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Integrated Assessment Modelling of Future Air Quality in the UK to 2050, and Synergies with Net Zero Strategies

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Abstract: Integrated assessment modelling (IAM) has been successfully used in the development of international agreements to reduce transboundary pollution in Europe, based on the GAINS model of IIASA. At a national level in the UK a similar approach has been taken with the UK Integrated Assessment Model, UKIAM, superimposing pollution abatement measures and behavioural change on energy projections designed to meet targets set for reduction of greenhouse gas emissions, and allowing for natural and imported contributions from other countries and shipping. This paper describes how UKIAM has been used in development of proposed targets for reduction of fine particulate $PM_{2.5}$ in the Environment Act, exploring scenarios encompassing different levels of ambition up to 2050 with associated health and other environmental benefits. There are two $PM_{2.5}$ targets, an annual mean concentration target setting a maximum concentration to be reached by a future year, and a population exposure reduction target with benefits for health across the whole population. The work goes further, to also demonstrate links to social deprivation. There is a strong connection between climate measures aimed at reducing net GHG emissions to zero by 2050 and future air quality, which may be positive or negative, as illustrated by sectoral studies for road transport where electrification of the fleet needs to match the evolution of energy production, and for domestic heating where use of wood for heating is an air quality issue. UKIAM has been validated against air pollution measurements and other modelling, but there are many uncertainties including future energy projections. New work is beginning to link UKIAM directly with the TIMES model addressing future energy projections, to explore different uptake scenarios for hydrogen production and use with respect to air quality.

Keywords: integrated assessment modelling; $PM_{2.5}$ concentrations; exceedance of WHO guideline

1. Introduction

Integrated assessment modelling (IAM) has been successfully used in the development of international agreements to reduce transboundary pollution in Europe, based on the GAINS model of IIASA (https://gains.iiasa.ac.at/models/). At a national level in the UK a similar approach has been taken with the UK Integrated Assessment Model, UKIAM [1,2]. The UKIAM has recently been used in development of proposed targets for reduction of fine particulate $PM_{2.5}$ in the Environment Act 2021 (c.30) (https://www.legislation.gov.uk/ukpga/2021/30/), exploring a range of scenarios encompassing different levels of ambition up to 2050 with associated health and other environmental benefits.

These scenarios reflect different levels of effort and ambition in reducing emissions of $PM_{2.5}$ and its precursors, and include consideration of co-benefits of climate measures required to reach Net Zero. The targets to be set in the Environment Act 2021 are aimed at reducing overall population exposure and associated health impacts, and providing a limit on the maximum concentrations to

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address improvements for those with the highest levels of exposure. The scenarios modelled were designed to reduce $PM_{2.5}$ concentrations, but with a view to remaining compliant with international obligations such as the Gothenburg Protocol (https://unece.org/gothenburg-protocol), and National Emission Ceilings Regulations (NECR) and the National Air Pollution Control Programme (NAPCP) for key pollutants (NH_3, SO_2, NOx, $PM_{2.5}$ & VOC's). Targets were then developed which could enhance the approach taken in the Clean Air Strategy 2019 (CAS) (https://www.gov.uk/government/publications/clean-air-strategy-2019) which included a commitment to reduce $PM_{2.5}$ based on the number of people above a concentration threshold. These new targets address both concentrations and population exposure:

- Annual Mean Concentration Target (AMCT), which sets a maximum concentration to be reached by a specified future year; and
- Population Exposure Reduction Target (PERT), which will reduce concentrations and health impacts for everyone.

Extensive analysis of scenarios showing different levels of ambition [3] was provided as evidence for the consultation on environmental targets (https://consult.defra.gov.uk/natural-environment-policy/consultation-on-environmental-targets/).

2. UKIAM

The central model used for this scenario analysis is the UK Integrated Assessment Model [1,2] developed at Imperial College with support from the UK Centre for Ecology and Hydrology. This has been linked to the Scenario Modelling Tool, SMT, (https://smt.ricardo-aea.com/) based on National Atmospheric Emission Inventory (NAEI) emissions [4], and defining emissions for future scenarios based on projections for energy, transport and agriculture reflecting climate measures and additional air pollution abatement measures. Figure 1 gives an overall schematic representation of the approach.

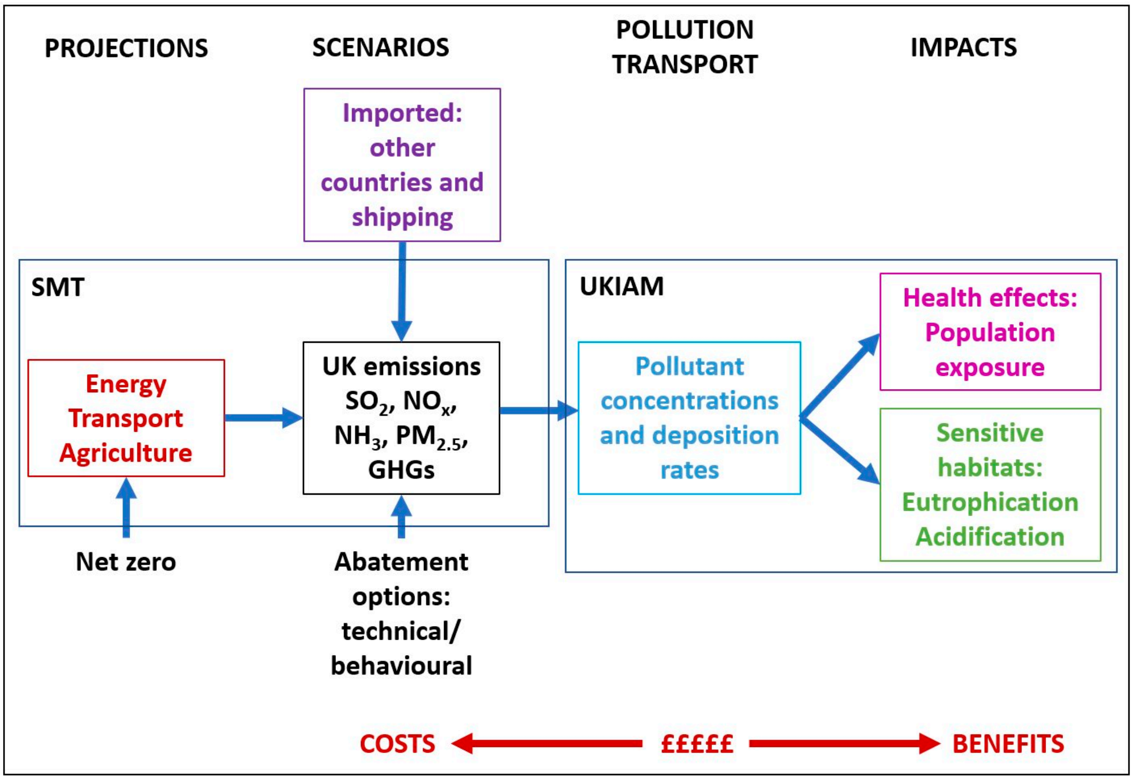

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Figure 1. Schematic representation of approach in UKIAM**.**

The UKIAM is fast to run, enabling modelling of atmospheric concentrations and exposure of the UK population for a large number of scenarios and sensitivity studies, as well as giving detailed source apportionment. The UKIAM combines contributions from primary $PM_{2.5}$ emissions which are more local in scale and concentrated in urban areas, with longer range contributions from secondary inorganic aerosol formed during atmospheric transport from precursor emissions of SO_2, NO_x and NH_3. These are superimposed on other natural components such as sea salt and natural dust, and secondary organic aerosol, which remain fixed over time as an "irreducible" component in the modelling, but collectively form an important contribution to overall concentrations. The model includes imported contributions from other countries and shipping (accounting for IMO legislation and Nitrogen Emission Control Areas), as well as a detailed break-down for UK sources distinguishing contributions from the different devolved administrations and London. In parallel with $PM_{2.5}$ concentrations of NO_2 are also calculated as reduction also leads to improvement and co-benefits for health.

