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

Helen ApSimon [1], Tim Oxley [1,*], Huw Woodward [1], Daniel Mehlig [1], Mike Holland [2] and Sarah Reeves [3]

1 Centre for Environmental Policy, Imperial College London, London SW7 2AZ, UK
2 EMRC, 2 New Building, Whitchurch Hill, Reading RG8 7PW, UK
3 Department for Environment, Food and Rural Affairs, 2 Marsham Street, London SW1P 4DF, UK
* Correspondence: t.oxley@imperial.ac.uk

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 the reduction of greenhouse gas emissions and allowing for natural and imported contributions from other countries and shipping. This paper describes how the UKIAM was used in the development of proposed targets for the reduction of fine particulate $PM_{2.5}$ in the UK Environment Act, exploring scenarios encompassing different levels of ambition in reducing the emissions of air pollutants 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, also demonstrating 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 the use of wood for heating is an air quality issue. The UKIAM has been validated against air pollution measurements and other types of modelling, but there are many uncertainties, including future energy projections.

Keywords: integrated assessment modelling; $PM_{2.5}$ concentrations; target setting; UK Environment Act

Citation: ApSimon, H.; Oxley, T.; Woodward, H.; Mehlig, D.; Holland, M.; Reeves, S. Integrated Assessment Modelling of Future Air Quality in the UK to 2050 and Synergies with Net-Zero Strategies. *Atmosphere* **2023**, *14*, 525. https://doi.org/10.3390/atmos14030525

Academic Editor: Célia Alves

Received: 3 February 2023
Revised: 3 March 2023
Accepted: 7 March 2023
Published: 9 March 2023

1. Introduction

Integrated assessment modelling (IAM), based on the GAINS model of IIASA (https://gains.iiasa.ac.at/models/ (accessed on 1 February 2023), has provided the basis for the development of international agreements to reduce transboundary pollution in Europe. At the national scale 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 the development of proposed targets for reduction of fine particulate $PM_{2.5}$ in the UK Environment Act 2021 (c.30) (https://www.legislation.gov.uk/ukpga/2021/30/ (accessed on 1 February 2023)), 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 health co-benefits and synergies with climate measures required to reach net zero. Synergies with climate measures are highlighted by the sensitivity studies focusing on road transport and domestic combustion discussed below.

The targets set in the Environment Act 2021 are aimed at reducing overall population exposure and associated health impacts and identifying maximum target concentrations to address improvements for those with the highest levels of exposure. These targets are based on annual average background concentrations, and they provide the basis for estimating population exposure [2] and source apportionment of concentrations [1]. 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 (accessed on 1 February 2023)), 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). New targets were then developed that could enhance the approach taken in the Clean Air Strategy 2019 (CAS) (https://www.gov.uk/government/publications/clean-air-strategy-2019 (accessed on 1 February 2023)), with the CAS including 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;
- Population exposure reduction target (PERT), which will reduce concentrations and health impacts for everyone.

Extensive analyses of scenarios showing different levels of ambition [3] were provided as evidence for the consultation on environmental targets (https://consult.defra.gov.uk/natural-environment-policy/consultation-on-environmental-targets/ (accessed on 1 February 2023)).

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. The UKIAM operates on the basis of annual averages, using source–receptor relationships for all source/pollutant combinations captured by the model. Primary $PM_{2.5}$ (and NOx/NO_2) are modelled at a 1 × 1 km resolution using an internal Gaussian plume model and annual average wind rose. Secondary inorganic aerosols (SIA) are modelled at a 5 × 5 km resolution based on precursor emissions of NH_3, SO_2, and NOx, combined with source–receptor relationships calculated by the Lagrangian FRAME model [4–6]; the FRAME model also provides footprints for sulphur and nitrogen deposition that are used for the calculation of critical load exceedances and other environmental impacts [7]. Finally, contributions from other countries are obtained using source–receptor relationships (0.5° × 0.25° resolution) calculated by the Eulerian EMEP model [8]. The model was validated against measurements (see Section 2.2) and compared with the Eulerian EMEP4UK model for modelling future years [9].

The UKIAM was linked to a scenario modelling tool, SMT, (https://smt.ricardo-aea.com/ (accessed on 1 February 2023)) based on the National Atmospheric Emission Inventory (NAEI) emissions [10] and defines 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 this approach. With emissions projections combined with abatement strategies (including net zero) in the SMT, alternative scenarios and transboundary contributions are modelled by the UKIAM to derive pollutant concentrations and impacts on human health. The results provide the basis for developing new targets for $PM_{2.5}$ concentrations and reducing population exposure.

