The air quality health and economic costs and benefits of a zero carbon UK
NIHR129406

Protocol Paper

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Version	Date revised	Changes made	Reason
1-1	21st May 2020	'Electric vehicle' scenario for CCC report in 2020, now 'Committed policy' scenario	Delayed start to 1st July combined with Covid 19 lockdown disruption.
1-2	**4th Feb 2021**	'Switch funding from Martin Williams to Sean Beevers PI'	Martin died in 2020
1-2	**4th Feb 2021**	'revised base year from 2017 to 2019'	'More recent year and includes London ULEZ'

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Acknowledgement and logo: We are happy to comply with the requirements of the NIHR outputs and branding: https://www.nihr.ac.uk/researchers/manage-your-funding/manage-your-project/outputs-and-branding.htm

No **ethics approval** is required for this research

After looking at the ISRCTN, and because our research is not a randomised control trial, **we have registered with ResearchRegistry.com** (https://www.researchregistry.com/browse-the-registry#home/). You can search the site using the UIN : researchregistry5620 to find the NIHR project or contact Riaz Agha (riaz@researchregistry.com).

Study Steering Committee: Please find in the Oversight group nomination form the independent experts, who have agreed to sit on our SSC. (Dr Alison Gowers (PHE), Prof Paul Wilkinson (London School of Hygiene and Tropical Medicine), John Newington (UK's Dept Env, Food and Rural Affairs), Shaun Brace (DfT) who has expertise in aviation emissions, James Kopka (DfT) who has expertise in shipping emissions, and Prof Harry Rutter (Uni of Bath - Harry was included as an expert in active travel)) and Dr Peter Coleman (Department for Business, Energy and Industrial Strategy). We also have an Internal review panel (PI, CO-Is, the Climate Change Committee and Programme manager). . We have also promised to include two members from our PPI engagement activities on the SSC, but due to the Covid 19 pandemic these panels have been paused. We will re-engage once they are reinstated.

Research Plan

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

Background and scientific rationale: Climate change impacts air pollution, aeroallergens, the indoor environment, ultra-violet radiation, flooding, vector-borne diseases, and water and food-borne diseases[1]. In response, in 2015, the Lancet Commission was set up to map out the impacts of climate change, noting that;

'tackling climate change could offer the greatest global health opportunity of the 21st century'[2].

In Europe, comparison between 'current legislation' and an 80% reduction in greenhouse gases in 2050 concluded that health damage from ozone would decline significantly in both scenarios[3]. Elsewhere, Braspenning Radu *et al*[4] found that in Asia and other developing regions a combination of climate and air pollution policies were needed to bring future air pollution down to current levels.

Economic analyses have concluded that the benefits of climate action on air quality and public health could be $49/tonne of carbon dioxide (CO_2)[5], that a €2.5-7 billion saving in air pollution abatement could be made by implementing Kyoto policies in Europe[6], that a 40% reduction in European CO_2 equivalent emissions by 2030 would reduce premature deaths from particulate matter with a diameter <2.5 μm ($PM_{2.5}$) and ozone (O_3) from 311,000 to 288,000[7] and that wood burning in the UK residential sector could have a net air quality cost of £2.6 billion in 2022[8].

Despite these impacts, the review of climate change economics by Stern[9] made no attempt to quantify the benefits or disbenefits of climate change action on air quality and public health.

Air pollution has a wide range of impacts on health, including on respiratory and cardiovascular disease[10]. Although relative risks are small, exposure is ubiquitous, leading to large public health impacts[11,12]. Population scale approaches to reductions in exposure are most effective in this type of situation, and the widespread energy policy changes aimed at reducing greenhouse gas emissions provides just such an opportunity if chosen wisely.

In the UK, Williams *et al*[13] tested a number of non-Government climate policies demonstrating both the benefits and the risks in energy policy towards meeting CO_2 targets. Nitrogen Dioxide (NO_2) concentrations declined, due to switching to electric and hybrid vehicles, leading to between 4 892 000 and 7 178 000 life-years saved from 2011 to 2154. $PM_{2.5}$ concentrations in Great Britain were predicted to decrease between 42% and 44% by 2050 compared with 2011, in the scenarios that met the Climate Change Act targets. However, the $PM_{2.5}$ reductions were predicted to be tempered by a 2035 peak in domestic wood burning, and by a large projected increase in future demand for transport leading to potential increases in non-exhaust particulate matter emissions.

Although substantial overall improvements in absolute amounts of air pollution were predicted for 2050, none of the scenarios tested were Government policy, and they did not account for the changes brought about by signing the Paris agreement or by the UK commitment to net zero carbon emissions. This significantly reduced the impact of this work, as it did not test the early adoption of climate policies between 2020 and 2030, which is imperative if the UK is to meet the net zero target. It also masked the fact that socioeconomically disadvantaged populations continue to be the most exposed, up to 2050[13].

Finally, Doherty *et al*[14] reviewed studies examining health impacts of air pollution changes as a result of climate change policies – but only examined outdoor particulate matter and ozone. Some studies only addressed the effects of temperature on air pollution health impacts rather than to the far more important emissions changes; and most only considered mortality not morbidity. The health impacts in most of these studies are underestimated as a result of studying only some of the pollutants and excluding health outcomes in children[15].

Several policies under consideration in a climate change context may have adverse effects on air pollution (further discussion under objective 2.2) but the lack of detailed analysis in most previous work of the air pollution and health aspects fails to make the trade-offs explicit. This misses opportunities for further analysis to optimise such policies by mitigating the adverse aspects.

We will ensure that our study has policy impact by identifying policies with strong public support, that are most efficient and effective in reducing both carbon emissions and the health and economic burden of air pollution. We will study policy impacts on a wide range of air pollutants, their associated health and economic burden across the lifecourse from birth outcomes to life expectancy, as well as differential impacts across different parts of society such as rural and deprived communities. The results will be expressed in terms of separate health outcomes as well as the total monetary value of the benefits - we consider explicitly delineating the health benefits in this way may help support behavioural change. Comparison will be made between the benefits, the CCC estimates of costs, and other unquantified elements (which may include some costs of behavioural change, for example). Together with public and patient representatives we will explore the acceptance of these policies including those focused on indoor air quality and active travel. Community and stakeholder engagement are key components of this project to help us communicate findings to policymakers and the public.

While the full benefits of the zero-carbon strategy will be felt in 2050, we are also modelling the interim years, 2030 and 2040. The reason for this additional work is that to attain the 2050 goal, decisions on policies have to be made in the next few years and their additional benefits to air quality and health need to be evaluated now to maximise benefit in the short-medium term as well as the long term.

Research Questions:

1. Work Packages (WP) 1 and 2 (described below) will provide a comprehensive assessment of emissions, air quality, health and economic costs and benefits for each scenario to help answer the question:
   How can the UK's public health and economic burden from air pollution in 2030/40 and 2050 be reduced by the early introduction of the 2050 net-zero climate policies?

2. In WP3, via the BRC panels, citizens panels and science gallery we will engage with a large range of stakeholders to assess:
   What is the social acceptance of these policies across demographic and socioeconomically different parts of society?

3. WP3 includes a comprehensive assessment of impacts of different urban, rural socioeconomic and ethnic groups to answer:
   Is the burden/benefit of climate policies equally distributed across the population or do policies favour/disadvantage certain parts of the population?

4. Using the outcomes of WP1 and 2, in WP 3 there is a large stakeholder engagement with policy makers which aims to assess:
   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. WP1 will provide a comprehensive assessment of emissions and air quality exposure for each scenario separately, answering:
   What impact do individual actions have on air pollution and what can people do to reduce their contribution and exposure to it?

Design and theoretical/conceptual framework

The Government's new net-zero carbon emissions target requires that policies to reduce CO_2 be brought forward in time and/or made more ambitious. However, the act of switching from burning fossil fuels to using electricity, hydrogen and carbon capture and storage, earlier than planned, is expensive, requiring the policy benefits to outweigh the costs. One of the benefits for using more ambitious net-zero policies is the potential reduction of air pollution related health impacts and economic costs. This project has identified a set of future policy scenarios that are practical to implement, have strong public support and meet net-zero targets. Using the methods described in WPs 1 and 2, we will assess whether their health benefits outweigh their costs. To explore and encourage acceptance of these policies across different parts of society, in WP3, we will actively engage in a two-way communication with patient and public groups, public health practitioners and air pollution and climate policy makers.