Imported contributions to $PM_{2.5}$ from other countries and sea areas uses the same atmospheric modelling of their individual contributions as in the GAINS model based on the European Eulerian EMEP model [5]. The responses of concentrations and deposition to changes in emissions were derived using source-receptor matrices reflecting the response to unit changes in emission of each pollutant from each country or sea area. Transboundary contributions from other countries reflect scenarios developed by IIASA for the EU's 2nd Clean Air Outlook, with additional measures (WAM) [6]. Emissions from shipping have been modelled based upon the Ricardo Automatic Identification System, AIS, tracking data for the domestic and international fleets around the coast of the UK and in the North and Irish Seas [7]. Shipping around the UK has become a more significant source in relation to the large reductions in land-based emissions over recent years (see Figure S.1); for example, an estimated 660kt of NOx from international and in-transit shipping, combined with 75kt from domestic shipping, exceeds the 710kt of land-based NOx emissions in 2018.

A detailed description of the UKIAM is provided elsewhere [1,2]. This also includes broader applications of UKIAM, for example in relation to nitrogen deposition and protection of natural ecosystems from eutrophication [8].

2.1. Baseline Calculations

In the UKIAM, UK emissions for the base year (2018) and future projections take, as the starting point, the National Atmospheric Emissions Inventory, NAEI, and distinguish around 90 sources as subdivisions of CORINAIR SNAP sectors mapped across different regions of the UK (London, rest of England, Wales, Scotland and Northern Ireland). These define emissions in eleven categories, covering power generation, domestic and industrial combustion, industrial processes, solvents, transport and agricultural emissions. A sub-model, BRUTAL, simulates the road transport in more detail, accumulating emissions across different types of road on a bottom-up basis across the UK road network [9,10]. Alternative scenarios and abatement strategies, together with sensitivity studies and exploration of uncertainties, are undertaken by adjusting the emissions. Figure 2 gives a breakdown of UK emissions in 2018 together with a breakdown of the London emissions in 2018, highlighting the dominance of domestic combustion and road transport emission in urban areas. Further investigation of domestic combustion has indicated lower emissions from domestic wood burning than these original NAEI estimates, leading to sensitivity studies and alternative assumptions about dry and wet wood consumption, as discussed below.

In Figure 3 we show the total $PM_{2.5}$ concentration across the UK, showing a strong gradient from SE to NW which is influenced by transboundary contributions from Europe. Concentrations in London are also highlighted since this is where the highest concentrations and local pollution hotspots tend to be located; as we note in following sections, more extensive abatement measures and strategies are required to reduce concentrations across London towards the 2005 WHO guideline concentrations of $10 \mu g.m^{-3}$. Investigations are ongoing to assess the feasibility of achieving the revised

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2021 guideline of 5µg.m^{-3} across different regions of the UK [11], with preliminary finding suggesting that this may not be feasible in parts of the UK because of natural contributions.

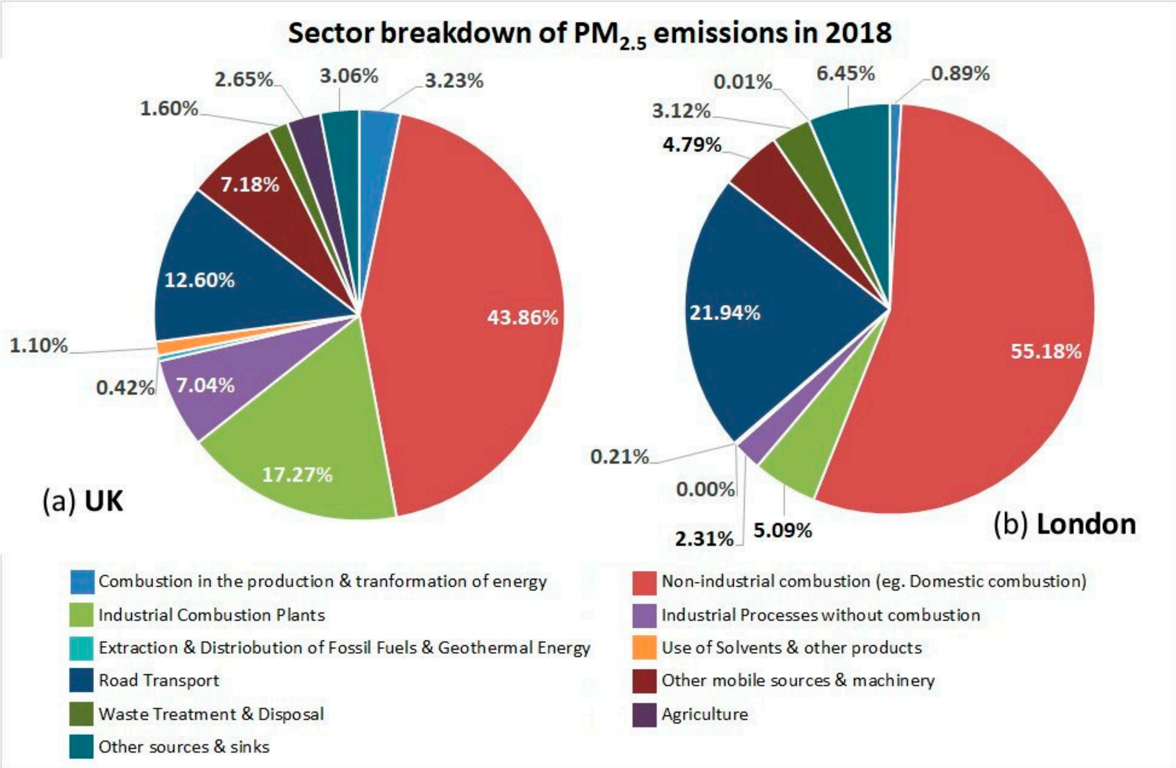

Figure 2. A sectoral breakdown of emissions in 2018, contrasting the contribution of emissions from different sectors nationally (a) with the domination of domestic combustion and road transport emissions in London (b).

Combining the mapped $PM_{2.5}$ concentrations on a 1x1km grid spanning the UK with population data gives an approximate estimate of population exposure, which can be used to assess health impacts [1]. In order to compare different areas of the UK a useful indicator is the derived population weighted mean concentration, PWMC, obtained by dividing the population exposure for a given region by the population - that is to compare the average outdoor concentration to which people are exposed in different areas or regions (see Table 1).

$$PWMC = \sum_{ij}(P_{ij} \times C_{ij})/\sum_{ij} P_{ij} \qquad (1)$$

Where the summation is over grid cells (i,j) in the UK or sub-region with population P_{ij} and concentration C_{ij}.

Table 1. Breakdown of contributions to national and regional $PM_{2.5}$ Population Weighted Mean Concentrations (PWMC) for the 2018 base year – µg/m^3.

	National	Urban	Rural	London	England	Scotland	Wales	Northern Ireland
UK Primary $PM_{2.5}$	2.208	2.505	1.181	3.683	2.379	1.133	1.530	1.759
UK SIA	2.078	2.122	1.925	2.569	2.227	1.036	1.790	1.093
Europe (p$PM_{2.5}$ & SIA)	1.217	1.222	1.204	1.619	1.272	0.714	1.217	1.237
Shipping	0.703	0.706	0.692	0.885	0.739	0.388	0.767	0.476
Natural/Other	2.952	2.986	2.840	3.584	3.088	2.182	2.627	1.874
TOTAL	9.159	9.54	7.843	12.34	9.705	5.452	7.931	6.439

For policy applications, it is also useful to provide source apportionment to quantify the relative importance of different sources, which is easily provided by the UKIAM modelling framework. A breakdown, giving source-apportionment of different contributions to the nationally averaged population weighted mean concentration in 2018 of 9.2μg.m^{-3}, is provided in the pie chart in Figure 4. Clearly the largest anthropogenic contribution comes from the overall contributions to secondary inorganic aerosol (SIA); with less than 0.2μg.m^{-3} primary $PM_{2.5}$ contributed by transboundary sources and shipping and the remainder being secondary, the total SIA exceeds 3.5μg.m^{-3}. The primary contribution weighted by the concentration of population in urban areas is also substantial. A more extensive breakdown of contributions of UK sources by SNAP sector, highlighting the difference in contributions between rural and urban areas, and between contributions to UK or London, has been illustrated elsewhere [1].