Confidence in the modelling is supported by an agreement with measurements and detailed model intercomparison [9] and in broader applications of UKIAM in relation to nitrogen deposition and the protection of natural ecosystems from eutrophication [7].

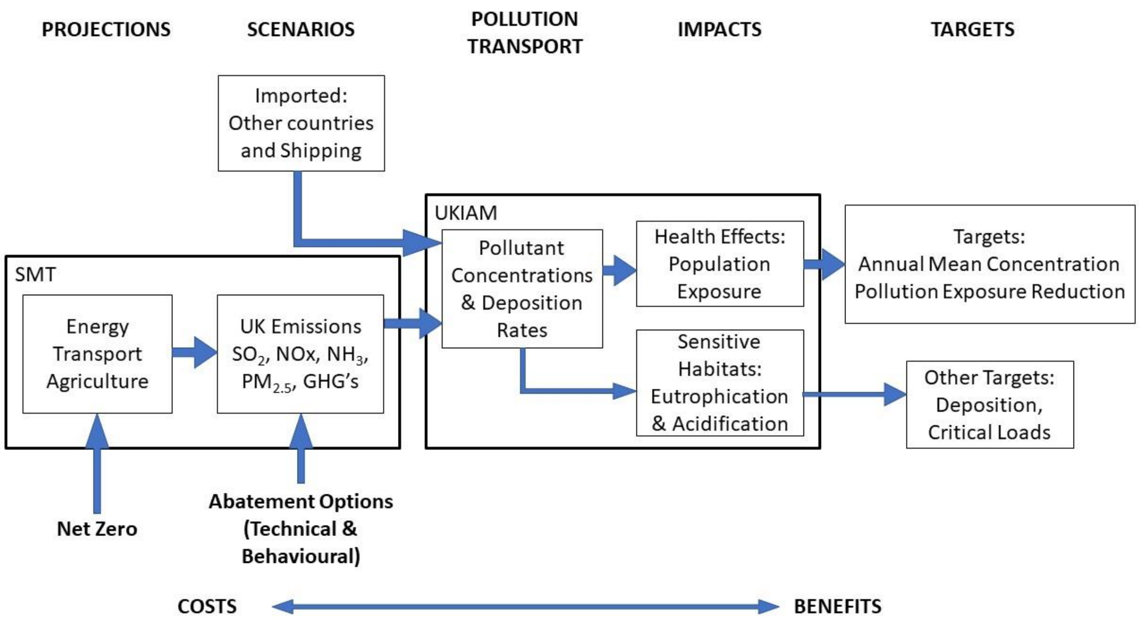

Figure 1. Schematic representation of approach with the scenario modelling tool (SMT) specifying UK emissions scenarios modelled by UKIAM and model outputs used to develop targets for annual mean concentrations and pollution exposure reduction.

The UKIAM is fast to run, enables the modelling of atmospheric concentrations and exposure of the UK population for a large number of scenarios and sensitivity studies, as well as provides 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, NOx, and NH_3. These are superimposed on other natural components, such as sea salt and natural dust, and secondary organic aerosol (SOA), which remains fixed over time as an "irreducible" component in the modelling but collectively forms an important contribution to overall concentrations. The model includes imported contributions to concentrations from other countries and shipping (accounting for International Maritime Organisation (IMO) legislation and Nitrogen Emission Control Areas), as well as a detailed breakdown of UK sources, distinguishing contributions from the different devolved administrations and London. The work presented here focusses on $PM_{2.5}$ concentrations. However, concentrations of NO_2 are also calculated by this model [2], as their reduction leads to further benefits for health [11].

Transboundary contributions to $PM_{2.5}$ imported from other countries and sea areas use the same atmospheric modelling of their individual contributions as in the GAINS model based on the European Eulerian EMEP model [8]. The responses of concentrations and deposition to changes in emissions were derived using source–receptor matrices reflecting the response to unit changes in the emission of each pollutant from each country or sea area. Transboundary contributions from other countries reflect scenarios developed by IIASA for the EU's Second Clean Air Outlook, with additional measures (WAM) [12]. Emissions from shipping are 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 [13]. 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 S1); for example, an estimated 660 kt of NOx from international and in-transit shipping, combined with 75 kt from domestic shipping, exceeds the 710 kt of land-based NOx emissions in 2018.