The proposed policy scenarios, to be explored, are those that are expected to reduce both climate change and air pollution emissions, that have gained public support through the UK Government's 'Clean Air Strategy' consultation and that are likely to have an important health impact. The ambition of each policy has been increased to meet net-zero targets using the CCC energy systems model; and the emissions and air pollution concentrations, for 2030, 2040 and 2050, will be forecast using a state of the science air pollution model, CMAQ-urban[16]. The planned scenarios are described below:

1. 'Committed Policy' scenarios in 2030/40/50: UK (and European) commitments already made under existing agreements such as the National Emissions Ceiling Directive (NECD), the UK Clean Air Zones, London Ultra-Low Emissions Zone and emissions reductions up to the 5th UK carbon budget; Also including:
   a. 2040 switchover date for sales of 'conventional petrol and diesel vehicles' and still allow plug-in hybrids and some non-plug-in hybrids after 2040
   b. A range of buildings policies: Improvements to energy efficiency of existing buildings; Phase-out of installation of oil boilers off the gas grid in the 2020s in favour of hybrid or pure heat pumps but continued use of biomass boilers at current levels; All new homes with high energy efficiency and heat pumps but able to use gas cooking.
2. 'Electric Vehicles' scenarios in 2030/40: The rapid uptake of electric vehicles, by ending petrol/diesel car sales in 2030 rather than 2040. The 2030 switchover date for sales of cars and vans, including an end to sales of plug-in and standard hybrids, with over 13m cars and vans in the vehicle stock by 2030 and 37m by 2040.
3. 'Road Transport' scenarios in 2030/40: a more comprehensive strategy framed around 'Avoid-Shift-Improve': combination of the 'Electric Vehicles' scenario; nationwide roll-out of 'smarter choices' policies and the promotion of active travel, leading to significant levels of modal shift towards active travel, largely by people who are not undertaking a significant amount of exercise currently (e.g. by commuting to work), with associated benefits from lower air pollution exposure (general population, traveller), air pollution mitigation, and increased physical activity, plus limiting the non-exhaust AQ impacts through the use of electric vehicles.
4. 'Shipping' scenarios in 2030/40: Switch to low-carbon shipping; A complete switch of shipping fuels to hydrogen/ammonia starting in the early 2030s – 33% switched by 2040 and 100% by 2050
5. 'Building' scenarios in 2030/40: The use of hybrid heat pumps, removal of biomass burning, as well as the benefits to indoor air quality exposure of switching from gas to electric cooking; Specific building decarbonisation policies include:
   a. Rapid deployment of hybrid heat pumps: 5m in 2030, rising to 15m by 2040;
   b. An end to gas cooking by 2040;
   c. Full switch of heating to a combination of electrification (75%) and hydrogen (25%) by 2050;

   d. Phase out of biomass boiler installation in 2020 and no biomass boilers being used to heat buildings by 2040.

6. 'Combined' scenario: 2050 combined forecast for all scenarios.

The impact of each policy scenario will be tested against two controls, a 2019 base year and the 'Committed Policy' scenarios in 2030, 2040 and 2050. For example, to test the 'Electric Vehicles' scenario in 2030, we will first run a 2030 'Committed policy' scenario and then replace the assumptions regarding electric vehicles with our new electric vehicle assumptions and run the model again. The difference between the two results will be the effect of the new 'Electric Vehicles' policy, and compared with 2019, the overall impacts from air pollution 'today'. This approach will be repeated to calculate the impacts of 'Electric Vehicles', 'Road Transport', 'Shipping' and 'Building' in 2030 and 2040, individually, plus a combined effect of all of the policies in 2050, 12 UK model runs in all. Furthermore, the performance and uncertainty of the CMAQ-urban model against UK measurements will be established using the 2019 base year model run.

To more fully account for the impact of improving air pollution related health, and to improve the chances of the policies being adopted, the health impacts of each scenario will be calculated for an extended number of mortality and morbidity outcomes, using methods that are consistent with current research, UK, and international standards. The subsequent economic analysis will also be consistent with the latest recommendations of HM Treasury and the Interdepartmental Group on Costs and Benefits, as well as identifying the benefits of our approach using Value of Information analysis focused on how the strategies for climate mitigation may change once health benefits of air pollution control are factored alongside GHG reductions. The differential exposure and health impact of each of the 12 policy scenarios will be stratified by population subgroups, including the socioeconomic deprived and ethnic minorities, across the country, for regions and major cities, to highlight the burden/benefit of policies across different populations.

To improve impact, a 2030 'Committed Policy' scenario will be prioritised early in the project, with the aim of producing air quality, health and economic results for 2030 for the CCC annual report, due out in September 2020. This will not only provide a clear indication of the influence that this policy will have on air pollution and health but also advertise to UK Government the project's other scenarios, to be delivered subsequently.

Results of our research will be communicated through Guy's and St Thomas' BRC Cardiovascular, Respiratory and Young People's Advisory Groups, as well as citizens panels throughout the UK. Young people will be important beneficiaries of our research in the long-term, and young people will be actively involved in guiding and shaping our research and outcome dissemination throughout the project cycle via workshops and our Study Steering Committee. In addition, a dedicated stakeholder engagement strategy will focus on national and local policy-makers, drawing on pre-existing strong links with the Department for the Environment, Food and Rural Affairs (Defra), the Department for Business Energy and Industrial Strategy (BEIS), the Department of Health and Social Care (DHSC), local authorities, Public Health England (PHE) and directors of public health as well as Non-Governmental Organisations (NGO's), the public and other campaign groups. The inclusion of Christian Brand as a CO-I will provide direct stakeholder links to the Department for Transport (DfT), Scottish Government, Transport for London (TfL), Sustrans, the World Health Organisation (WHO) Europe and WHO Global.

Control/comparator group As a control/comparator group, all scenarios will be compared with the 'Committed Policy' scenarios in 2030, 2040 and 2050 as well as 2019.

Study population

UK population of 66 million in 2019, with population projections incorporated for future years (https://www.ons.gov.uk/).

Outcome measures

From WP1 - Emissions and air pollution concentrations: UK emissions inventory of Nitrogen Oxides (NO_X), Carbon Monoxide (CO), Volatile Organic Compounds (VOC), Particulates with a diameter <10 µm (PM_{10}), $PM_{2.5}$, Sulphur Dioxide (SO_2) and Ammonia (NH_3) for 2019, 2030, 2040 and 2050 scenarios and associated air quality data for NO_X, NO_2, O_3, PM_{10} and $PM_{2.5}$ every 20m, summarised at UK Ward level.

From WP2 - Health: For each scenario, the health impact assessment including birth weight, asthma and lung development in children, bronchitis, lung cancer, stroke, respiratory and cardiovascular hospital admissions, work days lost, life years lost and life expectancy. **Economic:** For each scenario, the benefits linked to changes in the loss of amenity, lost production in the workplace and costs to the NHS for the air pollution health effects, the benefits linked to changes in premature mortality due to increases in physical activity from more active travel, plus the costs of implementing the CCC scenarios.

From WP3 - Socioeconomic: Exposure and health impact stratified by population subgroups at the national, rural and city level. **Public involvement and engagement:** Outcomes from BRC, citizens panels, policy makers, public health and transport meetings. Report on the social/policy acceptance of the scenarios and associated benefit:cost ratios, report to support engagement with policy makers and public priorities for future research. Art installation on the future impacts of air pollution and climate change co-developed with young people to generate project updates, young people's summaries and shareable social media content.

Methods for data collection

Data will be collected from collaborators on the project or from publicly available global datasets, including: the CCC energy model and scenario intervention cost outputs, the UK National Atmospheric Emissions Inventory (NAEI - http://naei.beis.gov.uk/), the European Monitoring and Evaluation Programme (EMEP - https://www.emep.int/) emissions inventories, non-EU emissions inventories from IIASA RCP database (http://www.iiasa.ac.at/web-apps/tnt/RcpDb), UK air quality measurements from DEFRA's AURN Network (https://uk-air.defra.gov.uk/networks/network-info?view=aurn), and the London Air Quality Network (https://www.londonair.org.uk/LondonAir/Default.aspx), meteorological measurements from BADC (http://www.badc.rl.ac.uk/), meteorological boundary conditions for 2030/40/50 from the Earth System Model (ESM2) and CMAQ-urban boundary conditions from the MOZART-4 model (https://www.acom.ucar.edu/wrf-chem/mozart.shtml) and the WCRP climate model (https://www.wcrp-climate.org/); UK population birth outcome and mortality data from the Office for National Statistics (https://www.ons.gov.uk/), hospital admissions from NHS Digital, International survey for Asthma, disease prevalence data from the Health Survey for England; information on ward level socioeconomic status and ethnicity from Office for National Statistics; public opinion on policy scenarios from members of the public via citizen panels. Socioeconomic data, including ethnicities, and Carstairs index from the Small Area Health Statistics Unit (SASHU) at Imperial College, London (ICL). Special Licence Access for 2002-17 travel activity data (incl. minutes and km per person per week for walking and cycling) included in trip stage data of the National Travel Survey (https://www.gov.uk/government/collections/national-travel-survey-statistics) will be obtained from the DfT. Current and future scenario based cycling mode shares and related car driver data for commuting from DfT Propensity to Cycling Tool (https://www.pct.bike/).

