Public Health England

Protecting and improving the nation's health

Estimation of costs to the NHS and social care due to the health impacts of air pollution

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Contents

Glossary of terms and abbreviations

Ambient air pollution	Pollution in the surrounding area.
Attributable cases	Resulting from a specified cause. In this case, all of the cases quantified are assumed to be due to the air pollutant.
Baseline	This refers to the 'steady state' of the risk factor assuming no change from current exposure levels. However, changes in the population (for example, ageing occur).
COMEAP	Committee on the Medical Effects of Air Pollutants. An expert committee that provides advice to government on the health effects of air pollutants.
Cumulative incidence	Successive additions of annual cases of a disease. For example the cumulative incidence between 2015 and 2025 would be the sum of the new diseases cases in each of those years.
Discounting	A technique which allows the calculation of present values of inputs and benefits which accrue in the future. Discounting is based on a time preference which assumes that individuals prefer to forego a part of the benefits if they accrue it now, rather than fully in the uncertain future. By the same reasoning, individuals prefer to delay costs rather than incur them in the present. The strength of this preference is expressed by the discount rate which is inserted in economic evaluations. Since modelled interventions act over the long term (20%), it was decided to use a discount rate of 1.5% for all costs and benefits, so as to be in line with the English government and the option used in the Guide to the methods of technology appraisal (1) for interventions which have effects lasting for many years. Note that NICE may update this recommendation in 2018, but the discount rate can easily be adjusted in the tool as relevant.
Distribution	The frequency of various outcomes in a sample population. The frequency or count of the occurrences of values within a particular group or interval, and in this way, the table summarizes the distribution of values in the sample.
Dose-response	Or exposure–response relationship, describes the change in health effect on an individual caused by differing levels of exposure (or doses) to a stressor (in this case an air pollutant)

	after a certain exposure time.
$\mu g/m^3$	Microgramme per metres cubed. Microgramme is a unit of mass equal to one millionth (1×10^{-6}) of a gram.
Incidence	The occurrence of new cases of the disease – not to be confused with prevalence.
Markov	A markov model assumes that future states depend only on the current state not on the events that occurred before it.
Microsimulation	A computer model that replicates real life as closely as possible using national population and disease statistics. It can test the long term impact of a range of different scenarios on future outcomes.
NO_2	Nitrogen dioxide is a noxious gas. It is a local, primary traffic pollutant and a biologically relevant indicator of exposure to air pollution with known health effects.
PHE	Public Health England.
$PM_{2.5}$	Fine particulate matter. It is an urban background pollutant which often disperses over a large area. PM consists of finely divided solids or liquids such as dust, fly ash, soot, smoke, aerosols, fumes, mists, and condensing vapours that can be suspended in the air.
Prevalence	This is the total number of cases of a disease in a particular population. This indicates how widespread the disease is.
Probability	This is the chance of a disease occurring. Probability always lies within 0 and 1.
Regression	A statistical technique for estimating the relationships among variables.
Simulation	The imitation of a real-world process or system over time, in this case the simulation of a virtual country population.

Executive summary

Following previous reports from the Committee on the Medical Effects of Air Pollutants (COMEAP) estimating the burden of mortality from loss of life from particulate air pollution (2), this report expands on these mortality estimates by modelling the potential health burden and costs to the NHS and social care system arising due to diseases related to air pollution. Alongside these analyses, an air pollution health and social care cost analysis tool was produced for use by local authorities. This tool allows local authorities, health professionals, and policy makers to quantify the estimated future burden on air pollution related diseases and subsequent costs to the NHS and social care system. Fine particulate matter ($PM_{2.5}$; <2.5 µm in diameter) and Nitrogen dioxide (NO_2) are key air pollutants with known long-term health effects. A microsimulation model was used to project $PM_{2.5}$ and NO_2 pollutant levels into the future, and estimated the number of new cases of disease arising under several hypothetical scenarios, to inform on the potential costs to the English health and social care system.

Microsimulation is a computer technique which is a robust method for modelling the long-term health impacts of chronic diseases into the future. The baseline year for simulations is 2015 since this is the most recent year for which data on pollutant and disease epidemiology was available, and the simulations were run over 20 years. The health effects of air pollution in the population of England was simulated, as well as 2 local authorities, namely Lambeth (inner city London) and South Lakeland (Cumbria), to represent 2 extremes in air pollutant concentrations.

The simulations were run as follows for England, Lambeth and South Lakeland separately:

1. $PM_{2.5}$

- A no-change baseline scenario where exposure stays at current levels,
- A scenario where concentrations are reduced by 1µg/m^3 in one year, 2017,
- A scenario which reduces every individual's exposure to background levels[1], in order to compute the total attributable number of new diseases caused by $PM_{2.5}$ pollution.

2. NO_2

- A no-change baseline scenario where exposure stays at current levels,
- A scenario where concentrations are reduced by 1 µg/m^3 in one year, 2017,

[1] Background levels of exposure would be non-anthropogenic, i.e. pollution that is not man made such as meteorological changes. An example would be volcanic ash or sea salt.

- A scenario where the EU Limit Value for NO_2 (40 µg/m^3 per year) is met in this area,
- A scenario which reduces exposure to zero for the whole population, in order to compute the total attributable number of new diseases caused by NO_2

A summary of the main findings and policy implications from the model results are as follows:

- In England, the total NHS and social care cost due to $PM_{2.5}$ in 2017 was estimated to be £41.20 million (based on data where there is more robust evidence for an association), increasing to £76.10 million when diseases are included where the evidence is associative or emerging.
- In England, the total cost to the NHS and social care due to NO_2 in 2017 is estimated to be £1.68 million (based on data where there is more robust evidence for an association), increasing to £81.06 million when diseases are included where the evidence is associative or emerging.
- Between 2017 and 2025, the total cost to the NHS and social care of air pollution in England for where there is more robust evidence for an association, is estimated to be £1.60 billion for $PM_{2.5}$ and NO_2 combined (£1.54 billion for $PM_{2.5}$ and £60.81 million for NO_2)
- If we include the NHS and social care costs for other diseases for which there is currently less robust evidence for an association, then the estimate is increased to a total of £2.81 billion for $PM_{2.5}$ and £2.75 billion for NO_2 in England between 2017 and 2025.

When all diseases are included (i.e. where there is robust and less robust evidence):

- In England, an estimated 1,327,424 new cases of disease attributable to $PM_{2.5}$ is predicted by 2035, equivalent to 2,248 new cases of disease per 100,000 population between 2017 and 2035.
- In England, an estimated 1,140,018 new cases of disease attributable to NO_2 is predicted by 2035, equivalent to 1,933 new cases of disease per 100,000 population between 2017 and 2035.
- The number of new cases of diseases per 100,000 attributable to $PM_{2.5}$ by 2035 was estimated at 3,242 in Lambeth and 861 for South Lakeland.
- When considering the total number of new cases attributable to NO_2 by 2035, estimates for Lambeth (3,331 new cases of disease per 100,000 population) were far higher than those for South Lakeland (1,013 new cases of disease per 100,000 population attributable to NO_2 pollution).

Results from these microsimulation models show that even small reductions in air pollutants could have an impact in terms of avoiding new cases of disease up to 20 years into the future, and therefore will result in cost savings in treatment, examination and/or social care expenditure. The comparison between regions – one with low and one with high air pollutant concentrations highlight the differential impact that various policies will have, and these results can also inform on the magnitude of the effect of current guidelines, and indicate that more ambitious targets for pollutant reductions could have much greater implications for health and healthcare expenditure. Further, demographics play an important role, since relatively old populations, where air pollution exists but is lower than average, could still benefit from even small reductions in pollution.

The total number of new cases attributable to NO_2, especially in high pollution areas such as Lambeth, are far in excess of the new cases of disease potentially avoided by meeting EU Limit for annual NO_2 concentrations. It may be that in areas of high air pollution, more ambitious targets for reduction should be sought.

Introduction

Air pollution has a significant impact upon public health, with both short (3-5) and long term exposure (6-8) increasing health risks relating to conditions including cardiovascular and respiratory diseases, as well as the risk of death. The health effects due to air pollution are a key priority for Public Health England (PHE), as outlined in the 2016/17 remit letter (9). Furthermore, reducing air pollution could have a number of co-benefits, for example, by increasing workers' productivity (10), increasing active travel and consequently physical activity (11, 12), and improving the health of vulnerable groups (children, elderly and socioeconomic deprived) and those with chronic conditions such as asthma and other respiratory diseases (12, 13).

Knowing how air pollution is likely to impact health and related healthcare costs over time is important for future policy and resource planning. The Environment Audit Committee estimated that excess mortality due to air pollution cost between £8.5bn and £20.2bn a year (14). However, little research exists on the different co-morbidities arising from pollution. Treating these morbidities is expensive, for both the NHS and the social care system, but no accurate estimates of the magnitude of the NHS and social care costs exist.

In light of this, and in response to the Environment Audit Committee conclusions (15), PHE sought to develop a modelling framework to quantify the present and future morbidity (in terms of medication prescription, secondary care, primary care visit) caused by ambient air pollution. In doing this the evidence generated makes the case for investing in prevention and early intervention at local and national levels, as well as allowing the necessary resources for the cases that cannot be prevented.

The UK Health Forum (UKHF), in collaboration with Imperial College (the School of Public Health and the Business School), has built on the UKHF's existing flexible microsimulation model (16-19) and tool (http://econdaproject.eu/tools.php) to include several outdoor air pollutants as risk factors: fine particulate matter with mass median diameter ≤2.5 μm ($PM_{2.5}$) and nitrogen dioxide (NO_2). $PM_{2.5}$ is largely an urban pollutant comprising a mixture of primary and secondary particles which disperses over a large area. NO_2 is a local, primary traffic pollutant and a biologically relevant indicator of exposure to air pollution with known health effects. The potential long term impact of these air pollutants has been modelled on a number of non-communicable diseases (NCDs). This includes those with strong evidence such as coronary heart disease (CHD), stroke, asthma, and lung cancer for PM, as well as health outcomes for which the evidence for a robust association is weaker (chronic obstructive pulmonary disease (COPD)), or emerging (diabetes, dementia and low birthweight). Each pollutant has been simulated independently. Some adjustments have been made to account for the overlap between each pollutant, however, it is possible that not all of the overlap has been accounted for. It is advised that the results from each pollutant are analysed and discussed separately.

This report provides the methods and results of the modelling exercise to quantify i) the NHS and social care costs (specifically, primary care, prescription, secondary care, and social care) associated with air pollution and ii) the future incidence and cumulative incidence cases of air pollution related diseases. Results for 3 case studies are described: England, London Borough of Lambeth and South Lakeland, Cumbria.

This report also provides a description of the spin-off tool developed to enable users to estimate the NHS and social care costs associated with air pollution in a specified local authority or district council.

Methods

The microsimulation model

The microsimulation is a valuable method for risk factor and chronic disease modelling because it enables dynamical trends in risk factors to be modelled over time at the individual level. The history of an individual's exposure to a risk factor is important. The microsimulation can record this history and use it to determine an individual's future risk of chronic diseases.

The model is formed of 2 modules (see Appendix 1).

Module 1 uses a nonlinear multivariate, categorical regression model fitted to cross-sectional risk factor data to create longitudinal projections of risk factors into the future. The categories are defined by 5-year age groups and sex. Within each age and sex category of the population the predicted percentage of each of the risk factor categories are constrained to sum to 100%. This module has been adapted to include predictions of exposure to long-term air pollution ($PM_{2.5}$ and NO_2), which account for of the high spatial variability of traffic-related air pollutants in particular.

Module 2 uses a microsimulation to produce longitudinal projections of chronic diseases and the associated NHS and social care costs to the year 2035. The impact of $PM_{2.5}$ and NO_2 are assessed individually and concentrations are assumed static until 2035.

The model is initialised with a virtual cohort of a chosen size (England, region or specified local authority). The exposure of individuals within the population is based on the module 1 – the study area with specific air pollution exposure distributions (for example, England, region, specific local authority).

An individual in the microsimulation is probabilistically assigned a risk factor value (exposure level) as a function of age, sex, and calendar year, the start year being set at 2015.

The model simulates births, deaths and population size as per population statistics from the Office for National Statistics (ONS) (20). Three populations were chosen: England, Lambeth, and South Lakeland. Lambeth and South Lakeland were chosen as case studies of local areas which illustrate different examples of the exposure spectrum: very high exposure with high spatial variability in Lambeth and low exposure with less spatial variability in South Lakeland. Each year a simulated individual is at risk of developing a new NCD, dying or surviving from an existing disease or from other causes. A list of potential air pollution related NCDs is specified during the initialisation stage of the simulation.

The microsimulation also incorporates an economic module which employs Markov-type simulations of long-term health benefits and health and social care costs.

Figure 1 illustrates the modular nature of the microsimulation. The economic module has been developed to include primary and secondary care, medication, and social care costs. Further technical details of the microsimulation can be found in Appendix 1.

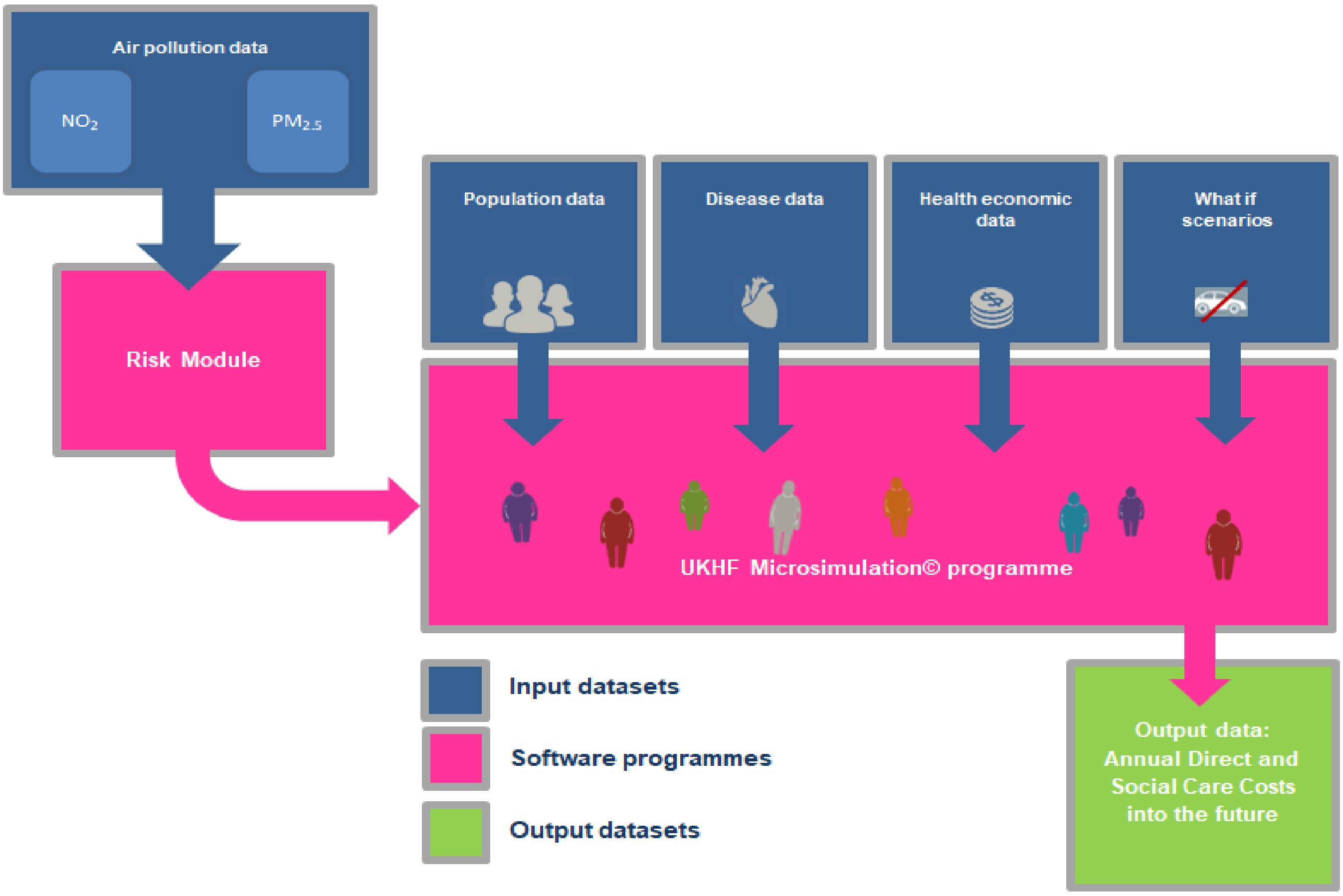

Figure 1. Pictorial representation of the microsimulation model showing the risk distribution module for each pollutant, and the modules of the microsimulation (population, disease, health economic, and scenario modules).

