future air pollution exposure inequalities remained for NO_2, these reduced over time and this was in part due to NZ policy. $PM_{2.5}$ exposure inequalities were less clear because the spatial contrast between the highest and lowest concentrations in UK is smaller than for NO_2.

Recognition of possible cobenefits across policy areas is important to achieve the efficient use of often limited resources. This study highlights a range of cobenefits, including lower GHG emissions, improved health through air pollution reductions and increased physical activity, reduced inequalities in air pollution exposure and positive economic impacts.

Additional information

CRediT contribution statement

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The mortality data used for this study were supplied by the Office for National Statistics, derived from the national death and birth registration and the census and held by the UK Small Area Health Statistics Unit (SAHSU). Hospital Episode Statistics data are copyright © 2024, reused with the permission of NHS England. All rights reserved. The Hospital Episode Statistics

data were obtained from NHS England. SAHSU holds approval both from the London – South East Research Ethics Committee (22/LO/0256) and from the Health Research Authority – Confidentiality Advisory Group (20/CAG/0028).

Data-sharing statement

The Small Area Health Statistics Unit does not have permission to supply data to third parties. The base year 2019 emissions (https://naei.beis.gov.uk/), UK air pollution measurements (https://uk-air.defra.gov.uk/networks/network-info?view=aurn), the Weather Researching and Forecasting (www.mmm.ucar.edu/models/wrf) and Community Multiscale Air Quality model code (www.epa.gov/cmaq/access-cmaq-source-code) are freely available. Future changes in emissions are provided in the supplementary information associated with the Assareh *et al*. paper.[1] Maps of results by local authority and more information on population, deaths or health incidence and prevalence data derived from published statistics are also available upon request from the corresponding author.

Ethics statement

No individual-level health data was used as part of this project. Data for the health impacts were aggregated at large spatial scales: Local Authority (Mortality) and Country (Morbidity), and so ethical approval was not required.

UK Small Area Health Statistics Unit holds approvals both from the London-South-East Research Ethics Committee (22/LO/0256) and from the Health Research Authority-Confidentiality Advisory Group (20/CAG/0028). The Hospital Episode Statistics data were obtained from NHS England, copyright © 2024, reused with the permission of NHS England. All rights reserved. The mortality data used were supplied by the Office for National Statistics (ONS), derived from the national mortality registrations.

Information governance statement

This study evaluated the health cobenefits of NZ policies by modelling changes in air pollution and physical activity. Health impacts were assessed using life table methods, exposure inequality was assessed and economic costs–benefits were estimated.

No identifiable personal data were used in this study. All data inputs – including air pollution concentrations, population characteristics and baseline health statistics – were derived from pre-aggregated or fully anonymised sources. Briefly, European emissions were acquired from the European Monitoring and Evaluation Programme (EMEP) Centre on Emission Inventories and Projections for 2019. UK anthropogenic emissions were taken from the National Atmospheric Emissions Inventory (NAEI). UK air pollution measurements were taken from online data sets under open government licence. Population data by sex and single year of age for England and Wales (E&W) and Scotland were obtained at Ward level from the Office of National Statistics (ONS) and from Northern Ireland Statistics and Research Agency (NISRA). Active travel data from DfT's Propensity to Cycling Tool (PCT) at Lower Super Output Area level were aggregated to Local Authority scale. Inequalities data were from the UK Census at Middle layer Super Output Area level. Baseline rates for mortality and morbidity were from a large number of available data sets described in Walton *et al.*,[2] 2025 (Supporting Information Annex 6). Further details of the data used are described in each of the four papers.

The research was conducted under the governance of Imperial College London, acting as Data Controller. All data processing took place in secure institutional environments and adhered to the UK General Data Protection Regulation (UK GDPR) and the Data Protection Act 2018.

No data linkage or processing of special category personal data was undertaken. A Data Protection Impact Assessment (DPIA) was not required, and ethical approval was not sought, as no identifiable or sensitive personal data were used. Researchers completed institutional information governance training.

Disclosure of interests

Full disclosure of interests: Completed ICMJE forms for all authors, including all related interests, are available in the toolkit on the NIHR Journals Library report publication page at https://doi.org/10.3310/GJSB3701.

Primary conflicts of interest: Sean Beevers is a member of the UK Air Quality Expert Group; clients include Defra (Project lead in the UK Modelling Ambient Air Quality project), Transport for London (Project lead for air pollution modelling in the London Atmospheric Emissions Inventory, and in the Ultra Low Emissions Zone consultations).

Mike Holland and Heather Walton are members of the UK Committee on the Medial Effects of Air Pollution (COMEAP).

Mike Holland has a consultancy role on the research on health impact quantification and valuation in the EU Horizon Programme (2023–5), VALESOR Project; Defra's SNAPCS Project, providing health and other impact quantification and valuation to support evaluation of air quality policies in the UK; Defra's Vice-chair of European Monitoring and Evaluation Programme (EMEP) under the UNECE Convention on Long Range Transboundary Air Pollution; For WHO, Attended the 2023 meeting of the Task Force on Health under the UNECE Convention on Long Range Transboundary Air Pollution; For Agence France Trésor, is a member of the Evaluation Council of the Green OAT (Obligations Assimilables du Trésor).