Detailed Work Package description

A more detailed description of the project is given in the following three WPs. WP 1 includes a description of the energy, emissions and air quality modelling, WP 2, the health and socio-economic modelling and WP 3, Dissemination of outputs via the PPI and stakeholder engagement aspects of the project.

Work package 1 - Energy, Emissions and Air Quality Modelling
Objective 1.1 - Creating UK and European emissions in 2019, and for 2030, 2040 and 2050 scenarios (Lead – Dajnak, CO-Is Beevers, Williams, Kitwiroon, Brand, Collaborator – Joffee)
A ***2019 'base year' anthropogenic emissions inventory*** will be created for the pollutants NO_X, CO, PM_{10}, $PM_{2.5}$, SO_2, HCl, VOC and NH_3, for the UK and Europe, down to individual UK roads using King's road emissions model[17]. The spatial scale of the emissions will be tailored to work with the CMAQ-urban air pollution model, including 50km grid resolution for Europe, 10km for UK and 2km for cities. The emissions also are grouped into 10 UNECE SNAP (Selected Nomenclature for Air Pollution) sources, such as energy production, road transport, industrial combustion etc, and will have sectors that are currently missing in the published inventories, added, including cooking emissions and diesel intermediate volatile organic compounds (IVOCs) emissions, using the methods described in Ots, *et al*[18,19]. These anthropogenic emissions will then be further processed into hourly gridded chemical species using scaling factors developed in the US-EU project, Air Quality Modelling Evaluation International Initiative (AQMEII) (http://aqmeii-eu.wikidot.com/), for use with the CMAQ-urban model. Biogenic emissions will be estimated using the Biogenic Emission Inventory System version 3 (BEIS3) model in the Sparse Matrix Operator Kerner Emissions (SMOKE) modelling system (https://www.cmascenter.org/smoke/) and calculated using USGS land cover data (http://landcover.usgs.gov/), high resolution MODIS-based land use[20] and meteorological data from the Weather Researching and Forecasting (WRF) meteorological model (see WP2). Large industrial plant emissions will be included from the ~5,000 sources in the UK and taken from the NAEI database (http://naei.beis.gov.uk) including major power stations, iron and steel smelting and oil refineries. Aircraft emissions will be estimated on the ground and at height whilst planes climb out and approach the airport site. Other aircraft cruising emissions, will be calculated based on the IIASA 3-D aircraft emissions (https://tntcat.iiasa.ac.at/RcpDb).

Following the 2019 emissions, 2030, 2040 and 2050 UK scenario emissions will be created by linking the CCC energy model 'activity data', typically given as fuel used in Petajoules (PJ) or Billion Vehicle km (Bvkm) for road vehicles and using these data to scale the 2019 'activity data' by emissions sector. This requires linking emissions sources within the NAEI (370 different source and fuel types defined by NFR codes) to the relevant CCC energy model outputs and assigning both to the relevant SNAP sector used by the CMAQ-urban model. Here the project will benefit from previous work as part of an NIHR study[13] which at the time resulted in a total of 570 separate source/fuel emissions categories in the NAEI being predicted to each future year. Population from ONS (https://www.ons.gov.uk), and land use changes from carbon budgets between current and future years will also be accounted for in the emissions calculations.

The next stage is multiplying the future year's activity data by emissions factors that represent improvements in the emissions performance between 2019 and 2030/40/50, within each emissions sector. Here, use will be made of a combination of future NAEI 2030 emissions factors held by KCL, updated to include any new factors published recently and in the wider research literature. Finally, the road transport emissions will be calculated separately using King's road traffic model, which incorporates vehicle emissions factors from COPERT, real-world vehicle remote sensing data[21] and non-exhaust PM emissions factors, used in the London Atmospheric Emissions Inventory and based upon the work of Harrison *et al*[22]. The latter non-exhaust emissions will benefit from a current PhD at KCL, using detailed PM measurements to develop comprehensive non-exhaust emissions in the UK, including for electric vehicles. It will also benefit from another PhD with comprehensive construction vehicle emissions measurements.

The **2030/40/50 emissions for the other EU countries** will be derived from the EMEP European Emissions inventory, scaled to account for the National Emissions Ceiling Directive (NECD) obligations for each country in the EU, while for international aircraft and shipping sources, the emissions will be derived from the IIASA RCP database. The emissions for countries adopting a net-zero target will be investigated and incorporated into the model. The changes of land use for each country, reflecting the EU Land Use, Land Use Change and Forestry (LULUCF) sector, and in line with the Paris Agreement (https://ec.europa.eu/clima/policies/forests/lulucf), will also be taken into account as will the EU population projections for future years, obtained from the European Environment Agency (EEA). The countries outside the EU, the emissions projections will be based on estimates published by the Department of Economic and Social Affairs of the United Nations.

Objective 1.2 – Predicting air pollution in the UK in 2019 and for 2030, 2040 and 2050 scenarios (Lead – Kitwiroon, CO-Is Dajnak, Beevers, Williams, RA1)
An air pollution forecast will be made for the base year 2019 and future year 2030/40 and 2050 scenarios, by combining city, UK and European scale emissions (Objective 1.1); with a combination of the Weather Researching and Forecasting (WRF) meteorological model[23], the United States Environmental Protection Agency's (USEPA) Community Multiscale Air Quality model (CMAQ)[24], coupled with the Atmospheric Dispersion Modelling System (ADMS) roads model[25]. This is a novel model, that we describe as CMAQ-urban[16], and combines state of the science atmospheric chemistry and physics with the capability to output hourly NO_X, NO_2, PM_{10}, $PM_{2.5}$ and O_3 concentrations every 20m in the UK, addressing in detail all the policy applications for this project. The model does this using a number of nested grids, the first predicting European air pollution across a regular 50km, grid, then every 10km over the UK, every 2km over UK cities and finally every 20m close to roads. The model represents the long range transport of pollutants from sources 100 -1000s km away, important for pollutants like O_3 and PM, and in 3 dimensions, as it has 23 vertical layers, starting at ground level and finishing 15km up, at the boundary with the stratosphere.

The CMAQ-urban model uses the WRF meteorological model's hourly 3-dimensional outputs to drive dispersion, chemistry and deposition, for any forecast year, and includes future climate influences through the use of the global coupled carbon climate Earth System Model (ESM2)[26]. The CMAQ model also uses the Volatile Basis Set scheme (VBS)[27] to account for the chemical aging and volatility of organic gases and aerosols, simulating atmospheric chemistry using the CB05-TUCL gas-phase mechanism[28,29] and AE6 aerosol mechanism[30]. Chemical boundary conditions from beyond the European model domain will be derived from the global chemical transport model MOZART-4[31] and the NOAA GFDL-AM3 model[32]. Finally, the ADMS roads model will be used to describe the near field dispersion from roadways in CMAQ-urban, also using the hourly meteorological inputs from WRF. The near road chemistry will be simulated using a simple chemical scheme[33] and emissions double counting corrected at model run time.

A comprehensive model evaluation will be undertaken in 2019 using the comprehensive UK fixed site measurements of the UK air quality measurements from DEFRA's AURN Network (https://uk-air.defra.gov.uk/networks/network-info?view=aurn), and the London Air Quality Network (https://www.londonair.org.uk/LondonAir/Default.aspx) and following DEFRA's published model evaluation protocol[34]. Model uncertainty will be quantified as described in

Objective 2.2. Previously, CMAQ-urban has been used widely for both health research (e.g., [35,36]) and policy applications[13] and has undergone comprehensive evaluation as part of the recent UK model inter-comparison exercise (https://uk-air.defra.gov.uk/research/air-quality-modelling?view=intercomparison) and internationally, as part of the AQMEII project[37]. Its ability to forecast forwards future years has also been demonstrated recently in the published DEFRA report of UK compliance with $PM_{2.5}$ WHO guidelines in 2030 (https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/819781/air-quality-who-pm25-report.pdf).

An additional use of the CMAQ-urban model is as a predictor of outdoor air pollution for the novel and highly detailed King's London Hybrid Exposure Model (LHEM)[35], which is able to predict an individual's exposure to air pollution indoors as well as outdoors and whilst travelling. The contribution to indoor exposure from cooking sources in the LHEM model, is currently being investigated, using a large database of 132 individual household measurements indoors and outdoors and cooker details in London as part of the UKRC APEX project. It is the relative size of this cooking source to total exposure, predominantly NO_X and NO_2, that will help establish the impact of introducing electric cooking as a replacement for gas in the 'Building' scenario.