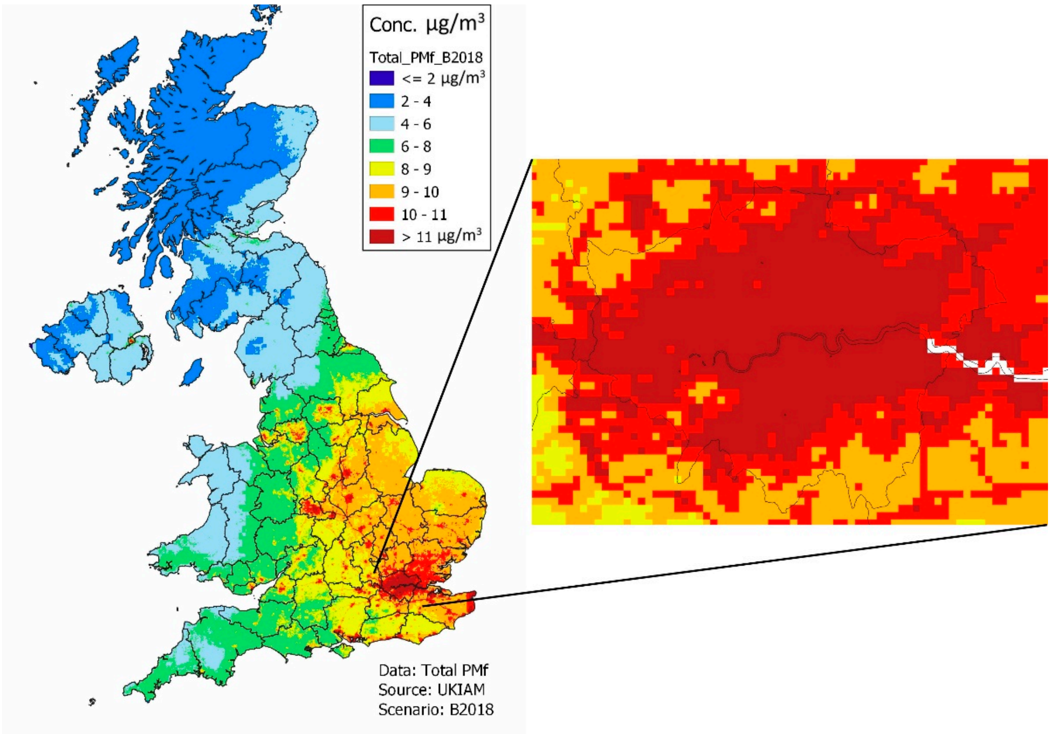

Figure 3. Total $PM_{2.5}$ concentrations show a gradient from SE to NW, with London showing persistently high concentrations in 2018.

Reduction of both primary and secondary contributions to exposure is the focus of policy and pollution abatement measures, reducing emissions from different sectors. In addition, there is the contribution from natural sources, which is not reducible, and from secondary organic aerosol (SOA), where biogenic emissions play an important role but scientific understanding is still evolving.

There are other significant and uncertain sources which contribute to total concentrations of $PM_{2.5}$ which deserve further analysis, beyond the application of measures to different sectors. These include non-exhaust emissions from road transport and domestic combustion of wood, which are examined further in Section 4, below. Additional uncertainties have been reported elsewhere [3,12], notably emissions from cooking which are not included in the NAEI but have been found to have a significant impact on exposure to $PM_{2.5}$ [13], and the non-linear response of SIA to changes in pre-cursor emissions [14].

Note that background concentrations from natural sources, and secondary organic aerosol, which is dominated by biogenic sources, remain effectively constant over time for these scenarios. For parts of the UK, especially in the southeast, which is enhanced by contributions from other countries and shipping, these together are already close to or even exceed 5μg.m^{-3} [1], indicating the difficulty of reaching the recently revised WHO guideline of 5μg.m^{-3} in these areas even with all anthropogenic emissions removed.

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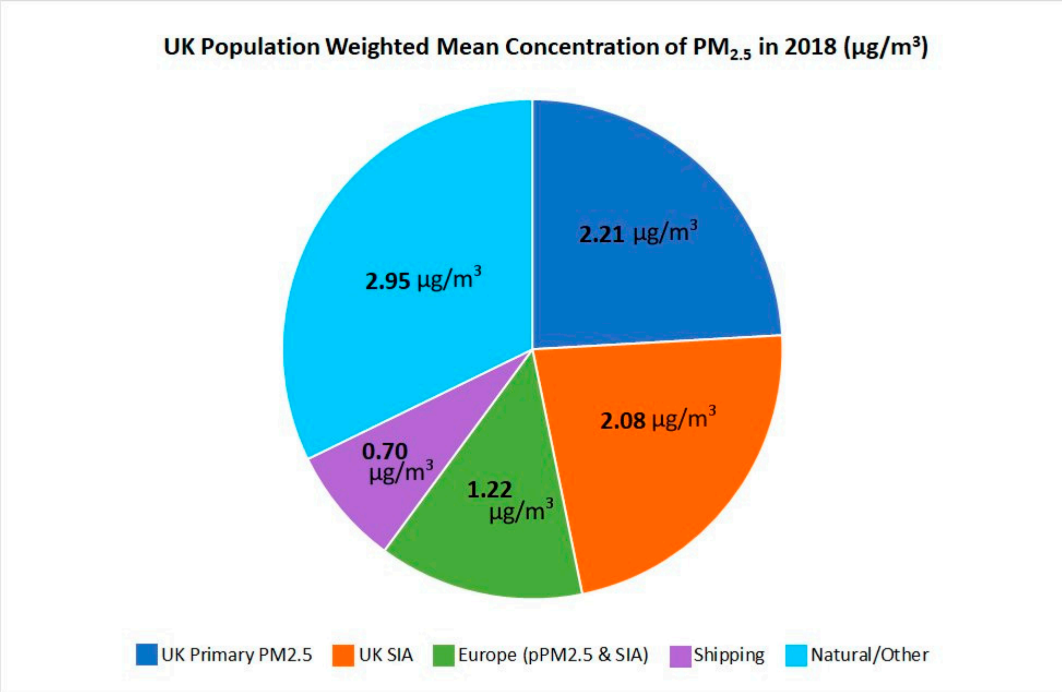

Figure 4. Contribution of national (UK), transboundary and natural sources on UK population.

2.2. Model Validation

Total concentrations are calculated by bringing all the separate contributions to $PM_{2.5}$ concentrations together, combining UK contributions with imported contributions for both primary $PM_{2.5}$ and SIA, superimposed on the irreducible contribution. The resulting concentrations are compared with measurements at national AURN background monitoring sites in Figure S.2 for 2018. There is some scatter, but the overall agreement is good with only a very small negative bias [14]. Here it is important to remember the uncertainties, including the additional interannual variability between years, whereas as UKIAM is based on annual average meteorological data.

A comprehensive evaluation of the UKIAM has been reported elsewhere [14] which includes a direct comparison against the complex Eulerian EMEP4UK model for selected core scenarios reported here. This is important because UKIAM is a reduced-form model which can evaluate multiple scenarios quickly whereas EMEP4UK is a complex ACTM with full chemistry which has been tested widely against measurement data [15–23] and shows good performance. Used in combination for policy support, this facilitates analysis of many alternative policy strategies at the same time as quantifying the potential effects of inter-annual variability in meteorology and non-linear atmospheric chemistry.

Modelling with EMEP4UK has also illustrated the interannual variability with population weighted mean concentrations. The modelling uncertainties noted above and elsewhere [3] are thought to have effects on population weighted mean concentrations within the ±1µg.m^{-3} range. Interannual variations in meteorology, however, suggest an uncertainty margin of 2µg.m^{-3} may be more suitable for years with more adverse meteorology.

3. Scenarios

A large number of scenarios were modelled to explore potential improvements in reducing $PM_{2.5}$ to inform the setting of targets, with a selection of future emission scenarios up to 2050 investigated with different levels of ambition in reducing emissions. The starting point illustrated above is the baseline scenario based on NAEI2018 emissions and emission projections published in 2020 (https://naei.beis.gov.uk/data/submission-archive), with some adjustments to allow for more recent estimates such as updated emission factors for new diesel cars (https://www.emisia.com/utilities/copert/). The baseline projections show large improvements in air

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quality, expected by 2030 as a result of existing measures/trends. Medium, high and speculative scenarios have been modelled with successively greater emission reductions applied to these baseline projections:

- The target *Baseline* reflects existing interventions and policies with a natural technology turnover; it assumes NAEI2018 projections with some adjustments reflecting more recent findings.
- The *Medium* scenario reflects implementation of proven technology with limited behavioural change, and assumes typical timescales and uptake rates.
- The *High* scenario reflects technology considered likely to be implementable in the future, combined with increased behavioural change, more rapid implementation timescales, and better uptake rates.
- The *Speculative* scenario reflects all feasible measures, including emerging technology, with significant behavioural change, and optimistic uptake rates and implementation timescales.