Uncertainty values accompany the output data representing the accuracy of the microsimulation as opposed to the confidence of the input data itself. Errors around the input data were not available.

Development of scenarios in the microsimulation

Two scenarios were developed to assess the impact of realistic scenarios on health and social care costs now and in the future (to 2035):

1. $PM_{2.5}$ model

- A no-change baseline scenario where exposure stays at current levels
- A scenario where concentrations are reduced by 1µg/m^3 in one year, 2017

- A scenario which reduces exposure to background levels for the whole population, in order to compute the total attributable number of new disease caused.

2. NO_2

- A no-change baseline scenario where exposure stays at current levels
- A scenario where concentrations are reduced by 1 µg/m^3 in one year, 2017
- A scenario where the EU Limit Values (40 µg/m^3 per year the annual average limit value) are met for all individuals
- A scenario which reduces exposure to zero for the whole population, in order to compute the total attributable number of new disease caused.

The EU Limit Value scenario was not run for $PM_{2.5}$ because England has met the EU Limit Values for $PM_{2.5.}$

Local authority tool

The local authority tool was built in C++ programming language. This is a 'spin-off' tool that is quicker and easier to run than the more complex microsimulation model. Users are able to input risk factor and population data using and Excel spreadsheet interface launched from the tool software program making it easy to use for the end user. Users can test the impact of different air pollution scenarios on the future burden of NCDs and the associated NHS and social care costs. The outputs are the prevalence of diseases and costs of diseases in terms of NHS primary care, prescription, secondary care and social care costs (note this varies from the microsimulation which produces both incidence and prevalence outputs). A full user guide is presented in Appendix 2 along with the final tool. A full methodology is presented in Appendix 1 and a comparison between the 2 methods is outlined below.

There are 4 main methodological differences between the microsimulation and the deterministic tool as outlined below.

1. Disease class

The key method of the disease class is to calculate an individual's risk (transition probability) of getting a disease based on their age, sex, current disease state, medical history and risk factor level. For stochastic transitions generated by microsimulation this probability is compared to an application-generated random number to determine if the transition takes place. In the deterministic tool this probability is included in the relevant life-disease table that both computes and lists the probabilities of being alive with no disease, within possible exclusive disease states and dead.

2. Risk factor trajectories

The microsimulation uses a representative distribution of $PM_{2.5}$ and NO_2 trajectories over time, for the whole population. In the case of $PM_{2.5}$ and NO_2 a value is sampled from this distribution and allocated to an individual in the simulation. Whereas, the tool uses only a small set of risk factor trajectories. A static or 'flat' trend was run such that exposure to each pollutant was held constant at current levels over time.

3. Population class

The microsimulation can process any specified population or cohort; the deterministic tool processes only cohorts. A population is a specified number of males and females whose age distributions and risk factor distributions are input as appropriate tab delimited text files while a cohort is made up of weighted individuals where the weight is calculated as shown in the following equation:

$$\text{cohort member weight}[i,j,k,l] = p_{sex}(i) \times p_{age}(j \mid i) \times p_{rf}(k \mid i,j)$$
$$\text{where } i \in [0,1],\ j \in [0,n], k \in [0,2]$$

Where,

$p_{sex}(i)$ is the probability of being male or female
$p_{age}(j|i)$ is the probability of having a certain age given sex
$p_{rf}(k|i,j)$ is the probability of being in a certain category given sex and age

4. Scenarios

The scenarios included within the microsimulation comprise:

- An annual decrease by 1 µg /m3 in $PM_{2.5}$ and NO_2 exposure for each individual.
- A "European Limit Values" scenario whereby all the highly exposed (>40 µg /m^3) individuals in the population of interest decrease their NO_2 exposure to the exact European threshold (40 µg /m^3).

These scenarios were not directly modelled in the tool because: there are only 3 trajectories which are based on the England tertile exposure cuts (for $PM_{2.5,}$ the exposures in the first year are 7.67, 12.9, 17.1 µg /m^3 and for $NO_{2,}$ the exposures in the first year are 10.5, 24.5 and 52.7 µg/m^3). Consequently, decreasing the annual exposure by a 1 µm /m^3 or applying a European Limit Values scenario in $PM_{2.5}$ and NO_2 would only affect 3 trajectories and might lead to great uncertainties if further assumptions are not being made. Future work could involve the evaluation of such assumptions. However, in order to take into consideration the structure of the tool, we have modelled a scenario whereby the proportion of individuals exposed as a percentage can be changed. Low, medium, high exposure was derived based on exposure tertlies across the total population in England. This was done so that the tool can draw on comparisons between groups. However, unlike the microsimulation, individual exposure trajectories were not possible in the tool.

Data collection for the microsimulation and tool

Air pollution data

We used air pollution concentration surfaces from land use regression (LUR) models covering England with a spatial resolution of 100m for $PM_{2.5}$ (21) and 200m for NO_2 (22). These models were developed to support epidemiological studies and have been extensively validated against measured concentrations from the Automatic Urban and Rural Network (AURN; www.airquality.co.uk).

When comparing measured versus modelled concentration the $PM_{2.5}$ model has a mean-squared error based R^2 (MSE-R^2) (i.e. fit around the 1:1 line) of 0.58 (22); the NO_2 model has R^2 = 0.57. Model R^2 in the magnitude of 0.50 to 0.60 are comparable to those reported in other studies, and are regarded as fit-for-propose for use in epidemiological investigations (21).

The $PM_{2.5}$ model aggregated to the local authority level compared well with $PM_{2.5}$ estimates produced by Defra at the local authority level which have been used by the DHSC Committee on the Medical Effects of Air Pollution (COMEAP). The Defra $PM_{2.5}$ estimates are on average 4 $\mu g/m^3$ lower than those from de Hoogh et al (2016) and the slope of the relationship is 0.60 when aggregated to local authorities; differences are not confined to urban or rural areas. Differences can be explained by i) the air pollution models (diffused dispersion model vs land use regression (LUR), i.e. deterministic vs statistical model), ii) the methods used to aggregate exposure to local authority level and iii) the granularity of the original surfaces (Defra: 1km x 1km, de Hoogh et al. (2016): 100m x 100m).

We adopted a method described in Gulliver et al. (2013), for extrapolation of 2009/2010 air pollution exposure estimates to 2015, the start year of the microsimulation (22). The method compares the difference in rural background concentrations at concomitant sites from the source year (i.e. the year of the model, in this case 2009/2010) and the target year (i.e. 2015) for exposure estimation. These absolute differences are then applied to extrapolate (i.e. reduce) modelled concentrations from source years to target year.

We obtained data from the AURN on rural background concentrations of NO_2 for 2009 and $PM_{2.5}$ for 2010 and for both pollutants for 2015. In England, there are 3 and 7 concomitant sites for $PM_{2.5}$ and NO_2, respectively, for all years, and with sufficient data for extrapolation purposes (i.e. at least 75% of days operating within each year). We used one site in Scotland (Auchencorth Moss) to represent $PM_{2.5}$ rural background concentrations in Northern England as there were no other geographically appropriate rural sites available. Table 1 shows average concentrations of $PM_{2.5}$ and NO_2 at rural background stations in each year and the difference in average concentrations between each pair of years. This illustrates the method used for forward extrapolation.

Table 1. Average rural and suburban background concentrations (µg/m^3) of $PM_{2.5}$ in 2010 and NO_2 in 2009 and for both pollutants in 2015 as well as absolute differences in concentrations between 2009/2010 and 2015.

Pollutant	N (sites)	Measured rural background concentrations		Extrapolation (differencing)
		2009/2010	2015	2009/2010 to 2015
$PM_{2.5}$	3	8.0	6.8	-1.2
NO_2	7	10.7	8.4	-2.3

Information on background concentrations were derived from 2015 satellite-derived $PM_{2.5}$ estimates. These estimates were obtained from the Atmospheric Composition Analysis Group at Dalhousie University, Canada (spatial scale ~ 620m x 620m). We subtracted dust and sea-salt free $PM_{2.5}$ estimates from total $PM_{2.5}$ estimates to obtain background $PM_{2.5}$ estimates. We did not include information on background NO_2 estimates as this data was not readily available for this study and most NO_2 is from anthropogenic sources with a very low, spatially non-varying background component. All the exposure input data by age and sex are presented in Appendix 3.

Exposure assignment

We intersected all postcode centroids (x,y locations) used for the collection of postcode headcount information as part of the 2011 census in England (n=1,227,431), with each air pollution surface to obtain $PM_{2.5}$ and NO_2 estimates for each postcode. We then applied a difference of -1.2 µg/m^3 to all $PM_{2.5}$ exposure estimates from the 2010 model and -2.3 µg/m^3 to all NO_2 exposure estimates from the 2009 model to forward extrapolate them for the 2015 situation (see Table 1 and related description above). In order to estimate exposures by 5-year age group and sex, we applied the census output area age-sex structure from the Office for National Statistics mid-year population estimates for 2015 to each postcode. We then derived exposure distributions by 5-year age group and sex for each exposure tertile specific to England. The same method was applied to extract background $PM_{2.5}$ exposures. Exposure tertiles for England were applied to Lambeth and South Lakeland. A summary of average prevalence for the 3 air pollution categories are shown in Table 2 and Table 3.

Table 2. Average prevalence for the 3 air pollution categories of $PM_{2.5}$ in 2015 for adults for the 3 regions of interest.

Pollutant	Population	Low air pollution prevalence (%) (< 12.3 µg/m^3)	Medium air pollution Prevalence (%) (12.3 to 13.5 µg/m^3)	High air pollution Prevalence (%) (≥ 13.5 µg/m^3)
$PM_{2.5}$	England, adults, male	33.6	33.0	33.4
$PM_{2.5}$	England, adults, female	33.6	33.2	33.3
$PM_{2.5}$	Lambeth, adults, male	0.0	0.0	100.0
$PM_{2.5}$	Lambeth, adults, female	0.0	0.0	100.0
$PM_{2.5}$	South Lakeland, adults, male	100.0	0.0	0.0

$PM_{2.5}$	South Lakeland, adults, female	100.0	0.0	0.0

Table 3. Average prevalence for the 3 air pollution categories of NO_2 in 2015 for adults for the 3 regions of interest.

Pollutant	Population	Low air pollution prevalence (%) (< 20.5 µg/m^3)	Medium air pollution Prevalence (%) (20.5 to 28.5 µg/m^3)	High air pollution Prevalence (%) (≥ 28.5 µg/m^3)
NO_2	England, adults, male	33.6	33.0	33.4
NO_2	England, adults, female	34.0	33.4	32.6
NO_2	Lambeth, adults, male	0.0	0.0	100.0
NO_2	Lambeth, adults, female	0.0	0.0	100.0
NO_2	South Lakeland, adults, male	83.6	12.0	4.4
NO_2	South Lakeland, adults, female	83.8	11.9	4.3

Disease data

A review of published literature and national statistics repositories was carried out to gather the necessary statistics for incidence, prevalence, mortality, survival, dose-response and quality of life utility weight for long-term air pollution-related diseases. The diseases included in the model were: asthma, cardiovascular disease (CVD), lung cancer, chronic obstructive pulmonary disease (COPD), stroke, diabetes, dementia and low birthweight, where relevant relative risks for the association between $PM_{2.5}$ or NO_2 exposure and incidence of disease are available, see Table 4. All these diseases were considered to be chronic, lifelong diseases with no remission possible, aside from diabetes and low birth weight which were considered non-terminal diseases from which simulated individuals could not die.

Where epidemiological parameters were not available, for instance survival rates for stroke, the parameters were computed from other sources of data. A summary of incidence, prevalence, mortality, and survival data used in the model as well as methods for computing parameters can be found in Appendix 1 (and appendix 4 for data in .txt format). Appendix 1 also provides the literature review and references for data inputs.

Dose-responses for pollutants in relation to morbidity were used as recommended by COMEAP and/or extracted from the relevant literature as presented in Table 4. Dose-response estimates for NO_2 and the morbidity outcomes were adjusted and reduced by 60% to take account of overlaps between risks based on COMEAP recommendations for mortality (23). However, no guidance exists for possible adjustments for NO_2 on $PM_{2.5}$ dose-response metrics. It must be noted that while some exposure-disease relationships have been reviewed and quantified by COMEAP (24), others have been sourced from emerging findings, and serve as the current best estimate as to what the true dose-response is. Therefore, the strength of the association with air pollution varied for each disease. Emerging health effects of pollution such as dementia and low birthweight were

excluded from the downloadable tool. See Table 4 for the dose-responses used, and see Appendix 1 for the methods for their selection and adjustment.
Table 5 summarises the findings in table 5, describing which diseases show robust associations with each pollutant ('stronger evidence') and those diseases where there are established associations and/or evidence is still emerging as to their effect ('weaker evidence').

Only dose-response relationships were available for adults, with the exception of asthma where dose-response functions were available.

Table 4. Characteristics of diseases modelled and dose-response estimates identified for each pollutant.