Understanding the uncertainty of the air pollution, health and economic analysis are important and will focus on the question - Are the recommendations that arise from the analysis robust in the face of the uncertainties that are present? Ensuring that recommendations are fit to inform policy development and that the presentation of information on uncertainty is both comprehensive, clear and comprehensible to a non-expert.

Assessment of components of the modelling 'system' have already been undertaken for example, for the 5th Carbon Budget[38], where Monte Carlo simulations of the econometric model of energy demand were used to quantify the uncertainty in CO_2 projections of between +15.0% and -19.3% by 2035 (a range of 34.3%, 153MtCO2 pa).

However, for the air pollution predictions a Monte Carlo approach to uncertainty estimation is not practical due to the large number of model inputs (>200) and the computer time required for each run. Also, our use of alternatives such as global sensitivity analysis and model emulation[39] is not a practical approach for this research. Hence, we propose an assessment of the model predictions in 2019 against > 200 UK measurements, for predictive RMSE, R^2 and bias, following published approaches to model evaluation[34] to give an estimate of the structural uncertainty and unquantified biases (Obj. 2.2), reflecting the 'lack of knowledge' of the model's description of the atmosphere.

Then we will undertake a number of model sensitivity tests of the changes in future emissions that are driving the changes in air pollution from 2019 into the future. To assess this 'parametric uncertainty' we will use multiple runs of the CMAQ model to calculate how future air pollution concentrations change as a result of changes in input emissions of NO_X, VOC's, NH_3, $PM_{2.5}$ and PM_{10}. The model results will be used to calculate the first and second order sensitivity values and using a Taylor Series expansion to estimate the changes in modelled concentrations due to simultaneous changes to these parameters. This knowledge of the model's parameter sensitivity, in combination with the absolute magnitude of the emissions change, will enable us, via Monte Carlo analysis, to qualitatively estimate the partial uncertainty range in our air pollution predictions. This would feed into the statistical analysis described in Obj. 2.2 below.

Finally, from UK measurements, an estimate of the inter annual variability of average pollutant concentrations will be made, to assess the impacts of using different base years (we have chosen 2019) from which to make future forecasts - an important 'Methodological uncertainty' to feed into Obj. 2.2.

Work package 2 - Health, economic and socio-economic impacts
Objective 2.1: UK Population exposure and health impact calculation (Lead – Walton, CO-Is Dajnak, Evangelopoulos, Holland, Fecht, Brand)
The health impact calculations will use life-table analysis to model the increase or decrease in baseline rates of mortality for the relevant pollutant concentration changes using concentration-response functions from the epidemiological literature and national/international committee recommendations. Future trends in births and mortality rates will be taken into account according to the methods described in Williams *et al*[13]. In addition to previously analysed mortality endpoints, morbidity outcomes as listed in below will be included, building on methods described in Walton *et al*[40]. Analysis will initially assess the health impacts of the concentration difference between leaving 2019 air pollution concentrations unchanged and the projected concentrations for all other scenarios including committed policies. The main comparison will then be the difference between this result for the net zero scenarios and the committed policy

Analysis will be at ward level with analysis at finer scales investigated. Air pollution estimates (output from Obj 1.2) will be mapped to ward level using the underlying population structure as weights to estimate air pollution exposure at the small area level. The mapping will be performed within a geographic information system by overlaying the air pollution grids with the ward boundaries and subsequently population-weighting the exposures using postcode headcount data. Ward-level averages of air pollution concentrations will be used to scale the relative risks or odds ratios using the appropriate conversion for each statistical model used in the original epidemiological studies. The scaled risks will then be applied to the appropriate baseline rates and population size to derive the health impacts.

Health outcome measures include life expectancy and life years lost, respiratory and cardiovascular hospital admissions, the effects on birth outcomes, lung function in children, asthma, bronchitis, stroke, lung cancer and work days lost. For mortality, life-table analysis will be used, following the methods of Miller and Hurley[41], as extended in Williams *et al*[13]; other health outcomes will follow Walton *et al*[40] and a current project (based on CRF recommendations from WHO[42]); results from a systematic review project of time-series studies for hospital admissions[43,44,45]; results from the ESCAPE study that pooled raw data from several cohorts across Europe (Pedersen *et al*[46] for low birthweight; Gehring *et al*[47] for asthma incidence) COMEAP recommendations (chronic bronchitis, COMEAP[48]) and other meta-analyses (Shah *et al*[49], stroke) or major cohort studies (Gauderman *et al*[50]), lung function growth). Work days lost will follow recommendations from a report to Defra[51]. The uncertainty around the central estimates for the CRFs and other assumptions (e.g. cutoffs for effects at specific concentrations) will be investigated. Implications of multi-pollutant model evidence for combining results across pollutants will also be explored (COMEAP[52]).

We will investigate the uncertainty around all the inputs used, and quantify them using the most appropriate probability distributions that best describe them. Then, we will perform health impact calculations, taking into account the variability of the inputs, by performing a Monte-Carlo simulation analysis. Monte-Carlo analysis would sample from the relevant distribution assumed for the input variables and would end up in predictions for the health impacts of air pollution by repeated random sampling. Moreover, 95% uncertainty intervals around the central estimates will be produced. The number of draws for the sampling procedure and the probability distributions for the inputs will be informed by the literature. Sensitivity analyses will be performed regarding the choice of the simulation inputs and how they may affect the health impact estimates. The outputs from this uncertainty analysis will feed into the overall uncertainty assessment described in Obj. 2.2.

Baseline disease rates will be obtained from ONS (birth outcomes, deaths), Hospital Episode Statistics (hospital admissions), and Lai *et al*[53] (International Survey of Asthma and Allergies in Childhood) (asthma incidence). For other outcomes a variety of sources will be used from the Health Survey for England, WHO recommendations[42] and registry data to, if necessary, baseline rates from the original cohorts defining the concentration-response functions.

We will also calculate the benefits of reduced mortality in terms of Life Years gained (and gain in life expectancy) from increased physical activity following the methods in a previous project[54]. We will use general trends of walking/cycling activity combined with relationships between physical activity and mortality. The method looks at the beneficial effects of cycling and increased pedestrianism on health in terms of calorie expenditure, using minutes per week of walking or cycling converted to Metabolic Equivalent Task (MET), which is a measure of calorie expenditure (e.g. sitting is a MET of 1), and finally convert the change in MET-hours per week of physical activity to a change in mortality using the relationship between physical activity and mortality in Kelly *et al*[55]. In previous work, we were constrained by available input data to use the linear relationship given in Kelly *et al*[55]. (This is also used in the WHO HEAT tool (www.heatwalkingcycling.org)). However, they have also shown that the same change in physical activity can have more benefit in those who were inactive beforehand. We can make use of the separate activity-response functions for moving between categories of 150+ min, 30-149 min and less than 30 min of moderate intensity if data on numbers of people projected to move between activity categories is available. Baseline data to be derived from the National Travel Survey, which includes travel diary data for walking and cycling (distances and durations for each journey stage). Weekly minutes per person can be derived from this, then categorized. Scenario data for cycling based on DfT PCT potentials, see above.

Objective 2.2: Health economic analysis (Lead – Holland, CO-Is Walton, Dajnak, Brand)

Economic analysis is an important tool for integrating the findings of this study with the wider policy-making environment. At the start of the study a detailed document will be prepared describing the framework for the economic analysis for other team members and stakeholders. Debate around this document will clarify the interaction between tasks, and with external stakeholders. It will also provide an opportunity for a gap analysis to avoid the omission of potentially important issues that will influence estimates of the efficiency of the policy interventions. Value of information analysis will be carried out to assess how the budget can most usefully be focused on missing elements and other uncertainties.

Two approaches can be used for valuation of health impacts of air pollutants, following UK government guidance. The simplest is the damage cost approach, which requires changes in emissions to be multiplied by cost per tonne of pollutant as quantified by Defra. Defra guidance indicates that this approach should only be used for cases where costs or benefits are up to £50 million as net present value. Health costs in this work will be significantly higher than £50 million, though the damage cost approach can be used in initial scoping of scenarios to provide a first indication of the benefits of the scenarios to be considered (acknowledging that there are further limitations to the approach, as it can only be used in relation to the pollution burden, and hence will not be useful for benefits of, e.g., active transport).