The scenarios are based on hypothetical measures identified through stakeholder engagement and literature review by Wood Plc, and the emissions describing these scenarios were produced by the Scenario Modelling Tool (SMT), developed by Ricardo Plc for Defra. In the case of road transport more detailed modelling of electrification of the fleet with the BRUTAL sub-model of UKIAM [9,10] is used, based upon projections of the uptake of electric vehicles specified by DfT [24].

Concentrations of $PM_{2.5}$ were calculated for the base year 2018, and then 2025, 2030, 2040 and 2050 with increasing uncertainties over time: details of the abatement measures and emissions for each scenario together with maps and other data on exposure have been documented elsewhere as evidence for the consultation on environmental targets [3]. In addition to the medium, high and speculative scenarios an additional scenario was modelled incorporating climate measures designed to reach Net Zero. This introduced relatively small improvements by 2030, increasing to give comparable improvements with the medium scenario by 2040 and 2050, but excluded any additional air pollution abatement measures beyond the co-benefit reductions of the climate measures. Further comparisons were made with a scenario aimed at meeting the UK emissions ceilings, set in the NECR 2018 (https://www.legislation.gov.uk/uksi/2018/129/) as this reflects international commitments for the year 2030, where it produces comparable improvements to the high scenario; in this context, comparable improvements in overall exposure can still give different improvements in the spatial distribution across the population.

Although these scenarios indicate successively substantial improvements in $PM_{2.5}$ concentrations, even with the most ambitious reductions there are still higher concentrations in London than in the rest of England and elsewhere, as noted for the 2018 baseline (see Table 1 & Figure 3). Additional hybrid scenarios were therefore also investigated by superimposing additional abatement in London on top of nation-wide abatement, clearly showing the potential benefits of combining greater effort to reduce emissions in London including behavioural change. However, they also emphasize the importance of uncertainties in urban emissions, especially key sources such as domestic wood-burning and missing sources in the NAEI such as cooking.

The Net Zero scenario is based on projections of future energy generation, derived by the DDM energy model for BEIS (Department for Business, Energy and Industrial Strategy), reflecting climate measures aimed at reaching net zero greenhouse gas emissions (https://www.gov.uk/government/publications/dynamic-dispatch-model-ddm). This is similar to the core scenario developed by the Climate Change Committee, CCC [25] and reflects the commitment to achieve Net Zero emissions from electricity production by 2035, the year in which new ICE (Internal Combustion Engine) cars and vans are phased out with replacement by electric vehicles. The air pollutant emissions have been derived by adapting emissions from the baseline, and do not therefore include any of the additional abatement measures in the medium, high and speculative scenarios above. It is also noted that BEIS do not include actions to reduce domestic wood-burning emissions, which therefore were retained as the emissions officially reported in the NAEI, although

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because of more recent evidence that these were overestimated, sensitivity runs were undertaken to alternative later estimates, as explained below.

The effects of these scenarios on emissions of $PM_{2.5}$ are evident in the reductions shown in Figure 5. With Business-As-Usual only there is a reduction of approx. 30kt $PM_{2.5}$ evident in the 2040 baseline relative to 2018. A further 7kt reduction is suggested in the *Medium* scenario, another 12kt with the *High* scenario, and up to 20kt with the *Speculative* scenario.

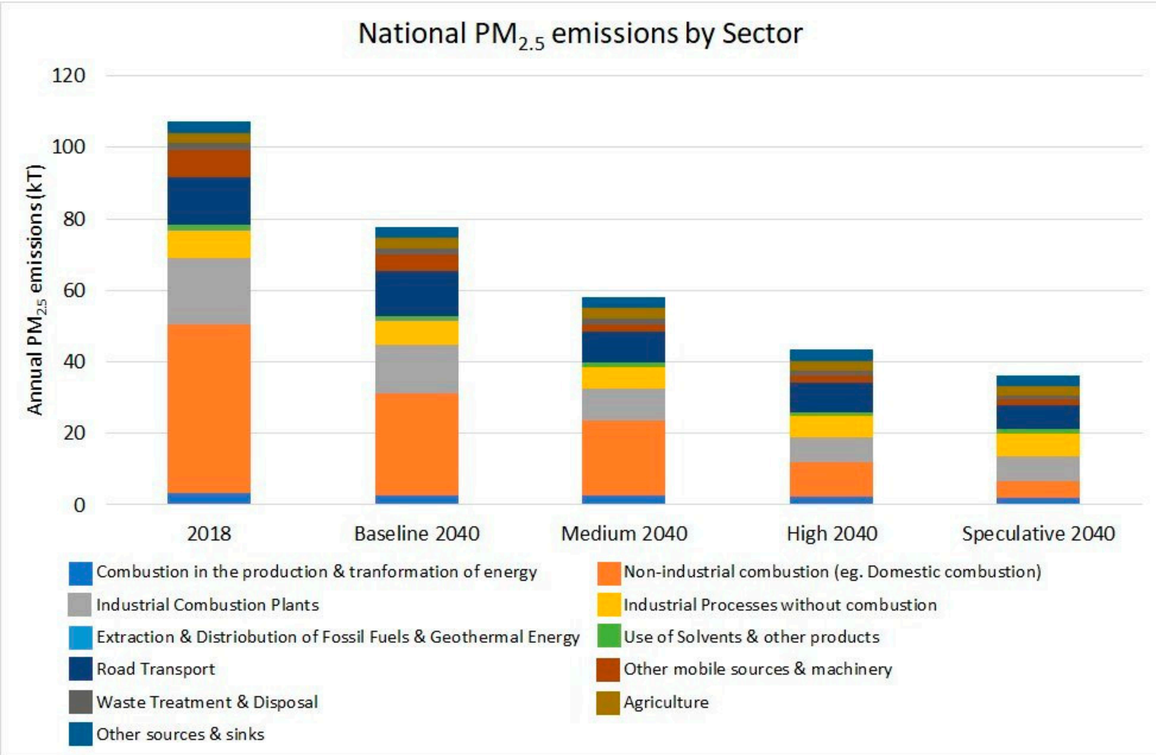

Figure 5. Reduction in emissions in different SNAP sectors for projected scenarios for 2040, relative to 2018.

4. Sectoral Studies

Alongside the scenario modelling described above, a number of additional sectoral and sensitivity studies were carried out in order to quantify and understand the sensitivity of impacts in response to emissions reductions in key sectors. Already noted above is the importance of addressing shipping emissions in the sea areas surrounding the UK. The impact of shipping on both air quality and nitrogen deposition has been reported elsewhere [7]. Here we report on studies carried out addressing road transport and domestic wood combustion which are the dominant emitting sectors of $PM_{2.5}$ (see Figure 5).

In relation to road transport the big reduction in NOx emissions gives substantial improvements in air quality, reducing both NO_2 and secondary $PM_{2.5}$. This is driven initially by improved emission control in new diesel vehicles post RDE testing, and is reinforced in the long term by electrification of the fleet [10]. With respect to primary $PM_{2.5}$ emissions, electrification has been shown to have a small effect because of the dominance of non-exhaust emissions. However, it is likely the amount and composition of non-exhaust emissions will change due to factors such as regenerative braking reducing brake wear or from heavier vehicles increasing tyre wear. In Figure 6 we highlight how electrification of the fleet in line with current government policies [24] significantly reduces NOx emissions relative to the 2030 baseline emissions; in relation to $PM_{2.5}$ emissions, exhaust emissions reduce with electrification, but non-exhaust emissions persist.

Apart from some technological measures to reduce non-exhaust emissions still in development [26], further reductions of $PM_{2.5}$ ultimately depend on reducing kilometres driven, especially in London and densely populated areas. This is dependent on behavioural change rather than technical

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measures, with associated uncertainties in the extent of implementation influenced by national measures like road charging, as well as local action in urban conurbations and by local authorities. Reductions in kilometres driven in urban areas, or restricted to major agglomerations and populated areas of London, will be relevant to urban planning and will requiring more detailed investigation for specific situations.

In the domestic sector, climate measures to cut out the use of coal and oil and reduce emissions from the use of gas can help to reduce $PM_{2.5}$, coupled with measures to reduce energy demand for heating. Combustion of hydrogen to reduce gas use does not avoid NOx emissions and may possibly enhance them in some circumstances, whereas heat pumps require some electricity. However, the biggest concern is domestic wood-burning for which the NAEI indicates very large emissions of primary $PM_{2.5}$, despite the limited energy generated. This constitutes a significant proportion of the domestic emissions shown in Figure 5, and there are indications that use of wood burning stoves is growing.