	Duration	Terminal	Life stage	Pollutant	
				$PM_{2.5}$	**NO_2**
Respiratory outcomes					
Asthma (children)	Chronic	Yes	Child	Khreis et al. 2016 (25) In children >6 years: OR 1.04 (1.02; 1.07) per 1µg/m^3 →Converted OR **1.48 (1.22 ; 1.97) per 10µg/m^3**	Khreis *et al.* 2016 (25) In children =<6 years : OR 1.08 (1.04; 1.12) per 4µg/m^3→*Converted to OR 1.212 (1.103; 1.328)* per 10µg/m^3→*REDUCED by 60%* → **1.08 (1.01; 1.12) per 10µg/m^3** In children >6 years: OR 1.03 (1.00; 1.06) per 4µg/m^3→*Converted to OR 1.08 (1.00; 1.16)* per 10µg/m^3→ *REDUCED by 60%* → **1.03 (1.00; 1.06) per 10µg/m^3**
Asthma (adults)	Chronic	Yes	Adult	NOT MODELLED	Jacquemin *et al.* 2015 (26) *In adults:* OR 1.10 (0.99;1.21) per 10µg/m^3 →*REDUCED by 60%* → **1.04 (0.996; 1.08*)* per 10µg/m^3**
Chronic Obstructive Pulmonary Disease (COPD)	Chronic	Yes	Adult	COMEAP 2016 (24) COMEAP recommend using PM_{10} estimate based on Cai et al. 2014 estimate for chronic phlegm in never smokers in sensitivity analyses: OR 1.32 (1.02; 1.71) per 10µg/m^3 of PM_{10} → scale to $PM_{2.5}$ using the conversion factor of $PM_{2.5}$-> PM_{10}: 0.7 (or PM_{10} -> $PM_{2.5}$:1.42) recently used in the air quality index, COMEAP: Converted to **1.49 (1.03; 2.14) per 10µg/m^3 of $PM_{2.5}$**	NOT MODELLED
Cardiovascular outcomes					
Coronary Heart Disease (CHD)	Chronic	Yes	Adult	Cesaroni et al. 2014 (27) Estimate used in CAPTOR tool from subgroup analysis of participants with additional information on CVD risk factors: HR 1.19 (1.01; 1.42) per	NOT MODELLED

				5$\mu g/m^3$→ Converted to **1.41 (1.00 - 2.01) per 10$\mu g/m^3$**	
Stroke	Chronic	Yes	Adult	Scheers et al. 2015 (28) HR 1.064 (1.021; 1.109) per 5$\mu g/m^3$ →Converted to **1.13 (1.04; 1.23) per 10$\mu g/m^3$**	NOT MODELLED
Diabetes	Chronic	No	Adult	Eze et al. 2015 (29) RR **1.10 (1.02; 1.18) per 10$\mu g/m^3$**	Eze *et al.* 2015 (29) RR 1.12 (1.05; 1.19) per 10$\mu g/m^3$→*REDUCED by 60%* → **1.05 (1.02; 1.07) per 10$\mu g/m^3$**
Cancer and other outcomes					
Lung cancer	Chronic	Yes	Adult	Hamra et al. 2014 (30) **RR 1.09 (1.04; 1.14) per 10$\mu g/m^3$**	Hamra et al. 2015 (31) RR 1.04 (1.01; 1.08) per 10$\mu g/m^3$→*REDUCED by 60%* → **1.02 (1.00; 1.03) per 10$\mu g/m^3$**
Low birth weight	Acute	No	Adult	Pedersen et al. 2013 (32) OR 1.18 (1.06; 1.33) per 5$\mu g/m^3$→Converted OR **1.39 (1.12; 1.77) per 10$\mu g/m^3$:**	Pedersen et al. 2013 (32) OR 1.09 (1.00; 1.19) per 10$\mu g/m^3$→*REDUCED by 60%* → **1.04 (1.00; 1.07) per 10$\mu g/m^3$**
Dementia	Chronic	Yes	Adult	NOT MODELLED	Oudin et al. 2016(33) HR 1.08 (1.00; 1.16) per 10$\mu g/m^3$ NOx. Scaling factor: NOx → NO2: 0.44 which was developed by Anderson et al. based on the ratio that fell midway between the average or roadside vs urban background monitoring sites in London for 2001 (see Online Supp 2) (34) Converted from NOx to NO2:HR 1.03 (1.00; 1.07) →REDUCED by 60% → **1.01 (1.01; 1.03) per 10$\mu g/m^3$ of NO_2**
NOTE: Dose-response estimates of pollutant-health outcomes shaded in red reflect health outcomes for which the evidence is weaker or is emerging evidence in relation to air pollution.					

Long term exposure to $PM_{2.5}$

There is strong evidence for a robust association of long term exposure to $PM_{2.5}$ with CHD (35-37), stroke (35-37), lung cancer (38) and asthma exacerbations (35-37). There is also increasingly strong evidence that associations with development of asthma in children may be causal (36).

Although there is some evidence of an association between the incidence or prevalence of chronic bronchitis and long-term exposure to air pollution (mainly particulate matter measured as PM_{10}) it is not sufficient to infer a robust relationship. COMEAP recommends that only sensitivity calculations are undertaken (39). There is emerging evidence of significant associations between $PM_{2.5}$ and low birth weight (35, 36), whilst evidence between diabetes and long term exposure to $PM_{2.5}$ has recently begun to emerge (35, 36).

Long term exposure to NO_2

The evidence for long-term exposure to NO_2 and health effects is less certain than that for fine particulate matter. It is possible that, to some extent, NO_2 acts as a marker of the effects of other traffic-related pollutants. The evidence has, however, strengthened in recent years and COMEAP note that the epidemiological and mechanistic evidence suggest that it would be sensible to regard NO_2 as causing some of the health impact found to be associated with it in epidemiological studies (40).

There is strong evidence a robust association for exacerbations of asthma (41) and NO_2. There is increasing evidence that the associations of long term exposure to NO_2 with development of asthma in children may be causal (36, 41).

The evidence between NO_2 exposure and diabetes (35, 36, 41), low birth weight (36, 41) and dementia (36) has recently begun to emerge. Compared to children, there is less evidence that asthma in adults is associated with NO_2 (35, 41) and lung cancer studies have revealed associations with NO_2 but the mode of action by which NO_2 could directly cause cancer is unclear. It may be acting as a marker for other pollutants (41).

Table 5. Summary of established robust associations ('strong evidence') and less robust associations ('weaker evidence') for $PM_{2.5}$ and NO_2

	Long term exposure to $PM_{2.5}$	Long term exposure to NO_2
Stronger evidence for an association	Coronary heart disease Stroke Lung cancer Asthma (children)	Asthma (children)
Evidence less certain or emerging evidence of associations	Chronic Obstructive Pulmonary Disease (as chronic bronchitis) Diabetes Low birth weight	Asthma (adults) Diabetes Lung cancer Low birth weight Dementia

Health and social care economic data

The main purpose of the project is to identify the direct NHS and social care costs associated with treatments and services for specific health conditions that are covered by public funds. We distinguish 5 different categories of health care and health care related costs: primary care costs, prescription costs, inpatient costs, outpatient costs, and social care costs. Additional types of care such as A&E and ambulance costs are also extracted from the literature when available and are listed below, but are not taken into account in the microsimulation model.

The main types of costs can be briefly defined as follows:

- Primary care is often the primary point of contact of someone seeking care. GP visits are the main source, but we have also included in the computation of the costs, when available, the different types of services offered by most of the GP practices. These include nurse visits, home visits, and phone/email/fax consultations.

- Prescription costs are usually estimated as the volume times the costs of primary care prescription.
- Inpatient costs are the total costs of treating a patient at hospital for a specific diagnosis (episode). They include day cases, elective and emergency admissions.
- Outpatient costs capture the costs of visits to specialists.
- There are large variations in the definition of social care. They are due to the lack of the data and the need to rely on some proxy measures, and the lack of a clear definition of what counts as social care. Social care costs usually capture costs related to informal cares that are funded publicly.

We have not included in our different costs indirect costs such as the loss of income when hospitalised.

In order to derive the NHS costs associated with each health condition, we used 2 different sources of data: costs extracted from the literature and the hospital episode statistics (HES). We identified the relevant literature using PubMed and MeSH terms, or Google when no peer-reviewed article reported the costs of interest. Appendix 5 describes the costs extracted from the literature in more detail. All the costs were adjusted for England, inflation, and prevalence when not available for 2015.

Primary care costs and prescriptions

We extracted primary care costs from the literature. In general, these costs included not only GP visits, but also most of the related services available from GP practices such as nurse visits, home visits, and phone/email/fax consultations. Prescription costs were also extracted from the literature. They cover, or have been adjusted, to represent all the prescriptions from an NHS primary care provider. Hospital based prescribing was not included.

Secondary care costs

Secondary care costs are composed of outpatient visits and inpatient hospital stays.

Outpatient care refers to visits to specialists. These costs were extracted from the literature.

Inpatients hospital stays were analysed using the Hospital Episodes Statistics (HES) data. We identified patients with the conditions of interest based on the main diagnosis at admission (ICD-10). Appendix 1 reports the list of ICD-10 codes selected for the analysis. The basic unit in the HES dataset is the finished consultant episode (FCE). This is the total treatment an individual remains under the care of a single consultant. Therefore, a single admission may consist of several episodes, but often is only one episode. In order to derive the healthcare utilisation of individuals suffering from the health conditions of interest, we adopted a conservative approach and considered only the episodes for which the main diagnosis was associated with the health condition of interest. We focused on

2010 as this was the most recent year for which we had all the relevant information, and we restricted our sample to finished episodes.

The NHS is funded through government taxation and each NHS Trust for the years this data come from was reimbursed based on a system called Payment by Results (PbR). (It is now done by NHS England and NHS Improvement). Each trust is reimbursed according to activity related to Healthcare Resource Groups (HRGs). HRGs are groups of similar clinical treatments that require common levels of health resources. Each FCE has a corresponding HRG derived based on the patient's primary diagnosis. Excel files containing the National Tariff Schedule (PbR) were downloaded from the National Archives of the Department of Health for fiscal years 2009 to 2010 and 2010 to 2011. There have been several structural and institutional reforms to reference cost collection. These are crucial when making comparisons between the years and to accurately link reference costs with HES. We matched the tariffs to HRG version 4.0. and estimated the cost for 2010.

Market Forces Factor (MFF) are applied to tariff reimbursements to account for regional differences in the cost of land, capital and labour. MFFs are calculated for each NHS provider and published alongside the National Reference Cost Index (RCI). Reimbursement to a Trust only occurs in the fiscal year an episode is completed. Therefore, if an episode commenced in March 2009 and closed in May 2009, the Trust would be reimbursed according to the PbR Tariffs for fiscal year 2009 to 2010. We matched the relevant MFF to our data, adjusted the tariffs with the MFF, and corrected the final costs for prevalence and inflation for 2015 for each health condition.

Social care

Social care comprises of a broad range of activities associated with the tasks of everyday living, from child protection services to end-of-life care. Social care is delivered by a wide range of organisations and professionals, and within families and communities. Key personnel involved in social care includes, but are not limited to, social workers, occupational therapists, nurses and care workers. Unlike the NHS, social care is not free at the point of use. Social care is delivered by various organisations across the country and funded through private out of pocket payments, by the local government or a mixture of the two. Councils are the single largest purchaser of care services; sourcing the finances from a mixture of central government grants, council tax, user charges, business rates, and contributions from the NHS. However, access to public social care services is means-tested and an individual needs to meet certain care requirements. The Kings' Fund estimates that at least 50% of expenditure is private as very few individuals meet the criteria for public social care (24).

The diverse and broad nature of social care activity, coupled by the fact that services are delivered by various organisations and bodies, relates to the lack of comprehensive data on utilisation of social care services. As a result, there are variations in the method used to estimate social care.

Overall cost per case

The microsimulation model uses cost per case to calculate the total healthcare costs incurred due to the prevalence of disease in a scenario.

Costs were available from the Imperial Business School in 3 different formats, see Appendix 5: they were provided as total costs (in £ million) for England or the UK depending on the study; as costs per case, or as cost per death.

Summary of NHS and social care cost input data

Table 6 summarises the sources of costs used in the microsimulation. Inpatient costs were estimated based on the Hospital and Episode Statistics (HES) data that represents all NHS admissions. The rest of the costs were extracted from the literature.[2]

All of the costs were adjusted using prevalence when necessary to represent the total cost per type of care and per disease group for England. For the microsimulation model, we need the cost per case that is the total cost divided by the prevalence in 2015. Therefore this figure is not necessarily equal to the unit cost as patients use different combinations and quantities of care. The implications of a low birthweight are wide and complex, with a large degree of heterogeneity. Furthermore, it can be a risk factor for other diseases, and therefore was too complex to cost. Therefore, we only provide epidemiological outputs for this condition.

Table 6. Summary of data sources used for type of care by chronic disease

	Stroke	Asthma	CHD	Lung Cancer	COPD	Dementia	Diabetes
Inpatient	H	H	H	H	H	L	H
Outpatient	L	L	L	L	L	L	L
Primary care	L	L	L	L	L	L	L
Prescriptions	L	L	L	L	L	L	L
Social care	L	L	L	L	L	L	L

Notes: H: hospital and episode statistics (HES); L: costs extracted from the literature

Relevant sources were collated using a systematic literature review with Mesh terms in PubMed, and completed using Google searches. We also considered NICE costing tools and/or economic modelling reports. While multiple studies from the search results were considered, the most relevant, recent studies were used for the final cost estimates. The search terms are summarised Appendix 5. The majority of search results were disregarded because they were theoretical, the cost breakdown was not granular enough or the figures were based on literature that had previously already been stated within the literature review. Papers which have been considered for the final cost estimate are listed in the consecutive tables, while it is also indicated which estimate was used for the final model. If the search with Mesh terms on PubMed returned no results, Google was consulted as a supporting search engine.

[2] We also considered using the Programme Budgeting data, but were advised by NHS England that it does not fully capture the actual health care expenditures, in particular for social care costs.

Appendix 5 provides an overview of the overall NHS and social care costs used in the microsimulation model per type of care. These costs were adjusted for inflation in 2015-16 using the Hospital and Community Health Services inflation index,[3] and divided by the prevalence in order to calculate a "cost per case".

Studies which are recommended not to be used for the final model are highlighted in a grey font. If more than one study reported costs, the final cost estimate was chosen based on recency, definition of care and approach used. It was shown that bottom up approaches lead to more precise estimates. As such, this methodology was preferred over others.

Table 7 presents the cost per case based on total prevalence of each disease. All of the sources are described in Appendix 5.

Table 7. Cost-per-case based on total prevalence of each disease, expressed in £ per case

Cost type (£ per case)	Primary Care	Social Care	Medication	Secondary care
Coronary Heart Disease (CHD)	71.57	109.70	818.60	1460.46
Stroke	36.45	76.05[1]	504.10	722.84
Asthma ALL AGES	21.28	0.50[1]	87.57	27.02
Lung cancer	51.73	89.38[1]	35.10	466.63
Chronic Obstructive Pulmonary Disease (COPD)	400.43	85.30[1]	126.79	587.48
Diabetes	375.00	601.56[1]	276.88	536.75
Dementia	430.62	6174.47	310.24	197.24

[1] indicates cost per death for palliative care

In the model costs were discounted at 1.5% for all costs and benefits, so as to be in line with the English government and the option used in the Guide to the methods of technology appraisal (1) for interventions which have effects lasting for many years.

Population data

Population projection data for 2015 was gathered from the ONS Open data (42) for England, Lambeth and South Lakeland. Data included the distribution of males and females by 5 year age group, birth rate by maternal age, and mortality rate by 5 year age group and sex as well as the total fertility rate. See Appendix 1 for sources of national and local authority data.

[3] Department of Health (2015.6 Pay & Price series.xls) "Hospital and Community Health Services (HCHS) pay and price inflation is a weighted average of 2 separate inflation indices, the Pay Cost Index (PCI) and the Health Service Cost Index (HSCI)"

Results

Results from the microsimulation are presented as rates per 100,000 population then scaled to the respective population for that year, as estimated by ONS population projections (43). Please note, that the number in the total column is calculated during the initial run of the simulation, then afterwards the rate per 100,000 tables have been scaled to the total population and the numbers rounded to the nearest integer. Therefore, there are slight rounding errors, such that small discrepancies between the sum of the row and the total column are observed.

The outputs are defined in the following ways:

A. Epidemiological outputs

1. Attributable incidence per 100,000 people or per total population over the simulation period.

The number of new cases of disease attributable to air pollution as a rate per 100,000 or per population.

2. Cumulative incidence per 100,000 people or per total population over the simulation period.

The total number of new cases of disease, divided by the total number of people in the population in a given year, and accumulated over a specified period of the simulation from year 2015. Therefore, the cumulative number of incident cases represents a sum of all of the incident cases from the start of the simulation.

3. Cumulative incidence avoided per 100,000 people or per total population over the simulation period.

The total number of incident cases of disease avoided since the start year 2015 as compared to baseline 'no-change' scenario. A positive value represents the number of cases avoided.

B. Economic outputs

These NHS and social care cost outputs include all of the diseases identified (i.e. those with 'stronger' and 'weaker' evidence).

4. Attributable NHS and social care costs per 100,000 people or per total population over the simulation period.

These are costs attributable to air pollution each year of the simulation from 2017 to 2035[4].

5. Annual NHS and social care costs avoided per 100,000 people or per total population over the simulation period.

The annual NHS and social care costs avoided as a result of each scenario relative to baseline.