The main analysis will be based on a full health impact pathway analysis, enabling economic value to be assessed for all quantified health impacts (e.g. changes in air pollution impacts, or benefits of active travel) of the scenarios considered. The appropriate framework for economic valuation for this activity will be based on environmental economic techniques, where value is based on expressed public preference for health and wellbeing, drawing on the economics research literature. Values will account for healthcare costs, loss of productivity (where workers, volunteers or carers are affected) and loss of welfare. The value of loss of welfare is assessed in the framework adopted by the IGCB (the UK's Interdepartmental Group on Costs and Benefits) using willingness to pay techniques that are commonly used in environmental economics to describe the value of a life year (VoLY), including by Defra[56]. The VoLY can be used directly in the assessment of mortality costs. For quantification of effects on morbidity, the IGCB approach adjusts the VoLY by the loss in quality adjusted life years (QALYs) associated with each type of impact. Approaches to discounting future values, and inflation of values over time to reflect income growth, will be consistent with HM Treasury guidance.

This approach will be fully consistent with practice in UK government. Earlier work by members of this research team, such as by Williams *et al*[13] (value of a life year) and Walton *et al*[40] (other health outcomes) followed a similar approach, though the precise methods used in those studies will need to be updated in this study, recognizing the availability of new evidence in the research literature and the updated national guidance. Where monetary values for specific health effects are not available from previous work carried out for Defra and other government departments, values will be derived by Holland, the team's environmental economist using the QALY based approach and through reference to the economic literature. Account will be taken of the latest UK research, for example the work on mortality valuation currently being undertaken for the Health and Safety Executive (HSE) and information from current research under COMEAP into the effects of pollutants on cardiovascular morbidity. Additional research elsewhere will also be reviewed, with particular account being taken of work in the context of Socio-Economic Assessment under the EU's REACH Regulation, managed by the European Chemicals Agency (ECHA) and also the OECD. In both cases, interest is focused on effects that are relevant to the analysis to be conducted in the proposed study.

Consideration will be given to wider co-benefits of the CCC interventions, where these can be quantified, using previous work[58] undertaken by a member of the proposed study team (Mike Holland) on the CCC's 4th Carbon Budget and for the NHS Sustainable Development Unit. That earlier work included account of additional health impacts including the benefits of active travel and changes in occupational accident rates.

Data on the costs of implementing the CCC scenarios will be derived directly by the CCC, outside of the study.

Coming towards the end of the study, the economic analysis is the appropriate place for uncertainties to be brought together. The focus of the uncertainty analysis will be on the robustness of the overall conclusions of the study rather than ranges around individual elements of the work (though these will contribute to the overall uncertainty). At the beginning of the research a detailed proposal for handling uncertainties will be developed, following discussion across the whole project team, to ensure common understanding and consistency. Without consistency the findings of the uncertainty analysis would be meaningless.

Account will be taken of three types of uncertainty:

- Those that can be defined in statistical terms, with range and probability distribution available. Consideration will need to be given to the quality of published ranges, as they may not fully characterize uncertainty.
- Methodological uncertainties that can be addressed using sensitivity analysis.
- Unquantified biases that affect the analysis, such as through the omission of some types of impact.

The proposed study team has examples of a multi-stage uncertainty analysis from previous work, for example for the European Commission[57] that was designed to evaluate the robustness of conclusions on national emission ceilings for major transboundary air pollutants. In that work, the statistical and methodological uncertainties across a wide range of health and other impacts were brought together using Monte Carlo analysis, to define the probability that the benefits of the scenarios under assessment would exceed the costs of pollution control. Unquantified biases were brought into play by first considering the likely sign of bias on the balance of costs and benefits, and a qualitative assessment (small, medium, large) of the likely size of the bias. These biases were then grouped by sign and size to give an indication of the potential for the unquantified elements to change the conclusions drawn from the assessment. Recognising the complexity of this part of the assessment, a short (1-2 page) form was developed to provide a concise but clear summary of the overall uncertainty assessment.

VOI analysis

Methods for quantifying the value of information have been described elsewhere (e.g. by Tuffaha, *et al*[59]; Wilson, *et al*[60]; Zabeo, *et al*[61]). With respect to the value of information associated with the proposed research, air pollution co-benefits of the CCC scenarios are of several types involving reduction of:

- Impacts to human health
- Burdens to the NHS
- Effects on productivity in the workforce
- Impacts to ecosystems and materials that are sensitive
- Impacts on energy use and supply (demand reduction, supply diversity, electrification, etc.)
- Less traffic congestion, less parking infrastructure and road expansions, less inequality and improved road safety due to fewer cars combined with more multi-modal mobility
- More active active lifestyles, one way to tackle the ‘obesity crisis’
- The need to undertake expensive measures specifically to reduce air pollution in hotspots.

Adding these to the scenario cost data already held by the CCC will promote efficiency in policy design. Defra estimates that the costs of air-pollution impacts to human health in the UK (including effects on productivity and the NHS) are in the region of £20 billion per year. Impacts to ecosystems and materials are lower, but still in the order of 10s or 100s of million pounds per year. Targeted action on small hotspot areas appears necessary to meet air quality limit values but can incur a very high price relative to the health benefits that are achieved. Better understanding of the links between air and the climate policies and associated co-benefits has the potential to increase the efficiency of policy-making in these areas. There are several ways in which information from the proposed study can improve the efficiency of policy-making, for example:

- Identifying actions where co-benefits may be largest in order that these can be properly accounted for in decision-making processes.
- Identifying the optimal time at which policies might promote specific technologies in order to maximise co-benefits. In some cases, a slight delay in purchase of new vehicles or equipment may prevent the adoption of technologies that are shortly-to be outdated.

Even a very small change in impacts as a consequence of recommendations made from the research would cover the costs of the research itself. Other research has demonstrated that the co-benefits through air quality improvement as a result of climate policies are substantial. Some studies even suggest that these co-benefits are sufficient to compensate for the costs of climate protection. Whilst these interactions between policies may be known in general terms (though this is not always the case), deeper understanding is required to optimise policy development. However, there are also examples where climate policy has clashed with air quality and other objectives including:

- Promotion of diesel vehicles through differential taxation on fuels, leading to increased emissions of $PM_{2.5}$ and NOx.
- Promotion of wood burning as a renewable power technology, leading to increased emissions of $PM_{2.5}$and potential loss of forest resources. The European Commission's impact assessment of the revision of its Renewable Energy Directive identified the potential for impact but stated that air pollutant emissions were covered under other legislation. On the grounds that the legislation referred to only controls, rather than eliminates, emissions, this ignores the inevitable increase in $PM_{2.5}$impact by treating a more polluting source as equivalent to less polluting technologies.
- Allowing "diesel farms" in the UK to bid to provide back-up capacity for the National Grid to cover against the intermittency of some renewable power technologies, leading to increased $PM_{2.5}$, NOx and noise.

By not accounting for the trade-offs that are present in these cases, consideration was not given to ways in which policy could be optimised to either eliminate or mitigate the trade-offs. Evaluating the value of information will be used throughout the study to improve the quality of the recommendations to be made.

Objective 2.3: Socio-economic analysis and inequalities
(Lead – Fecht, CO-Is RA1, Walton, Evangelopoulos, Dajnak, Holland)
The differential impact of the policy scenarios will be quantified across areas and populations with a view of highlighting potential exposure and health inequalities. Both small-area level air pollution at base year 2019 and for 2030, 2040 and 2050 scenarios as well as mortality and morbidity rates will be stratified by urban and rural locations, socioeconomic groups and ethnicities. National and regional trends will be analysed by exploring graphically and analytically differences at country, regional and city level.

Wards will be classified as rural or urban using the ONS rural/urban classification which is predominately based on population density in the local area. The potential of predicting urban/rural classification into the future will be explored making use of the ONS population projections at Local Authority level which will be proportionally applied to wards to predict changes in population density. Exposure and health impact differences will be explored by socioeconomic status using the small-area composite Carstairs Index as a proxy. The Carstairs Index has the advantage over alternatives in that it is a UK-wide deprivation score which includes information about unemployment, car ownership, overcrowding and low social class. No projections into the future are available but relative geographical structure of deprivation is expected to change little over the next 20 to 30 years based on comparisons of geographical deprivation patterns over the last 40 years[62]. The differential impact on ethnic minorities will be explored using ethnicity data from the national census at small area level. Ethnicity projections are currently not released by ONS but the use of experimental projections will be explored in collaboration with ONS.

Work package 3 – Public and stakeholder involvement and engagement
Objective 3.1: Stakeholder engagement and policy impact
(Lead – Williams, CO-I's Beevers, Walton, Dajnak, Brand)
We will seek to demonstrate the benefit that climate policy has on air pollution, and that the costs of achieving the net zero targets can be justified through air pollution, health and economic benefits. Our aim for short term policy impact, and to encourage longer term benefits, is to ensure air quality and health policy makers, particularly in Defra, DfT, Scottish Government, Department of Health and Social Care and Public Health England are linked with climate policy makers in BEIS and the CCC to ensure that they are all kept abreast of

our research findings. Given the important public health message, we are also aiming to engage with local authorities and directors of public health.