It should be noted that there are very large uncertainties in $PM_{2.5}$ emissions from wood burning, as emphasized by [27] and reported elsewhere by [12]. These reflect not only uncertainties in the quantities of wood burned and the type of wood, and whether wet or dry, but also on how it is burned in open grates or stoves with different efficiencies and modes of operation. Moreover, past estimates of domestic combustion of wood may have been overestimated [28], and there is an issue in how emissions are defined and reported internationally as to whether they include condensable matter, which can increase emissions up to threefold [29].

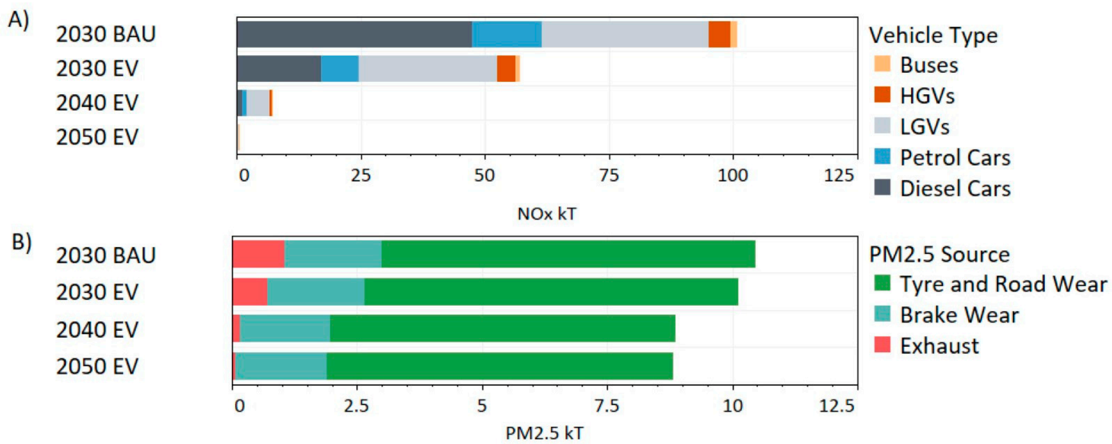

Figure 6. Projected emissions from road transport to 2050 for EV scenario, (a) NOx emissions, where colour shows the emissions from each vehicle type, and (b) $PM_{2.5}$ emissions where colour shows the emission source. Reproduced from [10].

The scenarios discussed here have adopted the NAEI2018 emissions, giving a high contribution to primary $PM_{2.5}$ concentrations in urban areas, and with potential for corresponding reduction in emissions with appropriate measures. More recent estimates [30] show the amount of wood burned has been revised downwards significantly compared with the NAEI 2018 data as a result of more detailed investigation of these emissions, which will be reflected in subsequent NAEI data and related projections. This has important implications for the potential reduction in $PM_{2.5}$ concentrations and has been investigated with sensitivity studies in relation to target setting [3].

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5. Results & Discussion

The UKIAM has been applied to the scenarios above to derive mapped concentrations of $PM_{2.5}$ on a 1x1 km grid across the UK. Figures 7 and 8 (& Figure S.3) show maps for the medium, high and speculative scenarios in 2030 and 2040, respectively. These clearly show the improvement over time for each scenario; and the reduction not only in areas of red calculated as above 10μg.m^{-3}, but also in the orange area between 9 and 10μg.m^{-3} and eventually in the yellow area between 8 and 9μg.m^{-3}, respectively. In this context, allowing for model uncertainties [12], those areas in orange are clearly at risk of exceeding 10μg m^{-3}; and in more adverse meteorological years areas in yellow may also be at risk, as noted above. The divergence between scenarios is also clear, with lower concentrations for the speculative scenario, which is the most successful in eliminating these higher concentration bands.

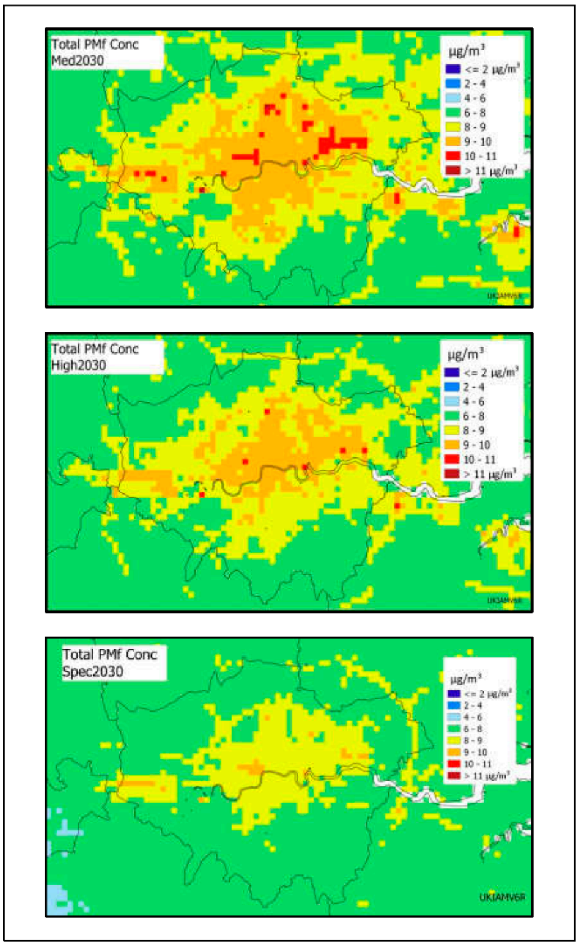

Figure 7. In 2030 there are still large areas at risk of exceeding 10 μgm^{-3}.

To assess the improvement in exposure, population weighted mean concentrations can be calculated using Equation (1), averaged over the whole UK population, broken down into urban and rural populations, and for specific regions such as London (see Table 1). As expected, there are successive improvements in population exposure with increasing levels of abatement from the medium to the speculative scenario, and over time. The Net Zero scenario gives reductions similar to the medium scenario, but that is without any additional air pollution abatement measures superimposed on the climate measures. This suggests that further investigation of combined climate and air pollution abatement scenarios would be useful, and this is now being undertaken.

Whereas these results show that significant reductions are possible across the whole UK, they highlight the much higher $PM_{2.5}$ concentrations across London, compared with the rest of the UK (see Figure S.3). In particular, the results show the difficulties of eliminating exceedance of the 2005 WHO guideline of 10μg.m^{-3} by 2030 (Figure 7), with large areas still at risk of exceeding this concentration.

Superimposing stronger measures in London and other areas of high concentrations, on top of national measures, may get closer to achieving this guideline. Such measures could be either London-wide or targeted on areas of higher concentrations within London – for example the enlarged London ULEZ.

Bearing in mind model uncertainties, the areas in orange, between 9 and 10μg.m^{-3}, are at high risk of exceeding the guideline; and allowing for more adverse meteorology in some years, even yellow areas could be at risk of exceeding the guideline. To remove such risk entirely is not possible, even looking forward beyond 2030. In 2030 there are still areas at risk of exceeding 10μg.m^{-3} even with the very ambitious speculative scenario (Figure 7), and superimposing stronger measures in London on the high scenario. However further improvements in the high scenario by 2040 almost entirely removes these areas (Figure 8). This is reflected in the process of setting the AMCT target below.

The speculative scenario is an extremely ambitious scenario, with optimistic assumptions about behavioural change and international (transboundary) contributions outside UK control. The question arises as to whether effective improvements in London could still be achieved by superimposing stronger measures in London on top of one of the other scenarios. A number of alternative combinations for stronger measures in London were evaluated [3], for example coupling the national medium scenario with stronger measures in London from the high scenario, or further reduction in cars within the extended ULEZ. The findings reflect plans in London towards meeting the WHO interim target of 10μg.m^{-3} [31].

These scenarios support the setting concentration targets, as discussed below, based on estimates of risk based on areas exceeding thresholds which allow for a margin of uncertainty of 1μg.m^{-3}.