6. Cumulative NHS and social care costs avoided per 100,000 people or per total population over the simulation period.

These are cumulative NHS and social care costs across the period of the simulation. The result for 2020 represents the cumulative costs avoided for the period 2015 to 2035.

The confidence limits that accompany the sets of output data represent the accuracy of the microsimulation (stochastic, or aleatoric uncertainty) as opposed to the confidence of the input data itself (parameter uncertainty). Errors around the input data were not available.

[4] Note that each scenario is implemented in 2017. The model was started from 2015 since this is in line with the date of the population statistics.

Summary results and regional comparisons

The following diagrams illustrate the population distribution by age and sex of each of the 3 regions of interest (England, Lambeth, South Lakeland). These show that the population of Lambeth is relatively young compared with England and South Lakeland with around 20% of 20 to 29 year olds, compared with 13% in England, and around 8% in South Lakeland. South Lakeland has a much older population, with around 15% of 60 to 69 year olds, compared with 6% in Lambeth and 11% in England. The differences in age profiles will contribute to differences in disease outcomes observed. Appendix 6 presents a comparison where exposure is held constant and run across different populations.

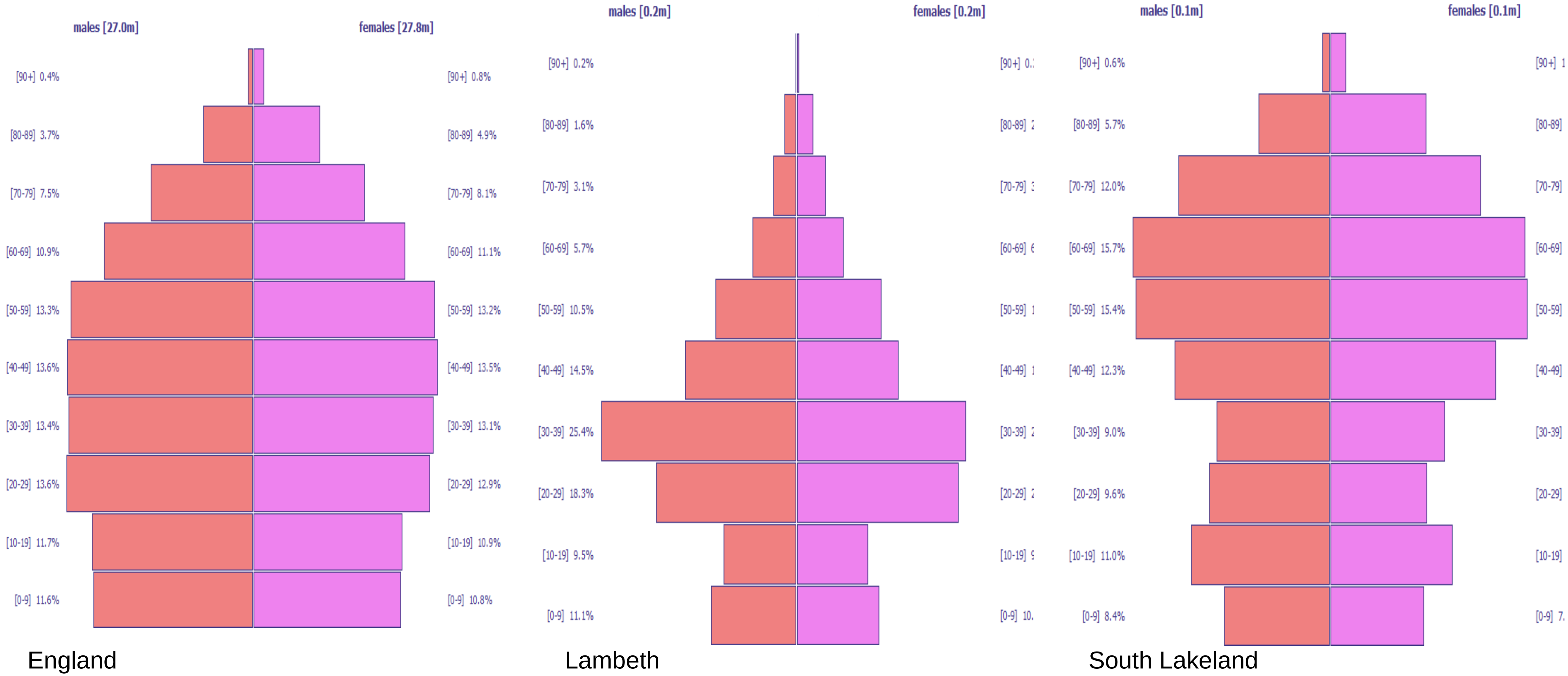

Figure 2 Population distribution by age group and sex for England, Lambeth and South Lakeland using mid year population estimates for 2015

Summary of the total disease cases and NHS and social care costs attributable to PM2.5 per 100,000 population and disease cases and NHS and social care costs avoided for each scenario.

Table 8 presents the cumulative incidence cases per 100,000 and total NHS and social care costs per population attributable to $PM_{2.5}$. In 2017 the attributable cases of disease due to $PM_{2.5}$ were estimated to be 114 per 100,000 population in England, with 159 and 44 attributable cases per 100,000 population in Lambeth and South Lakeland respectively. This represents a total NHS and social care cost of £76.10 million, 0.62 million and 0.08 million per total population for England, Lambeth and South Lakeland respectively.

From 2017 to 2025 the highest number of diseases attributable to air pollution from $PM_{2.5}$ by 2025 is observed in Lambeth. Attributable cases in Lambeth are 3 times that of South Lakeland (1,484 vs 413 per 100,000 cases by 2025 for Lambeth and South Lakeland respectively), while a total 1,062 cases per 100,000 were attributable to $PM_{2.5}$ in England. This represents a cumulative total NHS and social care cost of £2.81 billion, £22.07 million and £2.38 million in the total population of England, Lambeth, and South Lakeland respectively. From 2017 to 2035 it is predicted that 3,242 cumulative incidence cases per 100,000 population will be attributable to $PM_{2.5}$ exposure in Lambeth, compared with 861 cases per 100,000 population in South Lakeland and 2,248 per 100,000 population in England. This represents a total NHS and social care cost of £9.41 billion, £80.26 million and £7.45 million per population for England, Lambeth, and South Lakeland respectively.

Table 8. Cumulative incidence cases per 100,000 and total NHS+social care costs per £million/population attributable to $PM_{2.5}$

Year(s)	Region	Attributable cases/per 100,000	Attributable costs £million/population
In 2017	England	114 [±4]	76.10[±8.23]
	Lambeth	159 [±4]	0.62[±0.04]
	South Lakeland	44 [±4]	0.08[±0.02]
2017-2025	England	1,062 [±12]	2814.79[±27.28]
	Lambeth	1,484 [±12]	22.07[±0.13]
	South Lakeland	413[±11]	2.38[±0.06]
2017-2035	England	2,248 [±17]	9408.71[±45.38]
	Lambeth	3,242 [±17]	80.26[±0.23]
	South Lakeland	861 [±16]	7.45[±0.10]

Table 9 presents a summary of the cumulative incidence cases avoided and NHS and social care costs avoided by region and year for $PM_{2.5}$ for the 1µg/m^3 reduction scenario relative to baseline. Results are presented as rates per 100,000 population for comparative purposes. Reducing $PM_{2.5}$ by 1µg/m^3 would result in the highest number of cumulative incidence cases and NHS and social care costs avoided in Lambeth by 2025 and England by 2035. However, there are marginal differences between the regions which may be explained by both differences in air pollutant exposure and population demographics.

Table 9. Summary of cumulative incidence cases avoided per 100,000 and cumulative NHS and social care costs avoided per £million/100,000 by region for $PM_{2.5}$

Years	Region	**Scenario 1: 1µg/m^3 reduction in $PM_{2.5}$** Total cumulative new cases avoided per 100,000	Total cumulative costs avoided (£million/100,000)
2015-2025	England	146 [±9]	0.72[±0.05]
	Lambeth	153 [±9]	0.72[±0.04]
	South Lakeland	119 [±9]	0.60[±0.06]
2015-2035	England	314 [±9]	2.42[±0.08]
	Lambeth	310 [±9]	2.35[±0.07]
	South Lakeland	240 [±9]	2.05[±0.09]

Figures illustrating the comparisons by region, by disease, and scenario are presented in Appendix 7.

Summary of the total disease cases and NHS and social care costs attributable to NO2 and cases avoided for each scenario per 100,000 population

Table 10 presents the cumulative incidence cases per 100,000 and total NHS and social care costs per population attributable to NO_2. In 2017 the attributable cases of disease due to NO_2 are 109 per 100,000 population in England, with 179 and 57 attributable cases per 100,000 population in Lambeth and South Lakeland respectively. This represents a total cumulative NHS and social care cost of £79.26, £0.68, £0.10 million/population in England, Lambeth, and South Lakeland respectively.

From 2017 to 2025 the total number of attributable cases (per 100,000) of new disease if NO_2 levels remain the same is predicted to be 943 [±15], 1598 [±10], 491 [±15] for England, Lambeth, and South Lakeland respectively. This represents a total cumulative NHS and social care cost of £2.75 billion, £24.41 million, and £3.19 million/population for England, Lambeth, and South Lakeland respectively.

From 2017 to 2035 the total number of attributable cases of new disease if NO_2 levels remain the same are predicted to be 1933 [±22], 3331 [±16], and 1013 [±22] per 100,000 for England, Lambeth, and South Lakeland respectively. Therefore, the highest numbers of new cases of disease attributable to NO_2 are expected in Lambeth where incidence over time is expected to reach more than 3 times that of South Lakeland. This represents a total cumulative NHS and social care cost of £9.16 billion, £90.20 million, and £9.74 million per population for England, Lambeth, and South Lakeland respectively.

Table 10. Cumulative incidence cases per 100,000 and total NHS+social care costs per £million/population attributable to NO_2

		Attributable cases/per 100,000	Attributable costs £million/population
In 2017	England	109 [±5]	81.06[±16.31]
	Lambeth	179 [±3]	0.69[±0.06]
	South Lakeland	57 [±5]	0.10[±0.04]
2017-2025	England	943 [±15]	2749.91[±54.75]
	Lambeth	1598 [±10]	24.41[±0.23]
	South Lakeland	491 [±15]	3.19[±0.12]
2017-2035	England	1933 [±22]	9159.22[±92.71]
	Lambeth	3331 [±16]	90.20[±0.4]
	South Lakeland	1013 [±22]	9.74[±0.21]

Table 11 presents a summary of the cumulative incidence cases avoided and NHS and social care costs avoided for each scenario per 100,000 by region and year for NO_2. Results are presented as rates per 100,000 population for comparative purposes. Reducing NO_2 by 1µg/m^3 would result in approximately 30 cumulative incidence cases avoided by 2025 in each region illustrating little significance difference between regions. Though, by 2035 the highest disease cases avoided would be found in South Lakeland (70 cases per 100,000). This corresponds to NHS and social care costs avoided of £0.54 million, £0.60 million and £0.75 million per 100,000 in Lambeth, England, and South Lakeland respectively, scaled to £1.97 million, £355.28 million, and £0.78 million per total population.

Reducing NO_2 to meet the EU Limit Value is estimated to result in a substantial number of cumulative incidence cases avoided in Lambeth (463 cases per 100,000) compared with 170 cases in England and 25 cases in South Lakeland by 2025. By 2035 this increases to 956, 382, 59 cases for Lambeth, England, and South Lakeland respectively. This corresponds to NHS and social care costs avoided of £7.28 million, £2.84 million and £0.48 million per 100,000 in Lambeth, England, and South Lakeland respectively, scaled to £26.46 million, £1.7 billion, and £0.50 million per total population.

Table 11. Summary of cumulative incidence avoided per 100,000 and cumulative NHS and social care costs avoided per £million/100,000 by region for each scenario for NO_2

		Scenario 1: 1µg/m^3 reduction in NO_2		Scenario 2: EU Limit Values met for NO_2	
		Total cumulative new cases avoided	**Total cumulative costs avoided £million/100,000**	**Total cumulative new cases avoided**	**Total cumulative costs avoided £million/100,000**
2015 - 2025	England	32 [±13]	0.19[±0.1]	170 [±13]	0.78[±0.1]
	Lambeth	28 [±9]	0.15[±0.07]	463 [±9]	2.15[±0.07]
	South Lakeland	33 [±13]	0.30[±0.13]	25 [±13]	0.13[±0.13]
2015- 2035	England	59 [±13]	0.60[±0.16]	382 [±13]	2.84[±0.16]
	Lambeth	57 [±9]	0.54[±0.12]	956 [±9]	7.28[±0.11]
	South Lakeland	70 [±13]	0.75[±0.21]	59 [±13]	0.48[±0.21]

England results

The following results for England are presented by pollutant and are presented as total cases in the England population. Rates per 100,000 population are presented in Appendix 8a.

Epidemiological outputs for $PM_{2.5}$ in England

The total attributable new disease cases and relative NHS and social care costs were modelled, and scenarios quantifying the impact of a 1µg/m^3 reduction in 2017 in England was approximated. The diseases modelled were: asthma, COPD, diabetes, CHD, lung cancer, stroke, and low birthweight.

Estimating the total health and NHS and social care cost impacts of PM2.5 concentrations (the attributable burden of PM2.5)

By 2035 it was predicted that there would be 1,327,424 [±9919] new cases of disease attributable to $PM_{2.5}$. CHD and diabetes cases were the greatest contributors to the total cases attributable, with 348,878[±2561] and 273,767[±7683] attributable to $PM_{2.5}$ between 2017 and 2035, respectively (see Table 12).

Table 12. Cumulative incidence cases attributable to $PM_{2.5}$ in England, by disease and total between 2017 and 2035.

Year	CHD	Stroke	Asthma	Lung cancer	COPD	Diabetes	Low birthweight	Total
2017	16,136 [±556]	4,451 [±556]	5,564 [±556]	1,669 [±556]	11,684 [±556]	14,467 [±1669]	9,459 [±556]	63,430 [±2154]
2017-2025	154,053 [±1717]	47,499 [±1717]	62,992 [±1717]	20,636 [±1717]	112,235 [±1717]	127,578 [±5152]	82,924 [±1717]	607,917 [±6651]
2017-2035	348,878 [±2575]	106,331 [±2575]	133,356 [±2575]	44,290 [±2575]	246,916 [±2575]	273,767 [±7725]	173,886 [±2575]	1,327,424 [±9972]

Table 13 presents the NHS and social care costs attributable to $PM_{2.5}$ in England between 2017 and 2035. By 2035 it was predicted that there would be £9,409million [±45.4] (£9.41billion) NHS and social care costs attributable to $PM_{2.5}$. Secondary care and medication costs were the greatest contributors to the total cases attributable, with £4,538million [±32.18] (£4.5 billion) and £2,426million [±18.11] (£2.4 billion) attributable to $PM_{2.5}$ between 2017 and 2035, respectively (Table 13). NHS and social care costs attributable to $PM_{2.5}$ by disease and cost metric are presented in Appendix 8d.

Table 13. NHS and social care costs attributable to $PM_{2.5}$ in England, between 2017 and 2035 (£million)

	Primary Care	Secondary Care	Medication	Social Care	Total
In 2017	10.45[±2.59]	36.83[±5.84]	18.81[±3.29]	10.01[±4.02]	76.1[±8.2]
2017-2025	332.02[±8.59]	1368.7[±19.34]	718.53[±10.88]	395.54[±13.35]	2814.8[±27.3]
2017- 2035	1070.37[±14.27]	4537.67[±32.18]	2425.98[±18.11]	1374.69[±22.18]	9408.7[±45.4]

Modelling scenarios

Baseline scenario

In England, a total of 14,918,516 [±8503] new cases of disease were estimated to be accrued over 20 years in a no change scenario between 2015 and 2035 (see Table 14).