In the long term, our aim is to incorporate our research outputs in wider policies, for example using climate targets as part of the directors of public health aims of reducing exposure to air pollution. In addition, our project outputs represent an important part of the science-public policy interface, and here the aim would be to improve the effectiveness with which our messages are communicated to the widest range of stakeholders, so by engaging with NGOs and other interested stakeholders and the public, we hope to build on the existing public support, demonstrated by the UK Government's Clean Air Strategy consultation exercise, described previously.

To maximise dissemination and impact of the results of WP1 and 2 will be reported directly to DEFRA, DfT, Scottish Government, BEIS, DHSC, LAs, PHE and directors of Public Health, NGO's other stakeholders, our MRC Centre community advisory board and the study steering committee. Four half day meetings will enable external policy, specialist scientific, public health and public input into our research plan and for the research team to use this feedback to refine our research plan and inform the dissemination of our outputs, an important part of a developing research project. The findings will be particularly relevant to central government departments and policy-relevant briefings involving presentations of the results to key officials, will be given. In doing so, the project will provide an invaluable link between Defra's Clean Air Strategy and the recently amended UK Climate Change Act. In addition, both King's College and ICL have good links with PHE, local authorities and health professionals and adhoc briefings to these bodies will also be given.

Beevers will benefit the project at a strategic level through his strong links with the Royal College of Physicians and the Royal College of Paediatrics and Child Health.

CO-I Brand will benefit the project through his links with the DfT, Scottish Government, TfL, Sustrans, WHO Europe and WHO Global in relation to policies around active travel, climate and air quality policy.

We will also take every opportunity to publicise the work during and after the project at major conferences, King's own annual air pollution conference, held in London, through the CCC annual report to Government, as well as publishing findings in the scientific, medical literature and through conventional and social media.

Objective 3.2 – Public and community involvement and engagement
(Lead – Fecht, CO-I's, Beevers, RA3, collaborator Roberts)
Our patient and public involvement strategy has been previously outlined in response to the question: 'The ways in which patients and the public will be actively involved in the proposed research , including any training and support provided'? In brief we will include two patient and public representatives, on our Study Steering Committee, from Guy's and St Thomas' BRC Cardiovascular, Respiratory and Young People's Advisory Groups (YPAG), meeting 4 times during the project. At the start of each project year we will attend meetings of the BRC Cardiovascular, Respiratory and Young People's Advisory Group to present the overall project idea and proposed scenarios (Y1), the methodological development and preliminary results (Y2) and dissemination strategy (Y3). We will provide 3 hours of training to the PPI representatives to enable effective involvement, including short presentations and question and answer sessions, as well as support throughout the project. We will host three citizens' panels across the UK, during the first year of the project, aimed at getting input on the public acceptance, inequality and behavioural issues of the proposed policy scenarios. We will also engage with 'Mums for Lungs' and 'Parents4Future' (Yrs 2/3), testing insights from our research, to gain their support for a possible campaign. We will summarise the outcomes of each of these sessions to assess the impact of participants over the course of the project and how they shape our research.

This research is of profound relevance to patient groups affected by air pollution and the wider public, particularly young people who future policies will affect more. To ensure that we inform and engage with these publics we have identified specific target audiences: the 15-25 year olds living, working or studying in London (Lambeth & Southwark) and the BRC YPAG (14-18 year olds) to co-develop our approach to engage a wider group of teenagers and young adults. From existing dialogue with young people and the work of SGL we know that collaborations with artists enable effective engagement with complex scientific issues and are planning for an installation to attract 5,000 young people and a series of three workshops (~90 participants) for deeper dialogue with them. Broadly we expect outcomes to (1) increase knowledge and understanding of the challenges this research addresses, (2) inspire participants to share their perspectives on the research and potential policy changes, (3) change behaviours in response to current and emerging science and (3) increase their capacity to advocate to improve their circumstances in relation to both climate change and air pollution. These activities will take place in accessible public venues (i.e. where they target audiences are already such as local galleries) with the support of a range of public engagement professionals. Professional support will ensure the installation and workshops are appealing and effective. In addition we will generate project updates, young people's summaries and shareable social media content.

We will engage the support of an evaluation consultant (from the SGL network) who will ensure that the outcomes honed with young people and PPI groups are measurable as well as quantitative and qualitative methods to measure them. These will likely take the form of observations, surveys and analysis of contributions (i.e. comments/transcripts from workshops, meetings and social media). The analysis of these findings (also conducted with the evaluator) will lead to 1) more effective engagement practice within the project, 2) a short report to support engagement with policy makers and 3) heightened understanding of patient and public priorities for future research.

Research output will be widely publicised via the media to the general public. Together with the KCL, Oxford and ICL press offices we will draft press releases accompanying key publications to ensure accurate and responsible reporting in the local and national press. We will develop and maintain a dedicated social media campaign to disseminate study progress, milestones and relevant outcomes to a broad public including those unlikely to attend formal scientific meetings which will be overseen by the programme manager.

What do you intend to produce from your research?

In addition to the outputs described in 'Outcome Measures' above, we intend contributing the results of our research on the impacts of the 'Electric Vehicles' scenario to the CCC annual report in 2020, demonstrating the health and economic benefits of early adoption of EVs into the UK fleet. We will use this report to promote, to the UK Government, the remaining scenarios being considered.

We will produce three journal publications, in addition to the NIHR report, for the following areas: Nature Climate Change on the Air Pollution Modelling results, Lancet Public Health, on the health and economic impacts, BMJ Quality and Safety on the socio-economic impacts/PPI/stakeholder engagement.

We will present at two major international conferences, the Health Effects Institute conference or Planetary Health Alliance conference and the International Society for Environmental Epidemiology (ISEE) conference. The research team will present at approximately 25 UK and International conferences during the 3 year project and where appropriate will use these to promote the NIHR project.

The project will benefit from our recent experience of quantifying the health burden of air pollution in UK cities, which raised large amounts of media interest, for example our report on the health air quality health impacts in Birmingham[63] generated wide coverage by many UK media outlets (8 print outputs 5M daily audience, 4 broadcast 14M audience, 5 regional 9M audience and 17 online 400M unique users monthly). We will continue to work closely with our respective press offices (ICL and KCL) to engage effectively with the media during the reporting of our work.

The results of our work will be communicated widely to expert groups. As a consequence of our past research, several members of the team have been included on Government Expert Committees - the Committee on the Medical Effects of Air Pollutants (Heather Walton and Mike Holland) and the UK Air Quality Expert Group (Gary Fuller), as well as advising Defra on air pollution modelling (Beevers) and providing evidence to the Greater London Authority, Committee on the Environment (Beevers). We have contributed to a chapter in the CMO Annual report in the past[64] and other similar documents (Royal Society Global Environmental Research Committee[65]) and will capitalise on any similar invitations for relevant report contributions we receive to highlight the project results. Brand is member of the core WHO HEAT group as well as the UNECE Transport Health Environment Pan European Partnership (THE PEP) project steering committee, contributing to setting agendas and advising on strategic issues on transport, health and the environment. Also, one of our external steering committee members (AG) is on the WHO Task Force on Health – both are potential routes for international dissemination.

The burden of air pollution is still poorly understood by patients and the general public and through our PPI and stakeholder engagement we will develop a greater understanding of, and guidance on, addressing these complex issues with members of the public.

Our research may identify unanticipated outcomes which are the result of the complex interactions of different changes to emissions sources and pollutants at different scales. The methods we have proposed, linking the systems energy model with detailed emissions and the CMAQ-urban model, which accounts for the complex interactions of atmospheric physics and chemistry at continental to local scales, allows us to do this. Examples of unanticipated outcomes in our previous work in the UK included increased burning of biomass and non-exhaust PM_{10} and $PM_{2.5}$ emissions as possible future adverse consequences, both of which will be addressed through this proposed research.

What do you think the impact of your research will be and for whom?

The research is designed to influence the selection and timing of measures for climate mitigation in the UK in order to maximise important health co-benefits that are currently not accounted for. These are recognised in UK research and research in many other countries as being economically important and, by and large, socially just. Should our research lead to policies on climate and reduced air quality, our work will have an impact on the entire UK population, as well as wider ecosystem impacts. Furthermore, the impacts of air pollution are both local, city, but also at continental scales and so other European benefits will accrue from UK action. In the short term, our research will offer advice on what impact individuals have on air pollution and what people can do to reduce their contribution and exposure to it including whilst indoors, and any disproportionate effects on socially disadvantaged groups. This may foster, particularly in those directly engaged (~5000 young people and patients), behavioural change, when buying vehicles, heating boilers and cookers, boosting active transport and leading to a less exposed, healthier population, less dependent upon NHS care, as well as support for climate change policies more generally.