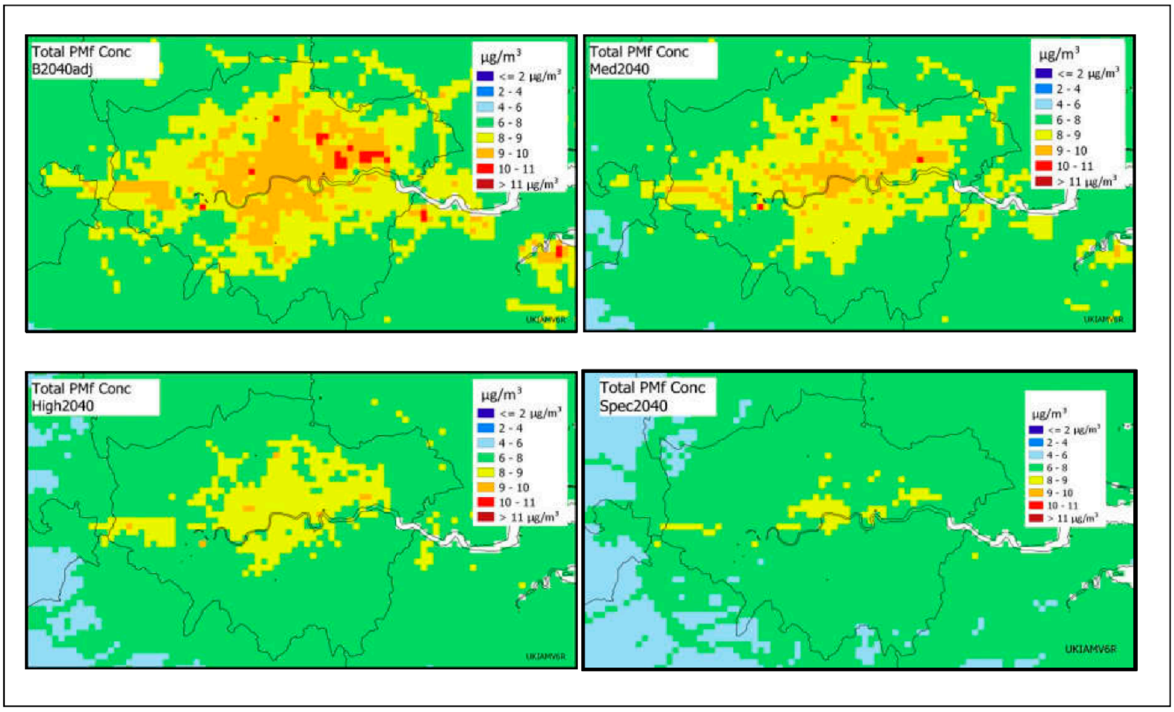

Figure 8. In 2040 the high ambition scenario almost removes all areas (orange) at risk of exceeding exceeding 10 μgm^{-3}.

5.1. Target Setting

Annual Mean Concentration Target (AMCT)

Limiting $PM_{2.5}$ concentrations where they are greatest, and reducing disparities in exposure to make sure that no populations are exposed to excessive concentrations, is the primary purpose of a concentration target. An annual mean concentration target (AMCT) requires that measured concentrations achieve the target level by the specified date. This represents a modelling challenge since individual measurements at specific locations are harder to predict with models than national averages. Modelling uncertainties can have a larger impact in a local context, and individual measurements may show greater variation due to changes in local meteorology which are difficult to replicate.

UKIAM modelling provides the annual average value for a grid square from which Population Weighted Mean Exceedance (PWME) can be calculated nationally or for different regions. Using these modelled results, the accumulated exceedance of different concentration thresholds can be derived and the risk of exceeding this value assigned. If the concentration is close to a threshold it will contribute less to the metric than if the concentration is exceeded by a large amount. The lower the accumulated exceedance the more likely that the region should meet a given target. This approach does not rely on measurements and locations of monitoring sites, and aims to avoid the risks associated with identifying individual grid squares. This is less intuitive and involves judgements on the degree of exposure exceedance and how this may align with subjective risks. When assessing whether a given concentration can be achieved it is also helpful to consider achieving a concentration 1µg.m^{-3} below to account for modelling uncertainties, and up to 2µg.m^{-3} to account for meteorological variations. The accumulated exceedance used as the basis of the assessment is focussed on London since this is where concentrations are highest.

This approach supports the derivation of a matrix of feasible targets for each scenario and year modelled (Figure 9). The different colours represent the likelihood of all measurements being below the given threshold by the date specified under different scenarios. This 'Traffic Light' diagram clearly shows how the 10µg.m^{-3} limit is progressively more likely to be achievable over time; in 2018 10µg.m^{-3} is very unlikely to be achievable (red), but, as noted above, with the *High* scenario it is unlikely to be achievable (orange) in 2030, but with *Speculative* measures applied in London it becomes possibly achievable (yellow). The NECR scenario is similar to the *High* scenario in 2030. In 2040, however, under the *High* scenario 10µg.m^{-3} is likely to be achievable (green). This is a useful perspective to support policy development as it clearly identifies when and how the WHO limit of 10µg.m^{-3} may be achievable.

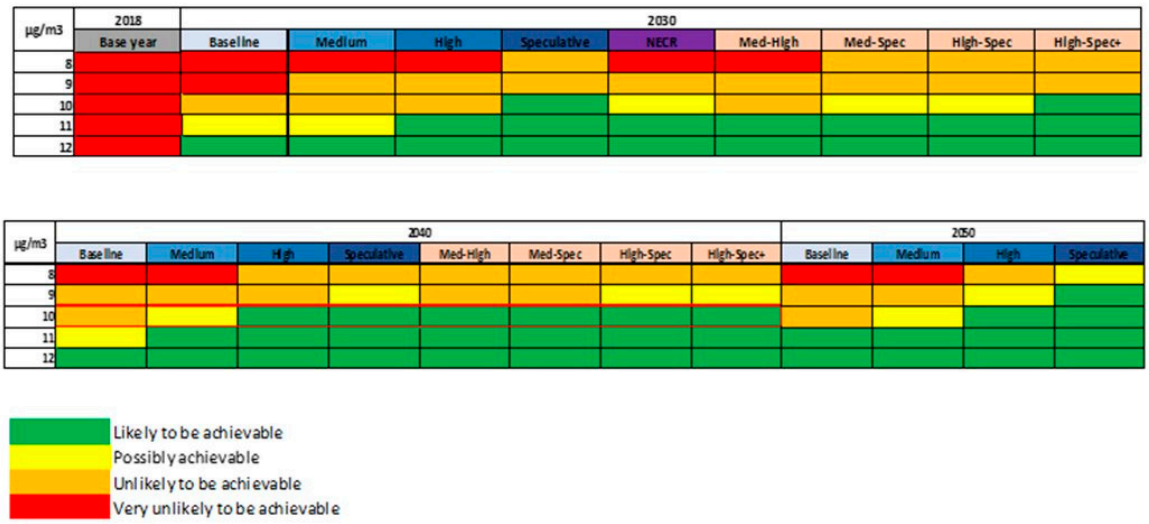

Figure 9. Risk of exceedance traffic light matrix of feasible targets for each scenario and year modelled, highlighting the degree of ambition needed to reach the target concentrations.

Population Exposure Reduction Target (PERT)

Whereas the AMCT should help to limit concentrations in areas where they are the highest, a population exposure reduction target (PERT) will help to reduce the adverse health impacts of air pollution across the whole population. The Environment Act 2021 proposes a 35% PERT by 2040

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relative to 2018, which appears achievable under the *High* scenario given the reductions in PWMC shown in Figure 10.