Scenario 1: the impact of reducing $PM_{2.5}$ concentrations by 1 µg/m^3 in one year (2017)

The impact of a 1 µg/m^3 reduction in $PM_{2.5}$ concentration in one year only (2017) was assessed in terms of the disease cases avoided, compared to the no change scenario: There were negligible differences in the first few years (2015 - 2017) in comparison to the baseline as this scenario does not take effect until 2017 (see Table 14).

Figure 3 shows the contribution of each disease to the total number of new cases of disease avoided by 2035 due to a 1µg/m^3 reduction in $PM_{2.5}$ in 2017. The highest number of disease cases attributable to $PM_{2.5}$ were for CHD, diabetes and COPD with 50,947 [±2689], 42,123 [±8066] and 40,312 [±2689] cumulative cases avoided by 2035 respectively. Low Birth Weight is shaded since the evidence is less robust for this disease.

Table 14. Total cumulative incidence cases and cases avoided for baseline and 1 μg/m^3 reduction in $PM_{2.5}$ in England.

Year	Baseline	Scenario 1: 1μg/m^3 reduction in $PM_{2.5}$	
	Cumulative incidence cases	Cumulative incidence cases	Cumulative incidence cases avoided (relative to baseline)
2015	628,325 [±1730]	629,421 [±1730]	-1,096 [±2120]
2015-2017	1,909,317 [±3021]	1,903,723 [±3021]	5,593 [±3702]
2015-2025	7,384,198 [±5958]	7,300,462 [±5958]	83,731 [±7297]
2015-2035	14,918,516 [±8503]	14,732,853 [±8503]	185,663 [±10414]

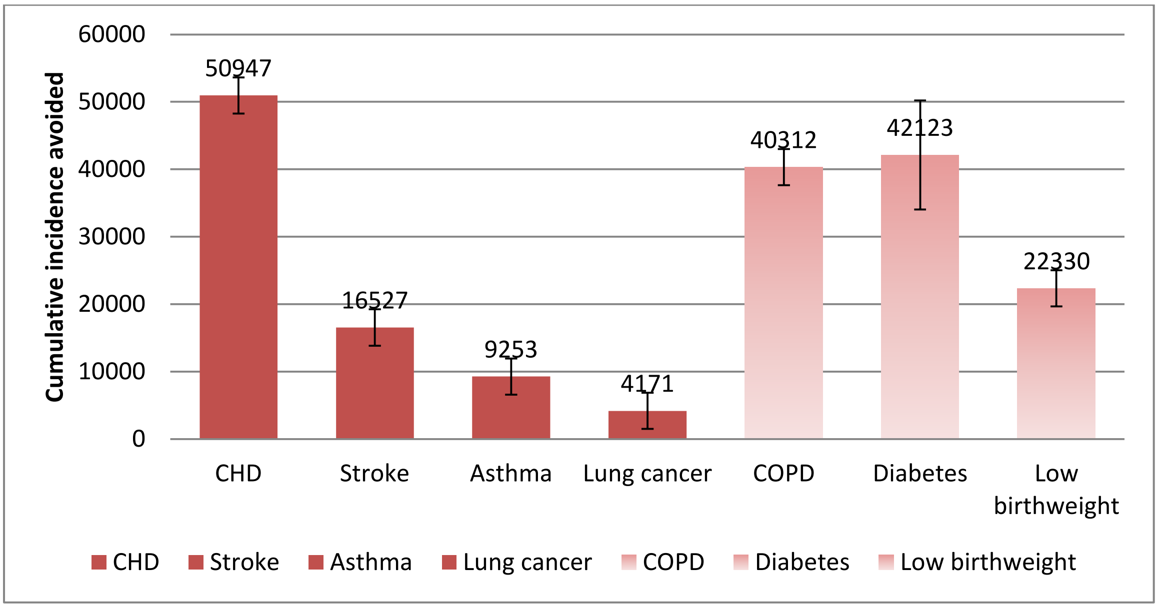

Figure 3. Cumulative incidence cases avoided for 1 μg/m^3 reduction in $PM_{2.5}$ (scenario 1) by 2035 in England, by disease. Note: COPD is chronic bronchitis only, and the evidence for diabetes and Low Birth Weight is less robust so are shaded.

NHS and social care cost outputs for $PM_{2.5}$ in England

Table 15 presents the NHS and social care costs avoided as a result of a 1 μg/m^3 reduction in $PM_{2.5}$ concentration compared to the no change scenario. Between 2015 and 2035, the total NHS and social care cost avoided was predicted to be of £1,379.07 [±132.43] million (£1.38billion). This largest contributor to this cost was secondary care costs £644.45 [±33.55] million (£0.64billion).

Table 15. Cumulative NHS and social care costs avoided for 1 μg/m^3 reduction in $PM_{2.5}$ relative to baseline in England (£million)

Years	Primary Care	Secondary Care	Medication	Social Care	Total
2015-2025	56.04[±35.73]	181.32[±20.69]	91.62[±11.3]	57.73[±14.9]	386.71[±45.32]
2015-2035	191.97[±124.49]	644.45[±33.55]	330.78[±18.31]	211.87[±24.05]	1379.07[±132.43]

Epidemiological outputs for NO_2 in England

For NO_2, the total attributable disease cases and NHS and social care costs, and the impact of a 1 µg/m^3 reduction in 2017 and meeting the EU Limit Values in England were estimated. The diseases modelled were: asthma, diabetes, low birth weight, dementia and lung cancer.

Estimating the total health and NHS and social care cost impacts of NO_2 concentrations (the attributable burden of NO_2)

Table 16 presents the cumulative incidence cases attributable to NO_2 in England, by disease between 2017 and 2035. By 2035 it was predicted that 1,140,018 [±11800] new cases of disease would be attributable to NO_2 in England. The highest number of new disease cases attributable to NO_2 were for diabetes and asthma (573,363 [±7725] and 335,491 [±2575] cases attributable to NO_2 by 2035 respectively).

Table 16. Cumulative incidence cases attributable to NO_2 in England, by disease and total between 2017 and 2035.

Year	Asthma	Diabetes	Lung cancer	Low birthweight	Dementia	Total
In 2017	18,361 [±556]	29,489 [±1669]	2226 [±556]	5564 [±556]	5008 [±1669]	60,648 [±2549]
2017-2025	160,185 [±1717]	269,511 [±5152]	17,734 [±1717]	49,794 [±1717]	42,303 [±5152]	539,527 [±7870]
2017-2035	335,491 [±2575]	573,363 [±7725]	42,002 [±2575]	102,545 [±2575]	86,617 [±7725]	1,140,018 [±11800]

Table 17 presents the total NHS and social care costs attributable to NO_2 from 2017 to 2035. By 2035 it was predicted that there would be £9,159.22million [±92.71] (£9.2 billion) new costs attributable to NO_2. Social care costs were the greatest contributors to the total cost attributable with £3,772.07 million [±88.59] (£3.8 billion) attributable to NO_2 between 2017 and 2035. Appendix 8d provides the total costs by disease.

Table 17. NHS and social care costs attributable to NO_2 in England, by disease and total between 2017 and 2035 (£million).

	Primary Care	Secondary Care	Medication	Social Care	Total
In 2017	12.61[±2.7]	17.09[±3.62]	10.95[±2.09]	40.41[±15.53]	81.06[±16.31]
2017-2025	469.87[±8.95]	642.75[±11.96]	399.8[±6.92]	1237.49[±52.22]	2749.91[±54.75]
2017-2035	1660.39[±14.88]	2302.76[±19.82]	1424[±11.48]	3772.07[±88.59]	9159.22[±92.71]

Modelling scenarios

Baseline scenario

In England, between the start year of the model (2015) and 2035, a total of 15,155,777 [±8917] new incident cases of disease were accrued (see Table 18).

Scenario 1: the impact of reducing NO_2 concentrations by 1 μg/m^3 in one year (2017)

Table 18 presents the disease impact of a 1 μg/m^3 reduction in NO_2 occuring in 2017 for one year only. Between 2015 and 2017 the model predicted that 2,773 [±4382] new cases of NO_2 related diseases would be avoided, compared to a no change-baseline in England. The total number of new cases of disease avoided between 2015 and 2035 was estimated to increase further to 34,693 [±12,321]. Figure 4 describes the breakdown of the cumulative cases avoided by disease: the greatest reductions were observed for diabetes (21,228 [± 8066] cases avoided by 2035) and asthma (6986 [±2689] cases avoided by 2035, for scenario 1).

Scenario 2: the impact of reducing NO_2 concentrations to meet the EU background Limit Values (40 μg/m^3) in one year (2017)

Table 18 presents the disease impact of reducing air pollution to meet the EU Limit Values of 40 μg/m^3 in 2017. It was predicted that 10,010 [±4,382] cases of disease would be avoided between 2015 and 2017. All avoided cases occurred in 2017 as there was no difference in 2015 and 2016 between the baseline and scenario 2 since the scenario started in 2017. By 2035, a cumulative total of 226,017 [±12,321] cases of disease were predicted to be avoided if EU Limit Values are met relative to baseline (exposure levels stay the same). As illustrated in Figure 4 the largest contributor to total cases avoided come from diabetes cases avoided (117,292 [± 8066]), and asthma cases avoided (70,299 [±2689]) between 2015 and 2035. Low Birth Weight and dementia are shaded since the evidence for these diseases is less robust. The impact on lung cancer was non-significant as indicated by the confidence limits.

Table 18. Total cumulative incidence cases and attributable cases avoided for 1 μg/m^3 reduction in NO_2 and meeting the EU Limit Values for NO_2 in England.

Year	Baseline	Scenario 1: 1μg/m^3 reduction in NO_2		Scenario 2: EU Limit Values met for NO_2	
	Cumulative incidence cases	Cumulative incidence cases	Cumulative incidence cases avoided (relative to baseline)	Cumulative incidence cases	Cumulative incidence cases avoided (relative to baseline)
2015	646,951 [±1815]	646,951 [±1815]	0 [±2509]	646,951 [±1815]	0 [±2509]
2015-2017	1,961,754 [±3170]	1,958,979 [±3170]	2773 [±4382]	1,951,742 [±3170]	10,010 [±4382]
2015-2025	7,516,151 [±62,50]	7,497,871 [±6250]	18,277 [±8635]	7,418,812 [±6250]	97,338 [±8635]
2015-2035	15,155,777 [±8917]	15,121,083 [±8917]	34,693 [±12321]	14,929,763 [±8917]	226,017 [±12321]

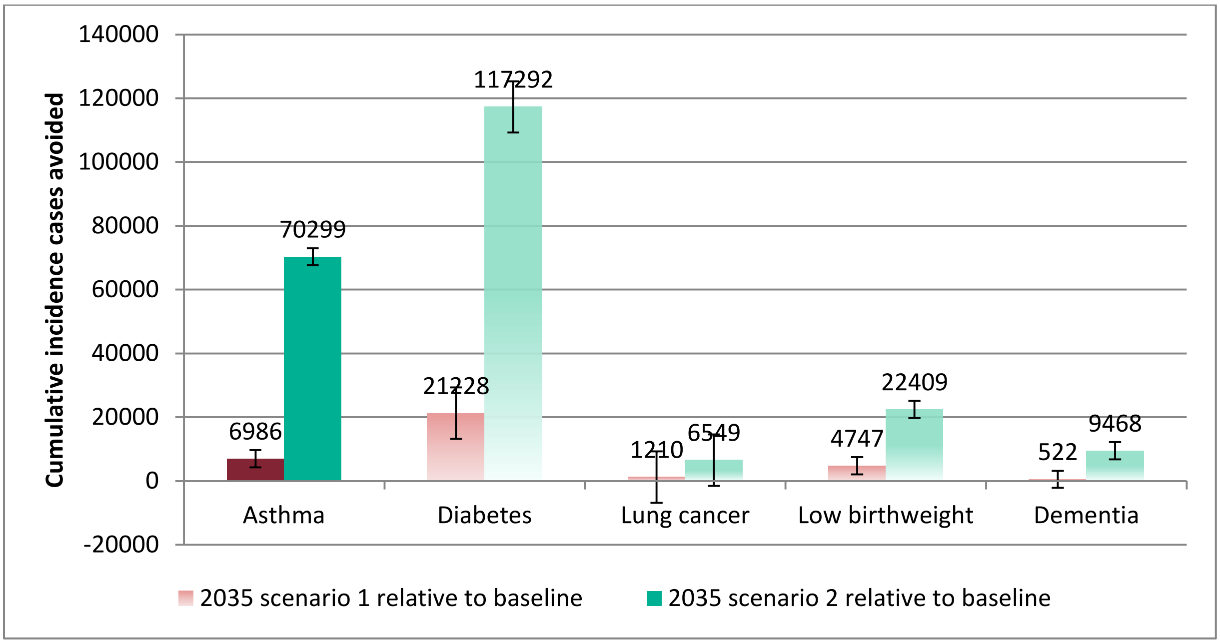

Figure 4. Cumulative incidence cases avoided for 1 µg/m$_3$ reduction in NO_2 (scenario 1) and meeting the EU Limit Values for NO_2 (scenario 2) by 2035 in England, by disease. Note: Diabetes, Lung cancer, Low Birth Weight and dementia is shaded since this the evidence is less robust.

NHS and social care cost outputs for NO_2 in England

Table 19 presents the NHS and social care costs avoided for 1 µg/m^3 reduction in NO_2 (scenario 1) and meeting the EU Limit Values for NO_2 (scenario 2) by 2025 and 2035 in England. For scenario1, between 2015 and 2035, the total NHS and social care costs avoided of £355.28 million [±95.76] was predicted. The largest contributor social care costs at £143.38 million [±91.46].

The impact of meeting the EU Limit Values relative to baseline predicted that between 2015 and 2035, a total cost avoided would be of £1700.45 million [±95.72] (£1.7 billion). The largest contributor to this was social care costs at £634.62 million [±91.42].

Table 19. NHS and social care costs avoided for 1 µg/m$_3$ reduction in NO_2 (scenario 1) and meeting the EU Limit Values for NO_2 (scenario 2) by 2025 and 2035 in England (£million)

	Years	Primary Care	Secondary Care	Medication	Social Care	Total
Scenario 1: 1µg/m^3 reduction in NO_2	2015- 2025	20.27[±9.72]	28.58[±13]	16.16[±7.47]	45.63[±56.51]	110.64[±59.27]
	2015-2035	66.01[±15.46]	92.75[±20.61]	53.14[±11.9]	143.38[±91.46]	355.28[±95.76]
Scenario 2: EU Limit Values met for NO_2	2015- 2025	84.83[±9.72]	119.38[±12.99]	73.08[±7.51]	173.12[±56.49]	450.41[±59.25]
	2015-2035	325.74[±15.44]	458.53[±20.58]	281.56[±11.91]	634.62[±91.42]	1700.45[±95.72]

Lambeth results

The following results for Lambeth are presented by pollutant and are presented as total cases in the Lambeth local authority population. Rates per 100,000 population are presented in Appendix 8b.

Epidemiological outputs for $PM_{2.5}$ in Lambeth

The total attributable new disease cases were modelled, and scenarios quantifying the impact of a 1 µg/m^3 reduction in 2017 due to $PM_{2.5}$ were approximated for Lambeth. The diseases modelled were: asthma, COPD, diabetes, low birthweight, CHD, lung cancer and stroke.

Estimating the total health and NHS and social care cost impacts of $PM_{2.5}$ concentrations (the attributable burden of $PM_{2.5}$)

The total new cases of diseases attributable to $PM_{2.5}$ from 2017 to 2035 were estimated in a second scenario. By 2035, an estimated 11,612 [±59] new cases of disease would be attributable to $PM_{2.5}$ (Table 20). Diabetes (2,509 [±47] cases), CHD (2,473 [±16] cases) and COPD (2,433 [±16] cases) were the greatest contributors to the total new cases attributable to $PM_{2.5}$ between 2017 and 2035, respectively.