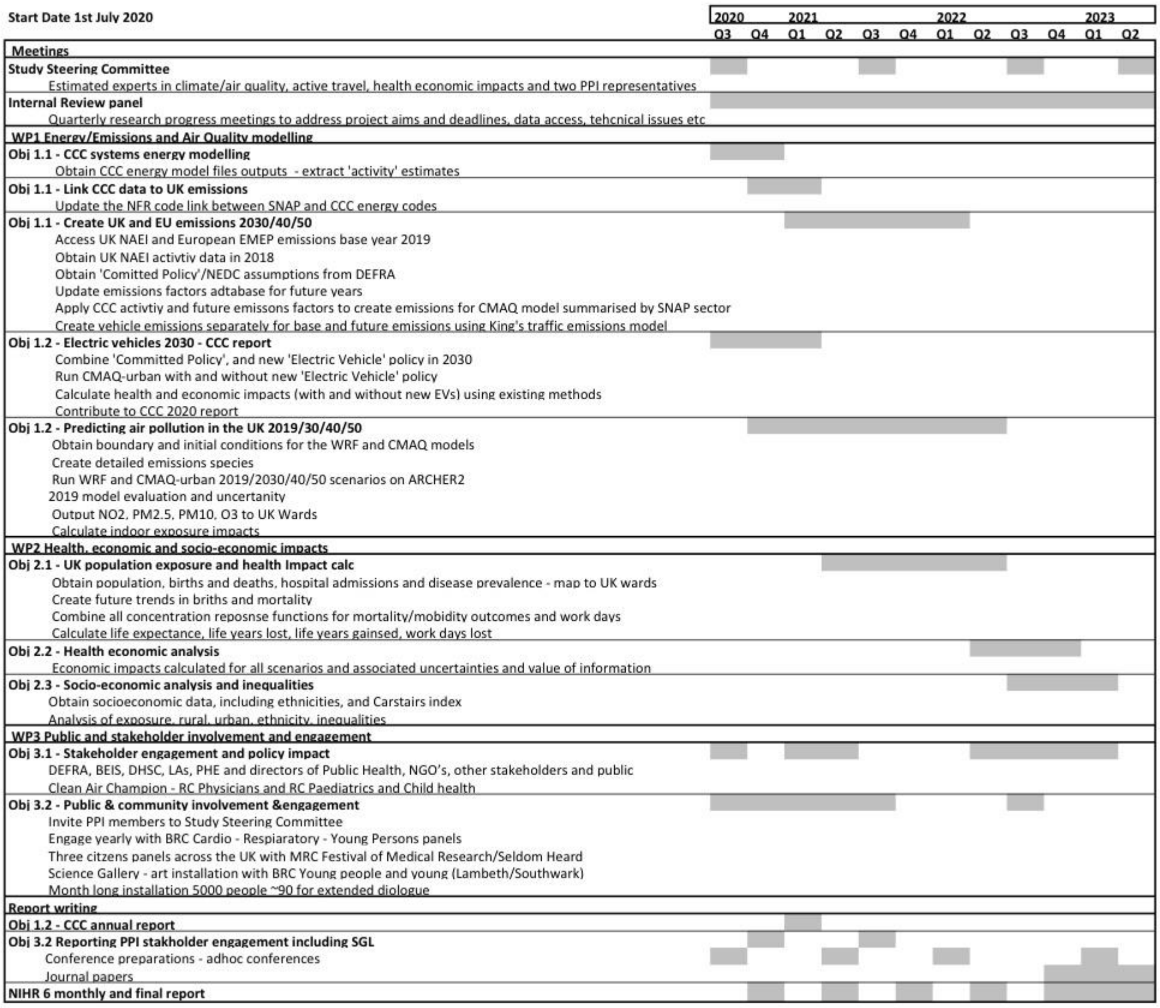
Project management and governance

The project timelines are given in Figure 1 below. In year 1 Q1 of the project the internal review panel meeting will provide a framework document for all the research team and Study Steering Committee members to add to and comment on. This will form the basis of the project plan and will be amended as the project develops. In general terms though WP 1 - will begin in year 1 with the energy systems model, emissions and air pollution data linkage as a first priority, along with the early commitment to the 'Electric Vehicle' scenario for the CCC report in 2020. The bulk of the work in WP 2 will be in years 2 and 3, since it relies on air pollution exposure information from WP 1. The bulk of the work in WP 3 is in year 1 engaging with the PPI groups and Science Gallery and then at regular intervals throughout the project. Engagement with policy makers and public health professionals will be around the time of the CCC report in year 1 and in year 3, once the bulk of the project's data becomes available.

The principal investigator of the project and contact for the NIHR will be Sean Beevers (PI), with objective leaders responsible for completion of individual objectives: David Dajnak (Objective 1.1); Nutthida Kitwiroon (Objective 1.2); Heather Walton (Objective 2.1); Mike Holland (Objective 2.2); Daniela Fecht (Objective 2.3); Sean Beevers (Objective 3.1) and Daniela Fecht (Objective 3.2). All objective leaders will be supported by project CO-I's, collaborators David Joffe and Stephen Roberts, consultant Mike Holland and newly appointed researchers RA1, RA2 and RA 3 [D Evangelopoulos].

To enhance the management and governance of the project we have included an experienced King's programme manager who will work with the PI to coordinate work packages, track project progress, schedule regular progress meetings, monitor and control the budget and prepare report documentation for the funder. The project will have an external study steering committee, meeting annually, and consisting of experts in climate and air quality policy, emissions and air quality modelling, active travel, health/economic impacts and PPI representatives. We have invited two participants from the BRC groups, will invite Dr Daniel Waterman from DEFRA, Dr Alison Gowers (PHE) with expertise in air pollution and health, Prof Paul Wilkinson (London School of Hygiene and Tropical Medicine) an academic studying air pollution/climate and health, plus others.

Figure 1 - Project research timetable



Although the project team will meet formally every quarter to monitor progress and resolve any outstanding issues, the PI's modelling team and other King's CO-Is have daily contact, ensuring good progress and resolving issues without delay. . Outside the project team Professor Frank Kelly will act as a mentor to the PI for the duration of the project. Prof. Kelly has extensive managerial experience as he has been Director of the Environmental Research Group (ERG) since 1998 and Head of Analytical, Environmental and Forensic Sciences Department at King's College London since 2003. In addition, his research leadership includes the roles of Director of the NIHR Health Protection Research Unit on Environmental Hazards (since 2014) and Deputy Director of the MRC Centre for Environment & Health (since 2009). Prof Kelly and the PI will meet formally on a 3 monthly basis to review progress and informally as required. The PI will enroll in a senior leadership programme within the first 12 months of the project.

Data management

Large amounts of data will be generated using the NERC ARCHER2 supercomputer, with data downloaded securely to King's dedicated storage servers. These are housed in air conditioned server rooms, have a building generator for backup electricity supply, as well as uninterruptible power supplies and are secured behind a private network. Servers themselves are built with RAID arrays to guard against disk failure and we back up all of our data to disk and then to tape, with an archive of tapes kept separately off site. All data collected and held within the study will comply with the Data Protection Act 1998, the KCL IT security policies are in compliance with the requirements of BS7799/ ISO27001:2005. Both King's College (registration number: Z7915194) and Imperial College (registration number: Z5940050) have Data Protection Registration.