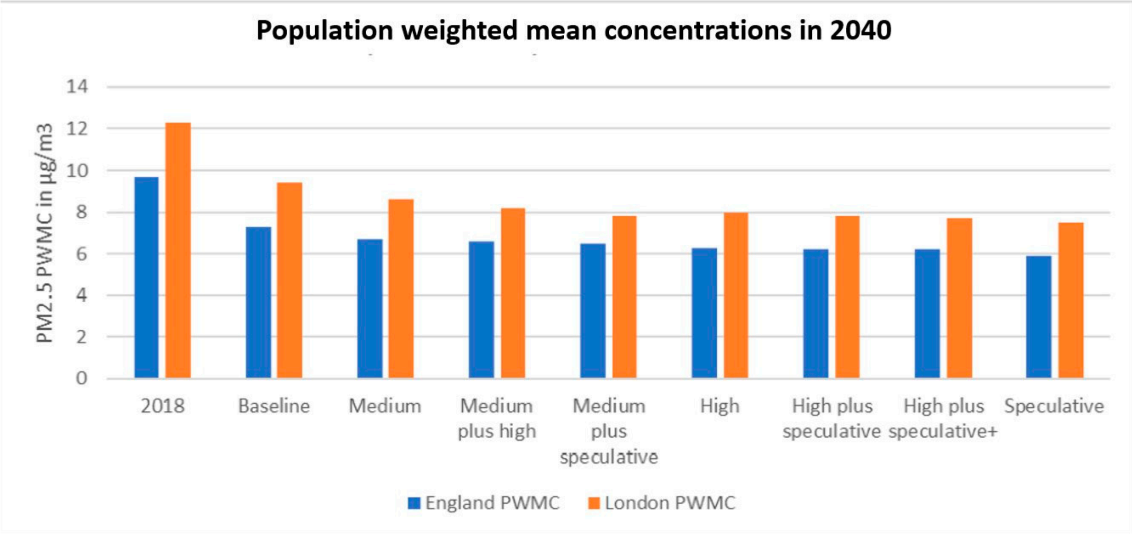

Figure 10. Population Weighted Mean Concentrations for the different scenarios in 2040; these provide the basis for deriving population health impacts and population exposure reduction targets alongside monitoring data.

The average annual mean concentration across urban background monitoring sites can be used as an indicator of current population exposure. The population weighted mean concentration (PWMC) can be derived as a good indicator of future population exposure, quantifiable from modelling results, and allows projections of future population exposure to be produced. One approach to assessing PERT's is to use the average of the modelled concentrations at urban background monitoring sites. This may be less robust than using the PWMC because modelling artefacts may affect individual grid squares and result in anomalies. Monitoring-based population exposure calculations may be expected to be slightly higher than exposures calculated from modelling because monitoring sites tend to be located in areas of higher concentration, whereas the PWMC captures concentrations across all grid squares. This is reflected in the comparison shown in Figure S.5.

This approach assumes that background monitoring sites are representative of the population exposure where they are located, and so align to the average grid concentration. In order to avoid complete reliance on modelling outputs, assessing progress in achieving the PERT should predominantly be based on monitors located at urban background locations. Monitor locations can be indirectly population weighted by strategically locating them in urban locations that are adequately representative of significant proportions of the population.

5.2. Monetised Benefits

Table S.2 shows the total cumulative air quality benefits for England, derived from reduced damage to health, productivity, ecosystems and soiling of buildings for the medium and high scenarios. Benefits are associated with reductions in $PM_{2.5}$ exposure and other air quality co-benefits such as reduction in NO_2. For the *Medium* scenario these benefits are estimated at £23.2 billion, and for the *High* scenario they are estimated at £37.9 billion.

The relevant cost data has predominately been drawn from existing tools and information in previous Defra reports. Where this was not possible external consultants undertook additional research to identify relevant cost data. This included literature reviews and interviews and workshops with key stakeholders.

For the majority of abatement measures there is both an initial capital cost and an ongoing operating cost. The equivalent annualised cost of measures is calculated by distributing capital costs over the lifetime of the measure and combining these costs with operational expenditure. A representative cost per year of the measures is then determined, which can then be compared with costs of other measures where lifetimes of costs differ. Setting the monetised benefits against the social costs summary appraisal statistics can enable quantification of metrics such as the Net Present Social Value and Benefit Cost Ratio. These metrics provide an indication of the net economic impact of the modelled scenarios.

Table 2 summarises results for the medium and high scenarios under central sensitivity assumptions. It is clear from this that the pathways suggested by the scenarios are likely to achieve good value for money since benefits outweighing costs. Further detailed analysis of the economic costs and benefits is reported elsewhere [3].

Table 2. Summary Cost Benefit Analysis Results, 2023-2040, discounted (2020 prices, *£m)*.

	Medium Scenario	High Scenario
Total Monetised Benefits	£108,324	£135,009
Total Costs	£17,915	£27,074
Net Present Value	£90,410	£107,935
Benefit Cost Ratio	6.0	5.0

5.3. Social Impacts & Deprivation

We have so far focused on the mean population exposure in order to quantify health impacts and monetised benefits of pollution abatement. However, there are also equity issues and concerns about higher $PM_{2.5}$ concentrations coinciding with more deprived members of society. A number of studies have shown a correlation between areas of greater deprivation and greater $PM_{2.5}$ exposures in England and within London [32–35]. As for these studies, we also used the Indicator of Multiple Deprivation (IMD) to explore any correlation between higher exposures and higher levels of deprivation (https://www.gov.uk/government/statistics/english-indices-of-deprivation-2019). A map of the IMD by Lower-layer Super Output Area (LSOA) is given in the Supplementary Material (Figure S.4). The IMD is derived for England from statistical data as a weighted average of seven different components: income, employment, education, health, crime, housing and living environment deprivation. The living environment deprivation domain contains an indicator for air quality, so there is a degree of statistical bias when relating $PM_{2.5}$ to the IMD. However, the bias was investigated and found to be of little significance due to the small weighting of the air quality index within the overall calculation of the IMD [36]. Figure S.4 shows that there are concentrations of deprivation in large cities and towns, including areas that have historically had large heavy industry, manufacturing and/or mining sectors, coastal towns and parts of London. These areas tend to coincide with those of greater primary $PM_{2.5}$ emissions and therefore greater concentrations, as seen in Figure 3.

In order to investigate the relation between concentrations and deprivation, we overlayed the 1x1km^2 map of $PM_{2.5}$ concentrations for each scenario over the IMD map and derived the population-weighted mean exposure for each IMD decile, sorted from most deprived (1) to least deprived (10). Figure 11(a) shows the trend in PWMC against deprivation deciles in England for each scenario. Note that the highest exposure does not coincide with the most deprived sector, but with the neighbouring decile, for all scenarios shown. It should be noted however that poor households are often found near major roads, where concentrations are higher due to traffic emissions. The approach used here may not pick up on these instances as the LSOAs are ordered by the average deprivation in each area, and the resolution of the maps used are not sufficient to resolve the effect of elevated concentrations near roads.

While Figure 11(a) is useful for showing the relation between $PM_{2.5}$ exposures and deciles for each scenario, it is difficult to compare the change in this relation between scenarios. In order to show the change in inequality between scenarios, independent of the overall mean exposure changes, we

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subtract the mean PWMC. Figure 11(b) shows the relation of the Delta PWMC (defined as the decile PWMC – mean PWMC) to the deprivation deciles for each scenario. Here it is seen that not only is the mean exposure reduced with each level of ambition for the scenarios considered, but also that the disparity in exposures across deciles is reduced. The baseline scenario in 2040 leads to a significant reduction in the disparity in exposures as compared with the 2018 baseline. There is then a steady decrease in the disparity between deciles for each scenario with increasing ambition. Further work is underway to understand the underlying factors behind the shape of these curves.

Figure S.6(a) and (b) show the equivalent figures for London only. Here the line is more linear and the highest exposure coincides with the decile of greatest deprivation. The relationship between exposure and the level of deprivation is stronger within London than that for England (note the greater scale for the y-axis), and is in part due to the greater overall $PM_{2.5}$ concentrations within London.

Further work is underway to investigate which measures are the key drivers for the reduction in exposure inequality seen for these scenarios. UKIAM is well placed as a tool for this purpose due to its capability to generate full source apportionment for concentration reductions. An index designed to quantify the degree of exposure inequality across deprivation deciles is under development.