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This synopsis was published based on current knowledge at the time and date of publication. NIHR is committed to being inclusive and will continually monitor best practice and guidance in relation to terminology and language to ensure that we remain relevant to our stakeholders.

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Award publications

This synopsis provided an overview of the research award *The air quality health and economic costs and benefits of a zero carbon UK*.

Other articles published as part of this thread are:

Assareh N, Beddows A, Stewart G, Holland M, Fecht D, Walton H, *et al.* What impact does net zero action on road transport and building heating have on exposure to UK air pollution? *Environ Sci Technol* 2025;**59**:1274–86. https://doi.org/10.1021/acs.est.4c05601

Walton H, David D, Mike H, Evangelopoulos D, Wood D, Brand C, *et al.* Health and associated economic benefits of reduced air pollution and increased physical activity from climate change policies in the UK. *Environ Int* 2025;**196**:109283. https://doi.org/10.1016/j.envint.2025.109283

Beevers S, Nosha A, Andrew B, Stewart G, Holland M, Fecht D, *et al.* Climate change policies reduce air pollution and increase physical activity: benefits, costs, inequalities, and indoor exposures. *Environ Int* 2025;**195**:109164. https://doi.org/10.1016/j.envint.2024.109164

Liu Y, David D, Nosha A, Beddows A, Stewart G, Holland M, *et al.* Impact of net zero policy scenarios on air pollution inequalities in England and Wales. *Environ Int* 2024;**193**:109065. https://doi.org/10.1016/j.envint.2024.109065

For more information about this research please view the award page (www.fundingawards.nihr.ac.uk/award/NIHR129406).

Additional outputs

Dajnak D, Assareh N, Kitwiroon N, Beddows A, Stewart G, Hicks W, Beevers S. Can the UK meet the World Health Organization $PM_{2.5}$ interim target of 10 µg m^{-3} by 2030? *Environ Int* 2023;**181**:108222. https://doi.org/10.1016/j.envint.2023.108222

We have presented our work at the International Society of Environmental Epidemiology – Athens, Greece – entitled: Pathway to WHO: Achieving clean air in the UK – Modelling air quality costs and benefits. URL: https://isee2022.org/wp-content/uploads/2022/09/ISEE_2022_Abstract_Book.pdf

We have presented our work at the International Society of Environmental Epidemiology (Taiwan) – entitled: What are the air pollution co-benefits of Net Zero in the UK? URL: https://2023.iseeconference.org/assets/E-Books/ISEE-2023-Abstract-E-Book.pdf

We have presented our work at the International Society of Exposure Science (Lisbon) – entitled: Can the UK achieve the $PM_{2.5}$ WHO 10 µg m^{-3} interim target by 2030? URL: https://inses.memberclicks.net/assets/images/Abstracts.Programs/2022%20Abstract.Program%20Book.pdf

We have also presented the health impact assessment analysis entitled 'Net Zero policies in the UK: The air pollution co benefits on mortality and morbidity' at the RespiraMi 2024 Conference which focused on 'Recent advances on air pollution and health' (Milan, Italy).

Collaborations and partnerships

UKHSA – Member of the scientific steering committee

Collaboration with the Grantham Institute for Climate Change

Defra – member of the scientific steering committee

BEIS (now DESNZ) – member of the scientific steering committee

DfT – member of the scientific steering committee

Partnership with the Climate Change Committee

Other engagement activities

Engagement-focused website, blog or social media channel – RSC podcast on climate and air. URL: www.youtube.com/watch?v=3aroki43Jwo

Participation in a Net Zero seminar – part of ERG's 30th anniversary celebration. URL: https://www.imperial.ac.uk/school-public-health/environmental-research-group/about-us/erg-30/

A talk – Invited to a University of Birmingham to give an overview of the NIHR project results – December 2023.

A broadcast for example TV/radio/film/podcast (other than news/press) – Net Zero Youth Voice – AirQuotes film premier London: URL: https://forma.org.uk/projects/air-quotes/

A broadcast for example TV/radio/film/podcast (other than news/press) – Net Zero Youth Voice – AirQuotes film premier Glasgow. URL: www.cca-glasgow.com/programme/encounters-with-climate-argyll-beacon-on-screen-and-air-quotes-premiere

Participation at the Great Exhibition Road Festival 2022.

A talk or presentation – Net-Zero Youth Voice Workshops.

Participation in a workshop – UKRI House of Commons meeting.

Participation in a workshop – Southbank University Academy – involved in AirQuotes film making.

A formal working group – BEIS and ICL on UK energy forecasts and policy discussion.

A formal working group – CCC and ICL – Traffic data discussion.

A formal working group – Ricardo, Defra and ICL National Atmospheric Emissions Inventory data access.