Project/research expertise

Dr Sean Beevers **(SB)** (Reader in Air Quality Modelling, KCL) has 15 years' experience in air pollution and emissions model development, air quality policy development in London, from the Congestion Charge to the Ultra-Low Emissions Zone, and manage 6 permanent staff and 4 phd students. SB has undertaken 12 research projects in the last 6 years and in the last 2 years SB has been PI on 2 projects with the largest project having a value of £1.3 million (£650k for KCL). ***Dr Mike Holland*** **(MH)** (honorary research fellow, ICL) is a member of the Committee on the Medical Effects of Air Pollutants (COMEAP), and an expert in the assessment of air pollution on human health as well as the development of air quality and climate policies including socio-economic, cost benefit and cost effectiveness analysis. MH developed the Impact Pathway Approach for health burdens for the European Commission and DEFRA and has undertaken the cost benefit analysis for air quality policy for both. MH is also a member of working parties on health effects of indoor and outdoor air quality for the UK's Royal College of Physicians and Royal College of Paediatrics and Child Health. ***Dr Daniela Fecht*** **(DF)** (Lecturer in Geospatial Health, ICL) has over 15 years' experience in studies of environment and health with a particular focus on air pollution and health inequalities. She is an external advisor to WHO on equity issues arising from air quality interventions and provided evidence for the London Mayor's Health Inequalities Strategy. She works closely with NIHR Imperial BRC Patient Experience Research Centre to broaden the scope of PPI activities in her research and includes members of the public throughout the research cycle. ***Dr Nutthida Kitwiroon (NK)*** (Head of Regional Scale Modelling, KCL) has over 10 years experience in operating the state-of-the-science numerical models such as MM5, the Weather Research and Forecasting (WRF) model and the Community Multiscale Air Quality Modelling system (CMAQ) model for European and UK air quality modelling. Nutthida had participated in the development of national and international research programmes especially in relation to emissions processing for atmospheric modelling. ***Dr David Dajnak (DD)*** (Deputy Manager King's Modelling Group) has more than 10 years of experience in the development of the London Atmospheric Emissions Inventory and air quality modelling in support of policy in London and has developed a UK health and economic impact assessment model. ***Dr David Joffe (DJ)*** is (Team Lead - Economy-Wide Analysis at the CCC) DJ leads the Central Analysis team at the Committee on Climate Change (CCC), the statutory advisors to the UK Government and Parliament established by the Climate Change Act in 2008. His role entails leading the overall analytical approach and for decarbonisation across the UK that is grounded in evidence. DJ was lead author of 'The Fifth Carbon Budget - The next step towards a low-carbon economy' (2015) and contributory author on 'Net Zero – The UK's Contribution to stopping global warming' (2019). ***Stephen Roberts (SR)*** (KCL Research Engagement Manager) works for Impact & Engagement Services (IES) supporting researchers across King's to maximise the societal impact of their work. SR has been PI on 4 projects (>£1M total value), has experience of reviewing proposals as well as participation on panels for multiple funders. SR has led departments with responsibility for >100 staff, multi-million pound budgets, a wide portfolio of programmes involving >500 researchers and reached >500,000 members of the public each year. ***Angela Lewis (AL)*** is the Environmental Research Group Programme Manager, responsible for the overall strategic and operational management of the ERG Research portfolio (in excess of £10M), including a NIHR funded Health Protection Research Unit and King's contribution to the MRC funded Centre for Environment and Health. ***Dr Dimitris Evangelopoulos (DE)*** (Research Associate in Environmental Epidemiology and Biostatistics, KCL) has experience in air pollution epidemiology, with particular interest in the implications of multi-pollutant modelling uncertainties and measurement error correction. DE has provided statistical advice in various research projects within the Environmental Research Group, KCL, and has acted as WHO advisor on the health impacts of NO_2 in Europe and the burden of disease attributable to air pollution for the WHO Global Air Quality Guidelines. ***Dr Heather Walton (HW)*** (Senior Lecturer in Environmental Health, KCL) specialises in health impact assessment. HW was involved in the cost benefit analysis of the UK National Air Quality Strategy 2007, has worked on quantification of health benefits for the UK Committee on the Medical Effects of Air Pollutants (COMEAP) since 1996 and is now Chair of the COMEAP sub-group on Quantification of Air Pollution Risk (QUARK). HW chaired the COMEAP working group on Quantification of Mortality and Hospital Admissions Associated with Ground-level Ozone[66] which fed into the 2017 Climate Change Risk Assessment Evidence Report[67]. HW was an invited expert for both the WHO projects 'Review of the Health Aspects of Air Pollution' and on 'Health Risks of Air Pollution in Europe' which set concentration-response functions for cost-benefit analysis of policies in Europe. HW has published reports on the health benefits of air pollution alert services, the health burden of air pollution in London, the air pollution and health benefits of different routes to meeting greenhouse gas emissions targets and developing methods to estimate fine scale exposure to nitrogen dioxide for the purpose of quantification across Europe. HW previously worked on air pollution in the scientific civil service, ensuring scientific evidence on air pollution and health was appropriately communicated to those developing policy. ***Dr Christian Brand (CB)*** (Associate Professor, University of Oxford) has over 20 years' experience in research and consultancy on understanding and evaluating transport and mobility and their impacts on energy use, air pollution, health and climate change. He is Co-I of the UK Energy Research Centre where he leads on integrated analyses of transport-energy-environment-health systems at various scales to support evidence based policy making. CB was Co-I in a number of active travel studies (EPSRC 'iConnect', EC FP7 'PASTA') that investigated determinants of active travel and its impact on physical activity, travel behaviour and carbon emissions. Other work relevant to this project include transport decarbonisation scenario and policy work (for UKERC, ClimateXChange, CCC); exploring the carbon and air quality implications of dieselgate; the role of lifestyle choices and social change in achieving multiple environmental goals; and wider co-benefits of transport electrification. CB is member of the HEAT core group and led the development of the carbon impacts module for version 4 of the tool (which apart from PA now includes AQ, crash risks and carbon impacts and their monetary valuations). CB will develop existing links to DfT, Scottish Government, TfL, Sustrans, WHO Europe and WHO Global.

Ethics/Regulatory approvals

Due to the population-level nature of the project, no human tissues or individual patient records will be accessed, nor will the analytical design include individual study participants or allow for identification of individuals. We do not therefore require ethics approval for this project. Health, socioeconomic and economic impact assessment will be performed by ONS approved researchers. More specifically, mortality, hospital admissions and birth data required for the proposed research will be taken from the UK Small Area Health Statistics Unit (SAHSU) database - http://www.imperial.ac.uk/school-public-health/epidemiology-and-biostatistics/small-area-health-statistics-unit/. The SAHSU's data holdings are covered by approval from the National Research Ethics Service (reference 17/LO/0846) and by the Health Research Authority's Confidentiality and Advisory Group (CAG) approval for section 251 support (reference 14/CAG/1039). We will follow internal SAHSU processes for project registration and data extraction. If it is necessary to access any data from ONS directly, we will use the usual ONS approved researcher processes. While the timing for these processes needs to be taken into account, the health, socio-economic and economic assessments start later in the project so we do not foresee any particular difficulties with this.

Success criteria and barriers to proposed work
Success

- To demonstrate how the UK's public health and economic burden from air pollution can be reduced by the early introduction, in the 2020/30's, of the 2050 net-zero climate policies.
- To gain social acceptance and support for these policies across demographic and socioeconomic different parts of society, through our PPI and engagement activities.
- Through our socioeconomic analysis, to identify and suggest policies that do not unduly disadvantage parts of the population.
- By demonstrating that the costs of UK climate action are less than the health and economic benefits of air pollution reduction, that one or more policy be supported by the project stakeholders and/or policy makers.
- Through evidence from this research, to provide a range of individual actions, that can be adopted by the general population, to reduce air pollution and their exposure to it.
- To demonstrate the importance of combining air pollution and climate change goals.

Risks	**Mitigation**
Loss of specialist personnel	All academic team members have worked together for many years and have permanent contracts. There are also dedicated 'backup' staff should key individuals leave during the project (risk register).
Loss of computing facilities	Much of the proposed work is computer intensive and so we have identified the ARCHER 2 supercomputer platform for this work. This is secure and reliable NERC/EPSRC funded platform that we have used for many years. Note there is a short period in April 2020, where the current ARCHER computer will be switched to ARCHER 2, however we have accounted for this in our project plans.
Access to critical information	All of our critical information is open access and models are mostly open source. Other software and model computer licenses are in place and access to data from ONS and Sashu fully costed.
Data security - loss of data	In addition to the ARCHER 2 data, all results will be stored on secure computer facilities on King's site and regular backups stored separately offsite.
Support for PI	In the form of mentoring from Profs Williams and Kelly and support from a KCL programme manager, Angela Lewis.
Project delivery at risk	We have regular contact between PI and KCL (daily), ICL, collaborators and consultants. Quarterly group meetings, clearly defined roles and deliverables. A highly experienced team.

What are the possible barriers for further research, development, adoption and implementation?

We are not aware of any intellectual property protection associated with the outputs of this research, with much of the input data being available under open Government license or freely available global datasets. The purchase of other population datasets from ONS and SASHU have been fully costed. The air pollution models, WRF and CMAQ are open source and the cost of all software licenses included in the project costings. The outputs will have no associated 3rd party IP. There are also no specific regulatory hurdles related to the project. We aim to minimise the risks related to methodological error by undertaking high quality research using state of the science models and health and economic impacts methods that are recognised internationally.

Whilst we have chosen recognisable policy scenarios with public support (feasibility) and have a considerable amount of engagement with which to maximise accessibility, there remain challenges to getting the scenarios implemented (acceptability) although we hope to minimise this risk through the project team's first hand knowledge of Government, especially , Mike Holland, Christian Brand and our collaborators the CCC.

What further funding or support will be required if this research is successful (e.g. from NIHR, other Government departments, local government, charity or industry)?

None at this stage.