Table 20. Cumulative incidence cases attributable to $PM_{2.5}$ in Lambeth, by disease and total between 2017 to 2035

Year	CHD	Stroke	Asthma	Lung cancer	COPD	Diabetes	Low birthweight	Total
2017	103 [±3]	30 [±3]	63 [±3]	10 [±3]	90 [±3]	113 [±10]	120 [±3]	529 [±12]
2017-2025	1,021 [±10]	278 [±10]	652 [±10]	120 [±10]	944 [±10]	1,083 [±31]	1,022 [±10]	5,120 [±40]
2017-2035	2,473 [±16]	706 [±16]	1,479 [±16]	298 [±16]	2,433 [±16]	2,509 [±47]	1,714 [±16]	11,612 [±61]

Table 21 presents the total NHS and social care costs attributable to $PM_{2.5}$ from 2017 to 2035 for Lambeth. By 2035 it was predicted that there would be £80.26[±0.23] million attributable to $PM_{2.5}$. Secondary care and medication costs were the greatest contributors to the total NHS and social care costs attributable, with £37.11 million [±0.16] and £19.67 million [±0.09] attributable to $PM_{2.5}$ between 2017 and 2035, respectively.

Table 21. NHS and social care costs attributable to $PM_{2.5}$ in Lambeth between 2017 to 2035 in the total population (£million)

Year(s)	Primary Care	Secondary care	Medication	Social Care	Total
In 2017	0.09[±0.01]	0.29[±0.03]	0.15[±0.02]	0.09[±0.02]	0.62[±0.04]
2017-2025	3.08[±0.04]	10.29[±0.09]	5.35[±0.05]	3.35[±0.07]	22.07[±0.13]
2017-2035	10.99[±0.07]	37.11[±0.16]	19.67[±0.09]	12.49[±0.12]	80.26[±0.23]

Modelling scenarios

Baseline scenario

A baseline scenario with no change in $PM_{2.5}$ concentrations in Lambeth, between 2015 and 2035 estimated that a total 79,867 [±36] new cases of diseases would occur over the 20 year period (see
Table 22).

Scenario 1: the impact of reducing $PM_{2.5}$ concentrations by 1µg/m^3 in one year (2017)

A 1µg/m^3 reduction in $PM_{2.5}$ concentration in 2017 was predicted to result in 50 [±20] new cases of $PM_{2.5}$-related diseases between 2015 and 2017 (Table 22). The total number of new cases avoided was estimated to increase to 1,110 [±50] between 2015 and 2035. Figure 5 shows the contribution of each disease to the total number of new cases of disease avoided by 2035 due to a 1µg/m^3 reduction in $PM_{2.5}$ in 2017. The highest were for CHD, COPD and diabetes, with 265 [±9], 259 [±9] and 227 [±45] cases avoided by 2035 respectively

Table 22. Total cumulative incidence cases and cases avoided for baseline and 1 µg/m^3 reduction in $PM_{2.5}$ in Lambeth.

Year	Baseline	Scenario 1: 1µg/m^3 reduction in $PM_{2.5}$	
	Cumulative incidence cases	Cumulative incidence cases	Cumulative incidence cases avoided (relative to baseline)
2015	3046 [±9]	3052 [±9]	-6 [±12]
2015-2017	9429 [±16]	9378 [±16]	50 [±20]
2015-2025	37982 [±29]	37449 [±29]	525 [±40]
2015-2035	79867 [±36]	78756 [±36]	1110 [±50]

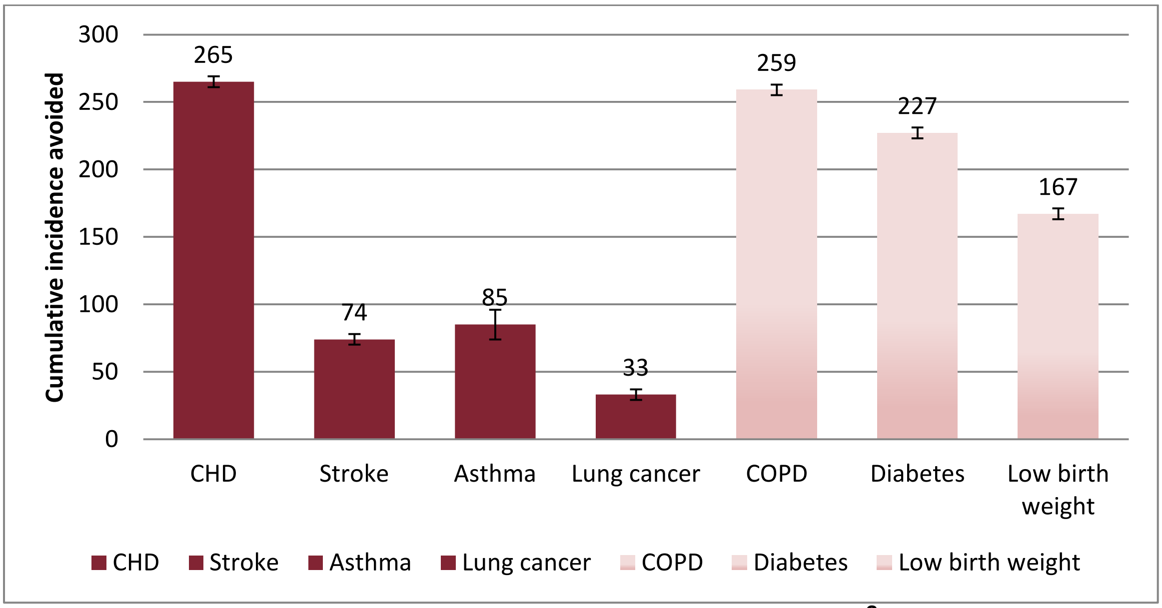

Figure 5. Cumulative incidence cases avoided for 1 µg/m^3 reduction in $PM_{2.5}$ (scenario 1) by 2035 in Lambeth, by disease. Note: COPD is chronic bronchitis only, and the evidence for diabetes and Low Birth Weight is less robust so are shaded.

NHS and social care cost outputs for $PM_{2.5}$ in Lambeth

Table 23 presents the NHS and social care costs avoided as a result of a 1 µg/m^3 reduction in $PM_{2.5}$ concentration compared to the no change scenario. Between 2015 and 2035, the total NHS and social care cost avoided was predicted to be £8.54 [±0.25] million which included the following costs: £1.22 [±0.08] million avoided in primary care £3.91 [±0.17] million avoided in secondary care, £2.06 [±0.1] million avoided in medication, and £1.35 [±0.13] million avoided in social care costs (Table 23).

Table 23. Total NHS and social care costs avoided due to 1 µg/m^3 reduction in $PM_{2.5}$ in Lambeth (£million)

	Years	Primary Care	Secondary Care	Medication	Social Care	Total
Scenario 1: 1µg/m^3 reduction in $PM_{2.5}$	2015-2025	0.37[±0.05]	1.1[±0.1]	0.59[±0.06]	0.41[±0.08]	2.47[±0.15]
	2015-2035	1.22[±0.08]	3.91[±0.17]	2.06[±0.1]	1.35[±0.13]	8.54[±0.25]

Epidemiological outputs for NO_2 in Lambeth

The total attributable new disease cases were modelled, and scenarios quantifying the impact of a 1 µg/m^3 reduction in 2017 and meeting the EU Limit Values were approximated for NO_2 in Lambeth until 2035. The diseases modelled were: asthma, diabetes, low birth weight, dementia and lung cancer.

Estimating the total health and NHS and social care cost impacts of NO_2 concentrations (the attributable burden of NO_2)

Between 2017 and 2035 the model predicted that 11,906 [±43] new cases of disease would be attributable to NO_2 in Lambeth (see Table 24). The highest number of new disease cases attributable to NO_2 were diabetes and asthma cases, with an estimated 6,109 [±42] and 3,871 [±16] attributable cases, respectively.

Table 24. Cumulative incidence cases attributable to NO_2 in Lambeth, by disease and total, between 2017 and 2035

Year	Asthma	Diabetes	Lung cancer	Low birthweight	Dementia	Total
2017	209 [±3]	266 [±5]	13 [±3]	76 [±3]	30 [±3]	594 [±7]
2025	1,934 [±10]	2,590 [±24]	131 [±9]	616 [±10]	238 [±10]	5,509 [±32]
2035	3,868 [±16]	6,107 [±42]	310 [±16]	1,042 [±16]	545 [±16]	11,903 [±54]

Table 25 presents the total NHS and social care costs attributable to NO_2 from 2017 to 2035 for Lambeth. By 2035 it was predicted that there would be £90.20 million [±0.40] costs attributable to NO_2. Social care costs were the greatest contributors to the total cases attributable, with £34.11 million [±0.37] attributable to NO_2 between 2017 and 2035.

Table 25. NHS and social care costs attributable to NO_2 in Lambeth between 2017 and 2035 (£million)

Year(s)	Primary Care	Secondary Care	Medication	Social Care	Total
In 2017	0.12[±0.01]	0.16[±0.02]	0.10[±0.01]	0.31[±0.06]	0.69[±0.06]
2017-2025	4.46[±0.04]	6.20[±0.06]	3.89[±0.04]	9.86[±0.21]	24.41[±0.23]
2017-2035	17.13[±0.08]	24.04[±0.11]	14.92[±0.06]	34.11[±0.37]	90.20[±0.40]

Baseline scenario

In a no-change, baseline scenario of NO_2, a cumulative 76,399 [±34] new cases of disease were predicted to be accrued until 2035 (Table 26). Between 2017 and 2035 the model predicted that 11,906 [±43] new cases of disease would be attributable to NO_2 in Lambeth, 16% of the total.

Scenario 1: the impact of reducing NO_2 concentrations by 1 μg/m^3 in one year (2017)

The impact of a 1 μg/m^3 reduction occuring in 2017 for one year in Lambeth only was assessed: between 2015 and 2017 the model predicted that 13 [±19] new cases of NO_2-related diseases would be avoided in Lambeth (Table 26). The total number of new cases of disease avoided between 2015 and 2035 was estimated to increase further to 206 [±48]. Figure 6 describes the breakdown of the cumulative cases avoided by disease: the greatest reductions were observed for diabetes (130 [±45] cases avoided by 2035) and asthma (49 [±9] cases avoided by 2035).

Scenario 2: the impact of reducing NO_2 concentrations to meet the EU Limit Values (40 μg/m^3) in one year (2017)

The health impact of Lambeth meeting the EU Limit Values for NO_2 in 2017 was projected to result in 168 [±19] new cases of disease avoided, increasing to 3,423 [±48] total new cases avoided between by 2035 (see Table 26). The breakdown of this result by disease in Figure 6 shows that, as for England, diabetes (1,761 [±45] cases avoided) and asthma (1132 [±9] cases avoided) are the largest contributors to this reduction in cumulative disease incidence, over 20 years in Lambeth.

Table 26. Total cumulative incidence cases and cases avoided for baseline, 1 μg/m^3 reduction in NO_2 and meeting the EU Limit Values for NO_2 in Lambeth.

Year	Baseline	Scenario 1: 1μg/m^3 reduction in NO_2		Scenario 2: EU Limit Values met for NO_2	
	Cumulative incidence cases	Cumulative incidence cases	Cumulative incidence cases avoided (relative to baseline)	Cumulative incidence cases	Cumulative incidence cases avoided (relative to baseline)
2015	3014 [±8]	3017 [±8]	-3 [±11]	3014 [±8]	0 [±11]
2015-2017	9289 [±14]	9277 [±14]	13 [±19]	9122 [±14]	168 [±19]
2015-2025	36839 [±26]	36745 [±26]	96 [±38]	35247 [±26]	1597 [±38]
2015-2035	76399 [±34]	76196 [±34]	206 [±48]	72986 [±34]	3423 [±48]

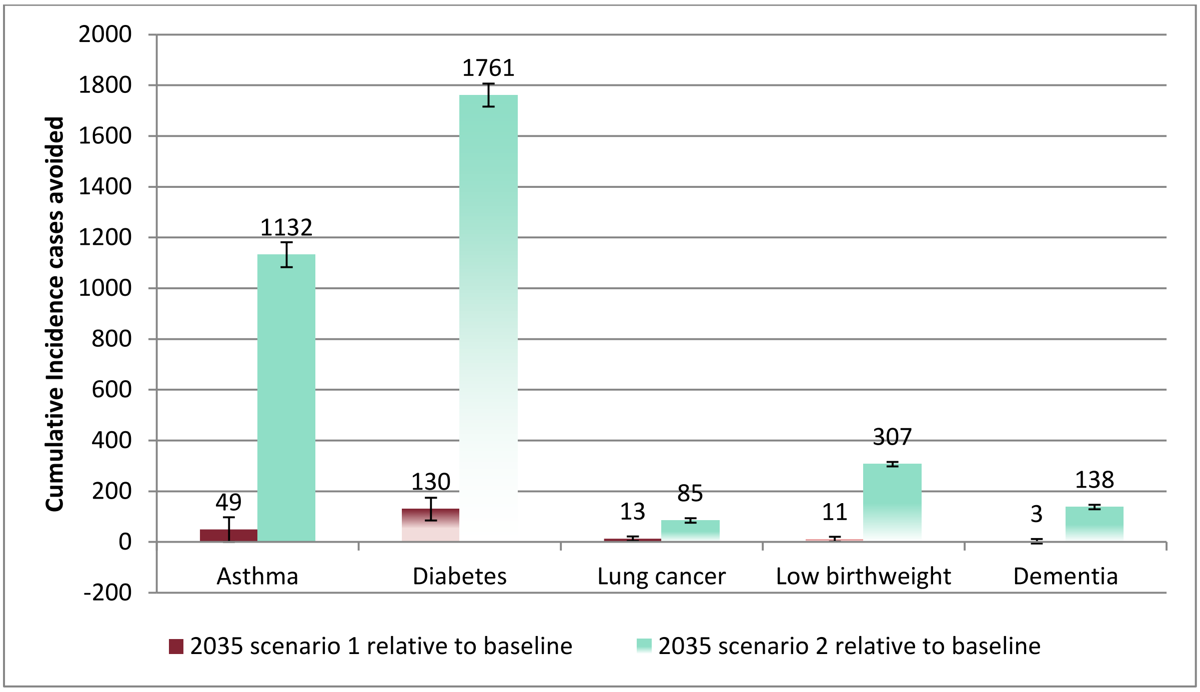

Figure 6. Cumulative incidence cases avoided for 1 µg/m^3 reduction in NO_2 (scenario 1) and meeting the EU Limit Values for NO_2 (scenario 2) by 2035 in Lambeth, by disease. Note: Evidence for diabetes, lung cancer, Low Birth Weight and dementia is less robust so are shaded.

NHS and social care cost outputs for NO_2 in Lambeth

The impact of a 1 µg/m^3 reduction in NO_2 concentration was assessed in terms of the NHS and social care costs avoided, compared to the no change scenario (Table 27).

Between 2015 and 2035, the total NHS and social care cost avoided was predicted to be £1.97 [±0.42] million which included the following costs: £0.38 [±0.08] million in primary care, £0.53 [±0.11] million avoided in secondary care, £0.32 [±0.06] million in medication, and £0.74 [±0.39] million in social care costs.

The impact of meeting the EU Limit Values was assessed in terms of the NHS and social care costs avoided, compared to the no change scenario:

Between 2015 and 2035, the total NHS and social care cost avoided was predicted to be of £26.46 [±0.41] million which included the following costs: £5.05 [±0.08] million in primary care, £7.08 [±0.11] million in secondary care, £4.40 [±0.06] million in medication, and £9.93 [±0.38] million in social care costs.