A formal working group – Defra and ICL Obtaining emissions for 2019/2030/2040.

As part of the project we hosted many internal and steering committee project meetings, that are too numerous to list.

Artistic and creative products

Film/Video/Animation – AirQuotes (2022). URL: https://vimeo.com/807838264

Film/Video/Animation – AirQuotes – Cameron's experience (2022).

About this synopsis

The contractual start date for this research was in July 2020. This article began editorial review in August 2024 and was accepted for publication in October 2025. The authors have been wholly responsible for all data collection, analysis and interpretation, and for writing up their work. The Public Health Research editors and publisher have tried to ensure the accuracy of the authors' article and would like to thank the reviewers for their constructive comments on the draft document. However, they do not accept liability for damages or losses arising from material published in this synopsis.

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Glossary

Air pollution Atmospheric constituents which negatively affect human health or damage the environment. This includes gases, such as nitrogen dioxide and ozone, and particulate matter.

Balanced Net Zero Pathway 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.

Benefit–cost ratio A financial metric used to evaluate the feasibility and efficiency of a project or investment. It is calculated by dividing the total expected benefits of a project by the total expected costs.

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

Climate Change Committee An independent, statutory body which advises the UK and devolved governments on achieving Net Zero.

Committee on the Medical Effects of Air Pollutants A panel of experts that provides independent advice to the UK government on the health effects of air pollution.

Community Multiscale Air Quality model A state-of-the-science chemical transport model used to predict air quality.

Cost–benefit analysis A systematic approach for evaluating the economic pros and cons of different choices, projects or investments. It involves comparing the total expected costs against the total expected benefits to determine whether the benefits outweigh the costs, and by how much.

Department for Energy Security and Net Zero A UK government department responsible for ensuring energy security and driving the transition to net-zero emissions.

Department for Transport A UK government department responsible for overseeing the transportation system across England, including roads, railways, aviation and maritime transport.

Estimation of morbidity from air pollution and its economic cost Estimating the morbidity from air pollution and its economic costs, a World Health Organization project.

Intergovernmental Panel on Climate Change The United Nations body responsible for assessing the science related to climate change.

Life-years gained/life-years lost A life-year is 1 year lived for one person. Life-years are then summed across the population and over time.

Net Zero emissions The IPCC considers Net Zero emissions to be achieved when anthropogenic emissions of greenhouse gases such as carbon dioxide are balanced by anthropogenic removals over a specified period.

Nitrogen dioxide A gas associated with adverse effects on human health.

Nitrogen oxides Produced in combustion processes, from nitrogen in the fuel, but mostly by direct combination of oxygen and nitrogen in flames. It is also produced by lightning and by microbial processes in soils; contributes to environmental effects such as acid rain and eutrophication as well as ozone formation and aerosol effects.

Ozone A gas which in the troposphere is formed by photochemical reactions between nitrogen oxides and VOC compounds. Ozone is a powerful oxidant and causes damage to mucous and respiratory tissues in animals and humans.

Particulate matter Refers to airborne mixtures of small solid particles and liquid droplets. Particulate matter is often categorised as particulate $\text{matter}_{2.5}$ (particles with a diameter smaller than 2.5 µm) and particulate matter_{10} (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 particulate $\text{matter}_{2.5}$ poses the greatest risk to health.

Transport for London A local government body responsible for managing the transportation system in Greater London, including public transit, roads and cycling infrastructure.

UK Department for Environment, Food and Rural Affairs Part of Department for Environment, Food and Rural Affairs' 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.

UK Health Security Agency 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.

Volatile Organic Compounds Organic chemicals that easily evaporate into the atmosphere.

Weather Researching and Forecasting model A meteorological model used in this research alongside Community Multiscale Air Quality to predict current and future air pollution.

Widespread Innovation pathway Which assumes greater success in reducing costs of low-carbon technologies, allowing more widespread electrification, and has a strong emphasis on active travel.

World Health Organization A specialised agency of the United Nations responsible for international public health.

List of abbreviations

BAU	Business as Usual
BNZP	Balanced Net Zero Pathway
CBA	cost–benefit analysis
CCC	Climate Change Committee
CEI	community engagement and involvement
COMEAP	Committee on the Medical Effects of Air Pollutants
CTM	chemical transport model
Defra	Department for Environment, Food and Rural Affairs
DESNZ	Department for Energy Security and Net Zero
DfT	Department for Transport
EMAPEC	Estimation of Morbidity from Air Pollution and its Economic Costs
EV	electric vehicle
GHG	greenhouse gas
IPCC	Intergovernmental Panel on Climate Change
LYG	life-years gained
NIHR	National Institute for Health and Care Research
NZ	Net Zero
PEC	Public Engagement Co-ordinator
PEE	Public Engagement Evaluator
PI	principal investigator
PM	particulate matter
PPI	patient and public involvement
TfL	Transport for London
UCL	University College London
UKHSA	UK Health Security Agency
VOCs	Volatile Organic Compounds
WHO	World Health Organization
WI	Widespread Innovation

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