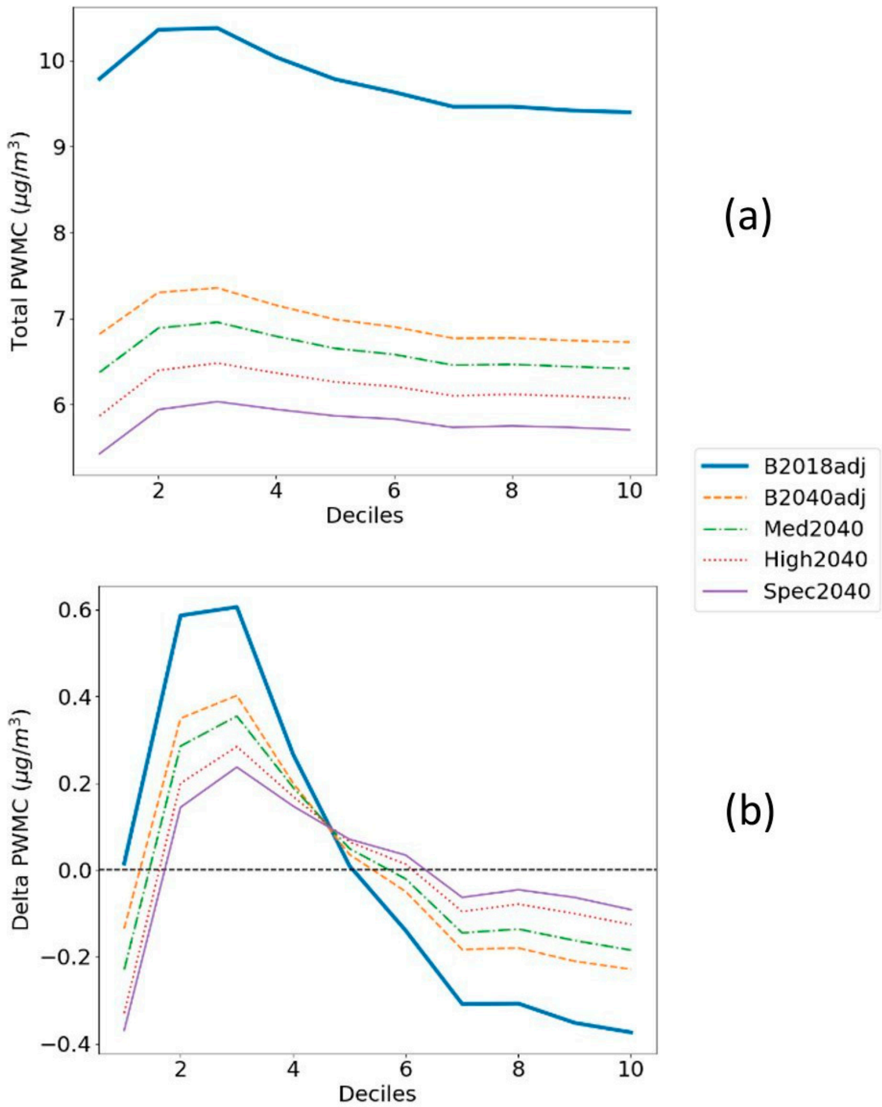

Figure 11. (a) PWMC for each deprivation decile and (b) the Delta PWMC for England for each deprivation decile for B2018adj and 2040 scenarios.

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6. Uncertainties

Throughout this work many uncertainties have been identified, with investigation where possible including model intercomparisons [14] and sensitivity studies, and suggestions for further work to refine the scenario assessment undertaken [3]. Improved information on emissions, including missing sources in the NAEI such as cooking and better data on wood-burning, can help to refine estimated concentrations and inform the setting of interim targets. But spatially detailed data to address localised hot spots may be problematic with respect to both modelling and measurements.

We have identified a wide range of uncertainties and assumptions related to the projected emissions and their abatement, the atmospheric modelling, and the resulting population exposure and impacts on health and the environment [3,12]. Some of these may result in optimistic assessments whilst others may be pessimistic, indeterminate or qualitative. However, they all need to be considered when setting targets for improvement of air quality. Comparisons with measurements suggests that the modelling bias is small, and allowances for model uncertainty of the order of 1$\mu g.m^{-3}$ should be made when assessing concentrations, but up to 2$\mu g.m^{-3}$ when allowing for adverse meteorological years.

Uncertainties may be evident in the modelling, in quantification of imported contributions – transboundary or shipping – which are outside UK control, in specification of UK emissions and the effects of abatement measures, and in deriving the impacts and benefits. Work is ongoing to investigate uncertainties in the measures contributing significantly to improvements, and to explore synergies between climate measures and improvement of air quality.

7. Conclusions

This paper has illustrated an integrated approach to assessing the combined effect of air pollution abatement measures superimposed on projections for energy, transport and agriculture reflecting Net Zero measures and climate policy. Scenario analysis has been used to support the setting of targets for improvement of $PM_{2.5}$ which address both overall population exposure related to health impacts, and maximum concentrations. On economic aspects assessment of monetised benefits has been undertaken, showing that for the selected scenarios to achieve the targets these justify the costs of abatement. Moreover, preliminary investigation of the deprivation index has shown that the disparity between higher exposure of more deprived communities and lower exposure of less deprived communities is narrowed over time and with increasing ambition of abatement strategies. The next task is to develop interim targets at five yearly intervals and a progressive stepwise strategy towards meeting the longer-term targets.

This work has also illustrated the dependence of improvements in air quality on the synergies between climate measures to reduce GHG's and emissions of air pollutants. Further work is required for deeper exploration of Net Zero scenarios, including use of hydrogen to reduce fossil fuel use. Work is also underway to explore a wider range of future agricultural scenarios where there is competition for land use for food production dependent on dietary change with climate measures for reforestation, biofuel production and peat restoration. The flexibility of the UKIAM allows simultaneous exploration of the implications for nitrogen pollution and environmental impacts of eutrophication on ecosystems and biodiversity.

Supplementary Materials: The following supporting information can be downloaded at the website of this paper posted on Preprints.org.

Author Contributions: Conceptualization, Helen ApSimon; Data curation, Tim Oxley and Huw Woodward; Investigation, Tim Oxley; Methodology, Helen ApSimon, Tim Oxley, Huw Woodward and Mike Holland; Software, Tim Oxley, Huw Woodward and Daniel Mehlig; Writing – original draft, Tim Oxley; Writing – review & editing, Helen ApSimon and Sarah Reeves.

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Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Glossary

ACTM	Atmospheric Chemical Transport Model (eg. EMEP4UK)
AQEG	Air Quality Expert Group, https://uk-air.defra.gov.uk/research/aqeg/
AURN	Automatic Urban and Rural Network of monitoring stations, https://uk-air.defra.gov.uk/networks/network-info?view=aurn
BRUTAL	Road Transport sub-model of the UKIAM (Oxley *et al*., 2009)
CLRTAP	UNECE Convention on Long-Range Transboundary Air Pollution; renamed as the Air Convention https://unece.org/environment-policy/air
CORINAIR	CORe INventory of AIR Emissions
EMEP	(1) Cooperative Programme for Monitoring and Evaluation of the Long-range Transmission of Air Pollutants in Europe (1984, Geneva Protocol) http://www.emep.int/ (2) Unified EMEP Eulerian model (Simpson et al., 2012; https://github.com/metno/emep-ctm
EMEP4UK	EMEP4UK model (Vieno *et al*., 2009; 2010; 2014; 2016)
GAINS	Greenhouse gas and Air pollution INteractions and Synergies; a development of the RAINS model to address the inter-relationships with effects of greenhouse gases (GHG), https://gains.iiasa.ac.at/models/
ICE	Internal Combustion Engine
IIASA	International Institute of Applied Systems Analysis, https://iiasa.ac.at/
IMO	International Maritime Organisation, https://www.imo.org/
NAEI	National Atmospheric Emissions Inventory (http://naei.beis.gov.uk)
NH_3	Ammonia
NH_4^+	Ammonium Aerosol, forming either ammonium nitrate (NO_3NH_4) or ammonium sulphate ($SO_4(NH_4)_2$)
NECA	Nitrogen Emission Control Area
NO_3^-	Nitrate Aerosol (in this paper this always refers to the fine (<2.5μm) NO_3^-)
NOx	Nitrogen Oxides comprised mainly of NO (Nitric Oxide) and NO_2 (Nitrogen Dioxide)
$PM_{2.5}$	Particulate Matter < 2.5μm diameter
PWMC	Population Weighted Mean Concentration, $PWMC = \sum_{ij}(P_{ij} \times C_{ij})/\sum_{ij} P_{ij}$, where the population in cell (ij) is P_{ij} and the concentration is C_{ij}
SIA	Secondary Inorganic Aerosol, formed by precursor emissions of NH_3, SO_2 and NOx ($SIA=SO_4^{2-}+NO_3^-+NH_4^+$)
SMT	Scenario Modelling Tool (https://smt.ricardo-aea.com/)
SNAP	Selected Nomenclature for Air Pollutants
SOA	Secondary Organic Aerosol, influenced by both biogenic and anthropogenic emissions
SO_2	Sulphur Dioxide
SO_4^{2-}	Sulphate Aerosol

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UKIAM	UK Integrated Assessment Model, developed by Imperial College London (ApSimon *et al.*, 2021a; Oxley *et al.*, 2013)
VOC	Volatile Organic Compounds

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