Table 27. NHS and social care costs avoided for 1 µg/m$_3$ reduction in NO_2 (scenario 1) and meeting the EU Limit Values for NO_2 (scenario 2) by 2025 and 2035 in Lambeth (£million)

	Year	Primary Care	Secondary Care	Medication	Social Care	Total

Scenario 1: 1µg/m^3 reduction in NO_2	2015- 2025	0.10[±0.05]	0.14[±0.07]	0.09[±0.04]	0.20[±0.23]	0.53[±0.25]
	2015-2035	0.38[±0.08]	0.53[±0.11]	0.32[±0.06]	0.74[±0.39]	1.97[±0.42]
Scenario 2: EU Limit Values met for NO_2	2015- 2025	1.36[±0.05]	1.88[±0.07]	1.19[±0.04]	3.03[±0.23]	7.46[±0.25]
	2015-2035	5.05[±0.08]	7.08[±0.11]	4.40[±0.06]	9.93[±0.38]	26.46[±0.41]

South Lakeland results

The following results for South Lakeland are presented by pollutant and as total cases in the South Lakeland population. Rates per 100,000 population are presented in Appendix 8c.

Epidemiological outputs for $PM_{2.5}$ in South Lakeland

The total attributable new disease cases were modelled, and scenarios quantifying the impact of a 1 µg/m^3 reduction in $PM_{2.5}$ concentrations in one year (2017) were approximated for South Lakeland. The diseases modelled were: asthma, COPD, diabetes, low birthweight, CHD, lung cancer and stroke.

Estimating the total health and NHS and social care cost impacts of $PM_{2.5}$ concentrations (the attributable burden of $PM_{2.5}$)

The total number of new cases of disease attributable to $PM_{2.5}$ are shown by disease in Table 28. From 2017 to 2035, 866[±17] new cases of disease were estimated to be attributable to exposure to $PM_{2.5}$ in South Lakeland. Incident CHD and diabetes cases were the greatest contributors with 277[±4] and 189[±13] cases attributable to $PM_{2.5}$ between 2017 and 2035, respectively.

Table 28. Cumulative incidence cases attributable to $PM_{2.5}$ in South Lakeland, by disease and total between 2017 and 2035.

Year	CHD	Stroke	Asthma	Lung cancer	COPD	Diabetes	Low birthweight	Total
2017	14[±1]	3[±1]	3[±1]	2[±1]	8[±1]	11[±3]	3[±1]	44[±4]
2017-2025	125[±3]	37[±3]	29[±3]	16[±3]	78[±3]	96[±9]	32[±3]	413[±12]
2017-2035	277[±4]	87[±4]	52[±4]	37[±4]	158[±4]	189[±13]	66[±4]	866[±17]

Table 29 presents the total NHS and social care costs attributable to $PM_{2.5}$ from 2017 to 2035. By 2035 it was predicted that there would be £7.45million [±0.10] attributable to $PM_{2.5}$. Secondary care and medication costs were the greatest contributors to the total cases attributable, with £3.59million [±0.07]and £1.91million [±0.04] attributable to $PM_{2.5}$ between 2017 and 2035 respectively.

Table 29. NHS and social care costs attributable to $PM_{2.5}$ in South Lakeland between 2017 and 2035 (£million)

Year(s)	Primary Care	Secondary Care	Medication	Social Care	Total
In 2017	0.01[±0.01]	0.04[±0.01]	0.02[±0.01]	0.01[±0.01]	0.08[±0.02]
2017-2025	0.30[±0.02]	1.15[±0.04]	0.60[±0.02]	0.33[±0.03]	2.38[±0.06]
2017-2035	0.90[±0.03]	3.59[±0.07]	1.91[±0.04]	1.05[±0.05]	7.45[±0.10]

Modelling scenarios

Baseline scenario

In the baseline scenario with no change in the $PM_{2.5}$ concentrations in South Lakeland over 20 years (2015 to 2035), a total 29,439[±5] new cases of disease were estimated to occur in the population (see Table 30).

Scenario 1: the impact of reducing $PM_{2.5}$ concentrations by 1 $\mu g/m^3$ in one year (2017)

Table 30 summarises the total number of new cases of disease avoided for 1$\mu g/m^3$ reduction during 2017 in $PM_{2.5}$ in South Lakeland between 2017, 9 [±6] cases of diseases were estimated to be avoided, increasing up to 240 [±9] new cases of disease avoided by 2035. Cases of CHD and diabetes showed the most important reductions relative to baseline for a 1$\mu g/m^3$ reduction in 2017: with 75 [±1] new cases of CHD avoided and 59 [±9] new cases of diabetes avoided in the South Lakeland population by 2035 (see Figure 7).

Table 30. Total cumulative incidence cases and cases avoided for baseline and 1 $\mu g/m^3$ reduction in $PM_{2.5}$ scenarios in South Lakeland.

Year	Baseline	Scenario 1: 1$\mu g/m^3$ reduction in $PM_{2.5}$	
	Cumulative incidence cases	Cumulative incidence cases	Cumulative incidence cases avoided (relative to baseline)
2015	1331[±3]	1336[±3]	-5 [±4]
2015-2017	4018[±5]	4008[±5]	9 [±6]
2015-2025	15111[±5]	14990[±5]	119 [±9]
2015-2035	29439[±5]	29190[±5]	240 [±9]

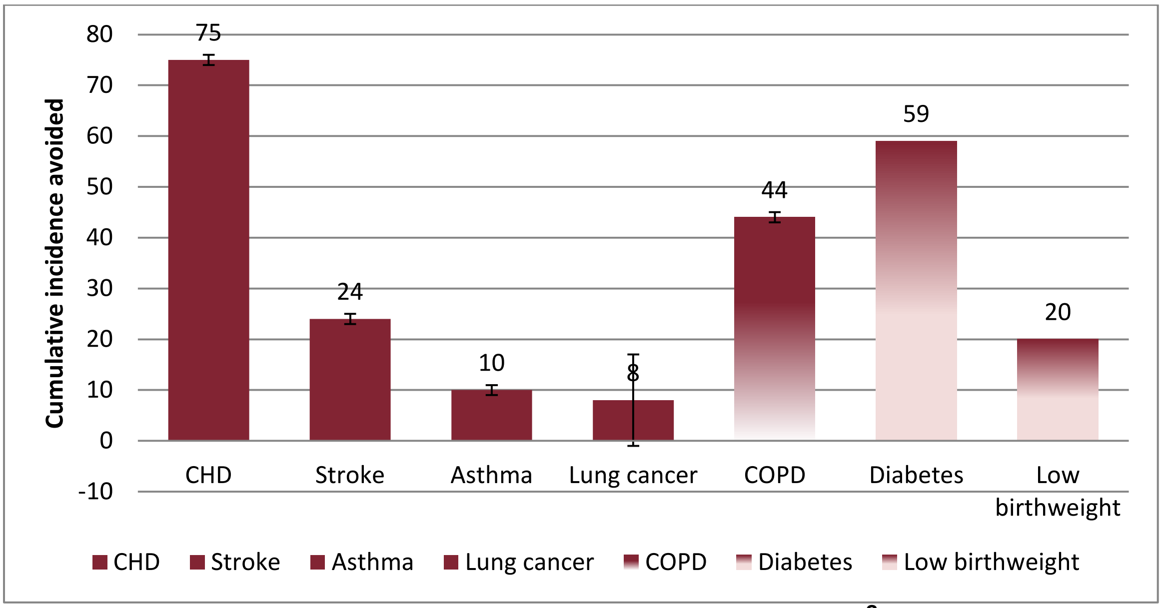

Figure 7. Cumulative incidence cases avoided for 1 µg/m^3 reduction in $PM_{2.5}$ (scenario 1) by 2035 in South Lakeland, by disease. Note: COPD is chronic bronchitis only, and the evidence for diabetes and Low Birth Weight is less robust so are shaded.

NHS and social care cost outputs for $PM_{2.5}$ in South Lakeland

Table 31 presents the NHS and social care costs avoided of a 1 µg/m^3 reduction in $PM_{2.5}$ concentration compared to the no change scenario. Between 2015 and 2035, a total cost avoided of £1.92 million [±0.09] was predicted, which included: £0.26 [±0.03] million in primary care, £0.9 [±0.06] million in secondary care, £0.46 million [±0.04] in medication, and £0.3million [±0.05] avoided in social care costs.

Table 31. NHS and social care costs avoided for a 1 µg/m^3 reduction in $PM_{2.5}$ scenarios in South Lakeland (£million)

	Year	Primary Care	Secondary Care	Medication	Social Care	Total
Scenario 1: 1µg/m^3 reduction in $PM_{2.5}$	2015- 2025	0.08[±0.02]	0.26[±0.04]	0.13[±0.02]	0.08[±0.03]	0.55[±0.06]
	2015-2035	0.26[±0.03]	0.9[±0.06]	0.46[±0.04]	0.3[±0.05]	1.92[±0.09]

Epidemiological outputs for NO2 in South Lakeland

The total attributable new disease cases were modelled, and scenarios quantifying the impact of a 1 µg/m^3 reduction in 2017, meeting the EU Limit Values were approximated for NO_2 in South Lakeland over to 2035. The diseases modelled were: asthma, diabetes, low birth weight, dementia and lung cancer.

Estimating the total health and NHS and social care cost impacts of NO_2 concentrations (the attributable burden of NO_2)

Between 2017 and 2035, 1032 [±22] new cases of disease were estimated to be attributable to NO_2 in South Lakeland (see Table 32). The highest number of new disease cases attributable to NO_2 were for diabetes, asthma and dementia, with an estimated 578 [±13] and 227 [±4] and 113 [±13] attributable new cases occurring by 2035, respectively.

Table 32. Cumulative incidence cases attributable to NO_2 in South Lakeland, by disease and total between 2017 and 2035.

Year	Asthma	Diabetes	Lung cancer	Low birthweight	Dementia	Total
2017	13 [±1]	33 [±3]	3 [±1]	3 [±1]	6 [±3]	59 [±5]
2025	108 [±3]	284 [±9]	24 [±3]	27 [±3]	57 [±9]	500 [±15]
2035	227 [±4]	578 [±13]	52 [±4]	62 [±4]	113 [±13]	1032 [±22]

Table 33 presents the total NHS and social care costs attributable to NO_2 from 2017 to 2035 for South Lakeland. By 2035 it was predicted that there would be £9.74million [±0.21] costs attributable to NO_2, with social care costs being the biggest contributor: £4.37million [±0.20].

Table 33. NHS and social care costs attributable to NO_2 in South Lakeland between 2017 and 2035 (£million).

	Primary Care	Secondary Care	Medication	Social Care	Total
2017	0.01[±0.01]	0.02[±0.01]	0.01[±0.00]	0.06[±0.04]	0.10[±0.04]
2017-2025	0.51[±0.02]	0.68[±0.02]	0.41[±0.01]	1.59[±0.12]	3.19[±0.12]
2017-2035	1.69[±0.03]	2.31[±0.04]	1.37[±0.02]	4.37[±0.20]	9.74[±0.21]

A quality assurance checklist can be found in Appendix 9. A comparison between the microsimulation and tool can be found in Appendix 10.

Modelling scenarios

Baseline scenario

Between the start year of the model in 2015 and 2035, a total of 32,267 [±6] cases of disease were estimated to arise in the South Lakeland population if no change occurred in NO_2 concentrations (see Table 34).

Scenario 1: the impact of reducing NO_2 concentrations by 1 $\mu g/m^3$ in one year (2017)

Table 34 presents the impact of reducing the NO_2 concentration by 1$\mu g/m^3$ in 2017 in South Lakeland: by 2017, 3 [±7] new cases of diseases were avoided, relative to baseline. However, by 2035, the model estimated 70 [±13] total new cases of disease would be avoided and these were largely due to 40 [±9] diabetes cases and 14 [±1] asthma cases avoided, as shown in Figure 8.

Scenario 2: the impact of reducing NO_2 concentrations to meet the EU Limit Values (40 μg/m^3) in one year (2017)

The impact of reducing air pollution to meet the EU Limit Values of 40 μg/m^3 for NO_2 in 2017 was modelled, with 1 [±7] case of diseases avoided between 2015 and 2017 (these non-significant differences in cases compared to a baseline scenario are seen in 2017, as there was no difference in 2015 and 2016 between the baseline and scenario 2). By 2035, a cumulative total of 59 [±13] cases of disease were estimated to have been avoided, when meeting EU Limit Values for NO_2 concentration in 2017 (see Table 34). As seen in Figure 8 the largest contributor to total cases avoided come from diabetes cases, and asthma: between 2015 and 2035, 31 [±9] and 18 [±1] cases were estimated to be avoided, respectively.

Table 34. Total cumulative incidence cases and cases avoided for baseline, 1 μg/m^3 reduction in NO_2 and meeting the EU Limit Values for NO_2 in South Lakeland.

Year	Baseline	Scenario 1: 1μg/m_3 reduction in NO_2		Scenario 2: EU Limit Values met for NO_2	
	Cumulative incidence cases	Cumulative incidence cases	Cumulative incidence cases avoided (relative to baseline)	Cumulative incidence cases	Cumulative incidence cases avoided (relative to baseline)
2015	1,457 [+-3]	1457 [+-3]	0 [±5]	1457 [+-3]	0 [±5]
2015-2017	4,386 [+-6]	4383 [+-6]	3 [±7]	4385 [+-6]	1 [±7]
2015-2025	16,451 [+-6]	16,416 [+-6]	33 [±13]	16,423 [+-6]	25 [±13]
2015-2035	32,267 [+-6]	32,194 [+-6]	70 [±13]	32,204 [+-6]	59 [±13]

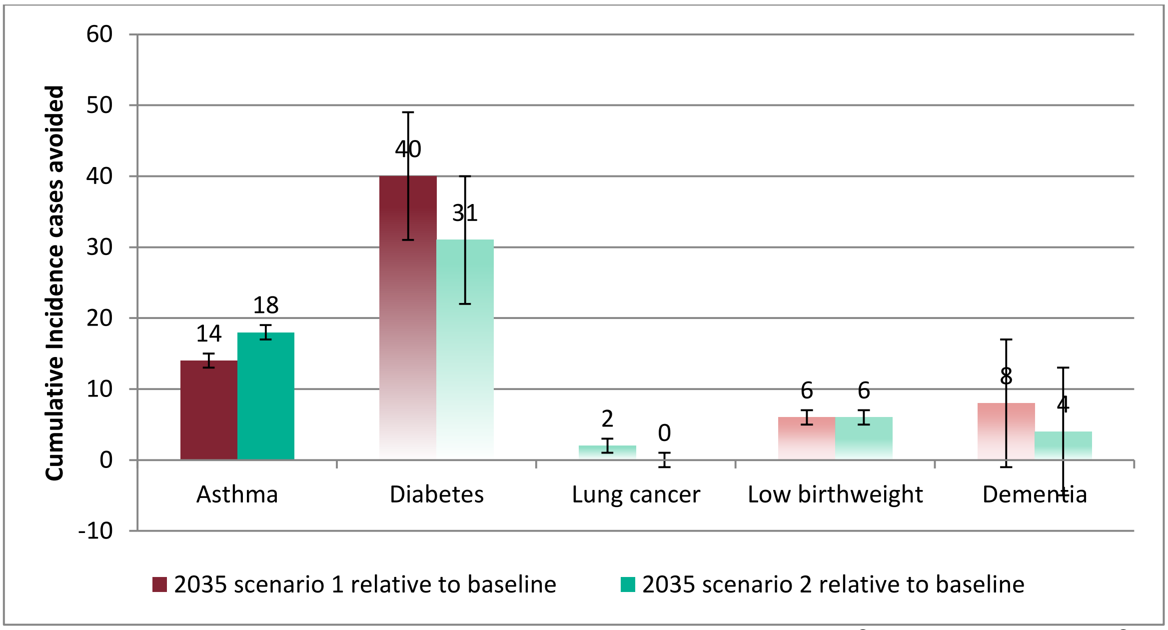

Figure 8. Cumulative incidence cases avoided for 1 μg/m^3 reduction in NO^2 (scenario 1) and meeting the EU Limit Values for NO_2 (scenario 2) by 2035 in South Lakeland, by

disease. Note: Evidence for diabetes, lung cancer, Low Birth Weight and dementia is less robust so are shaded.

NHS and social care cost outputs for NO_2 in South Lakeland

Table 35 presents the impact of a 1 µg/m^3 reduction in NO_2 concentration compared to the no change scenario. Between 2015 and 2035, the total NHS and social care cost avoided was predicted to be of £0.78 million [±0.22] with the largest contributor coming from social care costs: £0.38million [±0.21] avoided by 2035 (Table 35).

The impact of meeting the EU Limit Values was also assessed. Between 2015 and 2035, the total NHS and social care cost avoided was predicted to be £0.50 million [±0.22], with the largest contributor coming from social care £0.22 [±0.21] (Table 35).

Table 35. NHS and social care costs avoided for 1 µg/m_3 reduction in NO_2 (scenario 1) and meeting the EU Limit Values for NO_2 (scenario 2) by 2025 and 2035 in South Lakeland (£million)

	Years	Primary Care	Secondary Care	Medication	Social Care	Total
Scenario 1: 1µg/m^3 reduction in NO_2	2015- 2025	0.04[±0.02]	0.06[±0.03]	0.03[±0.02]	0.18[±0.13]	0.31[±0.14]
	2015-2035	0.13[±0.03]	0.17[±0.04]	0.10[±0.02]	0.38[±0.21]	0.78[±0.22]
Scenario 2: EU Limit Values met for NO_2	2015- 2025	0.02[±0.02]	0.03[±0.03]	0.02[±0.02]	0.06[±0.13]	0.13[±0.14]
	2015-2035	0.09[±0.03]	0.12[±0.04]	0.07[±0.02]	0.22[±0.21]	0.50[±0.22]

Discussion

This project aimed to develop a microsimulation model to quantify the total cost of air pollution to the NHS and social care, as well as provide a tool for use by local authorities to quantify the potential health and cost burden of air pollution under different scenarios.

Outputs for 3 case studies have been provided: England, Lambeth (relatively high air pollution), and South Lakeland (relatively low air pollution).

Between 2017 and 2025, the total cost to the NHS and Social Care of air pollution in England is estimated to be £1.60 billion for $PM_{2.5}$ and NO2 combined (£1.54 billion for $PM_{2.5}$ and £60.81 million for NO_2) where there is robust evidence for an association between exposure and disease. If we include the costs for diseases where there is less robust evidence for an association, then the estimate is increased to an overall total of £2.81 billion for $PM_{2.5}$ and £2.75 billion for NO_2 in England between 2017 and 2025.

Of the 3 regions, Lambeth was predicted to have the highest number of new cases per 100,000 of disease attributable to air pollution (for both $PM_{2.5}$ and NO_2) compared with South Lakeland and England. For $PM_{2.5}$ it was predicted there would be 3,242 attributable cases of disease per 100,000 by 2035 in Lambeth, compared with 2,248 [±17] and 861 [±17] in England and South Lakeland respectively, if $PM_{2.5}$ levels remain the same. For NO_2, the total number of attributable cases by 2035 are predicted to be 3331 [±17] per 100,000 in Lambeth, compared with 1013 [±22] and 1933 [±22] per 100,000 in South Lakeland and England respectively. These figures show the marked impact of high exposure levels on the future burden of disease – around a 3-fold increase when comparing high vs. low exposure.

For $PM_{2.5}$, we modelled a 1µg/m^3 reduction occurring in 2017 only. England has met the EU Limit Values for $PM_{2.5}$ (25 µg/m^3) therefore it was not deemed necessary to run this second scenario. For a 1µg/m^3 reduction in $PM_{2.5}$ the highest number of cumulative incidence cases avoided was observed in Lambeth, however, differences with England and South Lakeland were marginal, possibly due to demographic differences. That is, even though South Lakeland has low exposure to $PM_{2.5}$, it has both a relatively old population who are more at risk of air-pollution related disease. We showed that even small changes in air pollution in South Lakeland would have an important impact on disease outcomes. As an addition to the analyses presented above, we have run the model using the same exposure level, but different populations to illustrate the impact of population demographics alone on the outputs. We modelled Lambeth exposure on the South Lakeland population and vice versa. These analyses are presented in Appendix 6 and as expected, show that low exposure and a young population results in the smallest number of disease cases due to air pollution, while high exposure in an older population results in the highest number of disease cases due to air pollution. Broadly, being exposed to Lambeth NO_2 levels resulted in as much as 4 times as many diseases compared with South Lakeland NO_2 exposure levels regardless of population demographic.

For NO_2, we modelled 2 'what-if' scenarios – a 1µg/m^3 reduction in NO_2 occurring in 2017 alone, and a reduction in NO_2 to European Limit Values (40 µg/m^3) in 2017 alone. Reducing NO_2 by just 1µg/m^3 results in disease cases avoided across all regions. Interestingly, there was little difference in the cases avoided for the 1µg/m^3 reduction in NO_2 (32, 28, 33 cases per 100,000 for England, Lambeth, South Lakeland respectively by 2025) when comparing rates per 100,000. Again, differences in demographics as well as exposure level may explain this: Lambeth has a relatively young population, but high exposure levels and a low birth rate (Total Fertility Rate (TFR) =1.44), while South Lakeland has a relatively old population, low exposure levels, but also relatively high birth rates (TFR=1.77). Therefore, even though South Lakeland has low exposure levels of $NO_{2,}$ the larger population in the most vulnerable groups (the young and old) are affected by small changes in exposure levels. Exploring the data by disease, we observe that there are higher rates (per 100,000) of dementia at baseline in South Lakeland (6239 [±4] cumulative incidence cases by 2025), compared to Lambeth (1865 [±1] cumulative incidence cases by 2025), and therefore more cases may be avoided with small changes in pollution levels.

Reducing NO_2 to EU Limit Values would result in the greatest number of disease cases avoided in Lambeth, followed by England, when comparing standardised rates with those of South Lakeland. This is likely to be because individuals in Lambeth and England as a whole have much higher exposure levels than in South Lakeland. The effect would be small in South Lakeland since not many people are exposed to levels above the EU Limit Values.

When modelling a 1µg/m^3 reduction in the pollutants, we observed that there was a larger number of cumulative incidence cases avoided for $PM_{2.5}$ when compared with NO_2**.** One probable explanation for this is that the NO_2 relative risks were reduced by 60% from their original value, to take into account overlap with health effects from other pollutants, including $PM_{2.5.}$ Further, the evidence is less certain for NO_2 than $PM_{2.5.}$ This assumption is based on COMEAP recommendations for mortality (23). We did not adjust $PM_{2.5}$ dose-response functions for NO_2 since figures do not exist in the literature. Therefore, it was advised that we analysis and discuss each pollutant separately. Further work might quantify combined risks so that the total impact of each/all pollutants can be more accurately quantified.

Because we were interested in quantifying the total costs of air pollution to the NHS and social care our model, outputs include morbidity as opposed to mortality. This complements the data that has attempted to quantify total deaths due to air pollution using population attributable fractions (44).

Previous calculations of the costs of air pollution have estimated between £8.5bn and £20.2bn a year (14). This is based on the 'willingness to pay' approach (45). Whereas the costs quantified in the present study represent the costs of treating air-pollution related diseases in the NHS and social care system.

Limitations

As with all modelling studies there are a number of limitations to be mentioned.

It was only possible to include long-term effects when modelling air pollution since it is not possible to model short-term peaks within annual estimates. This is largely due to short-term peaks in air pollution being unpredictable, both temporally and geospatially, and driven by short-term meteorology. Air pollution varies day to day/week to week in a highly dynamic way. These variations also differ geographically, i.e. there are differences between North and South; $PM_{2.5}$ concentrations in Southern parts of England, for example, are often influenced by long-range transport from the continent while this is not the case in Northern parts of England. The relationship between short-term peaks and annual averages of exposure is therefore highly varied and not straightforward to predict based on annual averages alone. A future piece of work may seek to look at this nationally, perhaps comparing a London borough with an area in the north of England. Combining methods such as an agent based modelling approach with a microsimulation might enable short- and long-term effects to be modelled.

It was postulated that short-term peaks may lead to hospitalisation and therefore greater NHS costs. However, the project would require a much longer time scale to develop ways of incorporating both short and long-term effects. Further, it is unclear how short-term and long-term risk overlap. The microsimulation structure quantifies disease incidence/prevalence on an annual basis. Changing this structure (to , for example, daily updates) is not possible within the time frame of this study. In addition, there are lots of data limitations since the model would require daily/monthly disease incidence data in order to initialise the model population and quantify the impact of a daily spike in air pollution versus baseline levels. Modelling of ozone was initially in the scope for this project, but then was excluded from the analysis since ozone is related to short-term health effects only.

We modelled different scenarios within the microsimulation. However, it was not possible to include each of these scenarios in the tool. This was partly due to the time by which we received suggested alterations to the scenarios, but also due to the differences in the methods used between the microsimulation and tool. The microsimulation models individual exposure while the tool models weighted cohorts. Within the tool there are only 3 trajectories which are based on the England tertile exposure cuts (for $PM_{2.5,}$ the exposures in the first year are 7.67, 12.9, 17.1 μg/m^3 and for NO_2, the exposures in the first year are 10.5, 24.5 and 52.7 µg/m^3). Consequently, decreasing the annual exposure by 1 µg/m^3 or applying a European Limit Values scenario in $PM_{2.5}$ and NO_2 would only affect 3 trajectories and might lead to great uncertainties if further assumptions were not made. Future work could involve the evaluation of such assumptions. However, in order to take into consideration the structure of the tool, we have modelled a scenario in which a reduction in the percentage of individuals exposed to the pollutants can be simulated.

Results from the microsimulation modelling are limited by the assumptions and algorithms used. When modelling exposure to pollutants we assumed that the 2 pollutants were independent. However, we did adjust the NO_2 relative risks to take account of the potential overlap between NO_2 and $PM_{2.5}$ (based on recommendations for mortality (23)). Further work is required to better understand interacting risks on later disease outcomes. We also assumed static trends in exposure over time since we cannot be sure of how changes in policy (and meteorological changes) might alter trends. We assumed that individuals remain on the same percentile of exposure as they age, and this was deemed the best assumption.

Further, due to time constraints and data availability, it was not possible to take account of other factors such as deprivation. Research has shown that deprived sub-populations are more susceptible to the negative health effects of air pollution and that deprived sub-population are, at the same time, more likely to be exposed to higher air pollution levels (46). The microsimulation however assumes that the total population has the same risk, both in terms of air pollution exposure and health effects. Taking this into account might be possible in future work.

The microsimulation is a robust tool for modelling population level interventions in detail. It models every individual within the population and runs them through their lives. Individuals are randomly generated (age, sex, exposure) to reproduce exposure and population statistics. Individual trajectories are modelled from birth. We were unable to take account of migration.

Results from microsimulation modelling are also limited by the quality of the input data. The model requires the input of epidemiological data stratified by gender and 5 year age group for each disease. However, this data was not always available in this format for the simulation start year of 2015 (for example, stroke data was available for 2009 only). The assumption that the age and sex distribution, as well as the statistics for each epidemiological measure applies to the start year of the simulation (2015) may be a limitation. However, the distributions by age and sex are not expected to change dramatically over a few years, so the assumption is made that the latest health statistics available are applicable in the start year of the simulation.

Some of these health statistics were not available at all. These statistics were computed using available epidemiological data, and so the use of modelled data may be a limitation, however these are validated against other modelled data (for instance Global burden of Disease estimates (47) and so these provide the best estimate of the existing health statistics in the population.

The dose-response relationship for some diseases was established and validated by national or international committees (for example, COMEAP). However, after discussions with experts, some dose-response data was collected for diseases for which there was only emerging or novel evidence of a relationship with air pollution. These include conditions such as dementia and low birthweight. The outputs from modelling are presented in the appendices by disease, so that conclusions about health and cost burdens of air pollution can be drawn when excluding these emerging conditions, if required.

The modelling method assumes that LBW is a disease per se. A limitation extending from this would be that we do not take account of subsequent diseases brought about by low birthweight, for example, diabetes or CHD. The model therefore underestimates the long-term economic costs of low birthweight associated with air pollution. Another limitation is that we allow multiple births in the simulation (for example, twins), but we do take account of the possible impact of multiple births on low birthweight. Multiple births are simulated as a list of independent births having the same probability of causing low birthweight.

Most of the cost data were extracted from the literature and suffers from the usual limitations using this approach: each source adopts a different methodology, uses different sources of data, and makes different assumptions. Therefore, they are not fully comparable, although their different magnitudes are reliable estimates of the cost burdens.

The estimation of the costs was limited to the inputs that could be identified, and therefore was relying on the existence of available data. As such the costs estimates represent in many cases lower bound estimates of the true costs to the health or social care systems. Lung cancer costs were the most difficult to estimate, and costs from the literature only provided the financial burden of lung cancer over the last months of life. Dementia costs were taken from the HES database, however this does not include specialist hospitals, which implies that a conservative approach has been used (that is, Underestimation of the costs).

As the main objective of this project was to estimate the direct cost of pollution for the NHS and social care, social costs, such as sick leave and loss of income, were not accounted for. Therefore one should bear in mind that these costs represent only a share of the overall costs related to pollution.

Future work

As well as exploring short-term effects, there are a number of future avenues of work. It was not possible to explore health inequalities in air pollution, however further work might build on the existing tool to include cohorts of different social groups to quantify the impact of varying interventions on these groups. Since children are more susceptible to air pollution given its impact on asthma, and related exacerbations, and that there tend to be more children in the more deprived deciles in England, where PM_{10} and NO_2 concentrations are higher, then exploring the impact of interventions on children specifically is important. Further work is required to get obtain relative risks for children for some diseases. Currently, only relative risks for asthma for those under 18 years is available, however more granular data would enable outcomes in children to be quantified with greater granularity.

COMEAP are also considering the evidence for the effects of air pollution on cardiovascular disease and dementia so this may provide further information that could be incorporated.

Conclusion

The impacts of air pollution and the action required to address it are highly relevant to local government priorities: health, housing, transport, education, local economies, greenspace and quality of life. Local authorities have long had specific legal air quality powers to tackle air pollution locally where there is evidence from either the local or national assessment regimes that it exceeds legal limits. For example, there are currently 28 local authorities in England that are required to draw up local plans to bring forward compliance with legal limits on nitrogen dioxide. Until now, there has been no simple way for local authorities to estimate the potential savings to the public purse from taking local action on nitrogen dioxide, or from other harmful emissions including $PM_{2.5}$ from domestic chimneys and industrial sources. Alongside these specific obligations, strategic decisions on transport, planning and public health taken by local government all contribute to the quality of the air that people breathe in local communities. Many air quality problems, such as concentrations of nitrogen dioxide at the roadside, can be tackled most effectively at the local level and local authorities have to be able to set out a strong rationale for using public money on these initiatives. This tool may help local authorities make a more fully developed economic and financial case for reducing emissions.

The Government will publish a new draft Clean Air Strategy for consultation in spring 2018 and a final strategy by the end of the year. This strategy will set out the range of actions the Government will take in the coming years to tackle emissions of 5 key pollutants from a wide range of sources. There will be a need to continually improve our understanding of the important health, environmental and economic consequences of air pollution in order to deliver an ambitious programme of actions. This new research and resource for local authorities is an important step in transforming how we assess public health impacts in order to inform decisions at local level to improve air quality and the health of people living in affected areas.

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