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 (Selected Nomenclature for Air Pollutants) sectors mapped across different regions of the UK (London, England—excluding London—Wales, Scotland, and Northern Ireland). SNAP sectors define emissions in eleven categories, covering power generation, domestic and industrial combustion, industrial processes, solvents, transport, and agricultural emissions. A sub-model, BRUTAL, simulates road transport in more detail, accumulating emissions across different types of roads on a bottom-up basis across the UK road network [14,15]. Alternative scenarios and abatement strategies, together with sensitivity studies and an exploration of uncertainties, are undertaken by adjusting the emissions used as model inputs. Figure 2 gives a breakdown of UK emissions in 2018 together with a breakdown of London emissions in 2018, highlighting the dominance of emissions from domestic combustion and road transport in urban areas. Further investigation of domestic combustion indicated lower emissions from domestic wood burning than the original NAEI estimates, leading to sensitivity studies and alternative assumptions about dry and wet wood consumption, as discussed below.

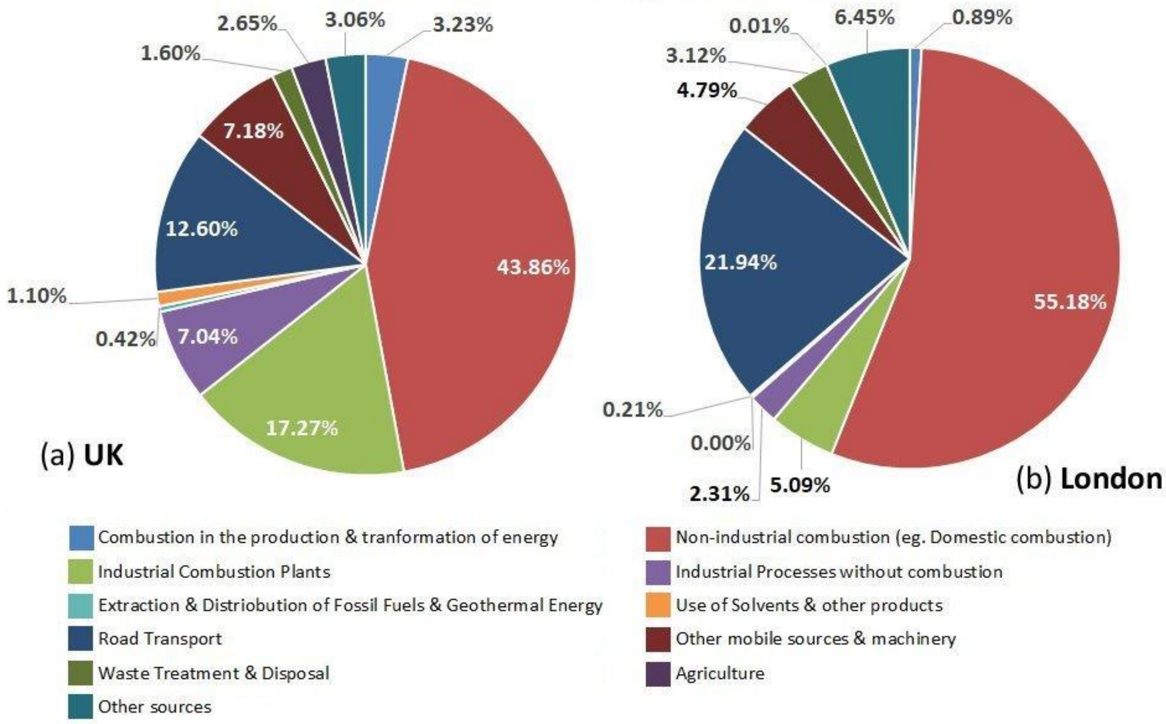

Figure 2. A sectoral breakdown of $PM_{2.5}$ emissions in 2018, contrasting to the contribution of emissions from different sectors nationally (**a**) with the domination of domestic combustion and road transport emissions in London (**b**).

Figure 3 shows the total $PM_{2.5}$ concentration across the UK, with 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 noted in following sections, more extensive abatement measures and strategies are required to reduce concentrations across London towards the 2005 WHO guideline concentrations of 10 μg m^{-3}. Investigations are ongoing to assess the feasibility of achieving the revised 2021 guideline of 5 μg m^{-3} [16] across different regions of the UK, with preliminary findings suggesting that this may not be feasible in parts of the UK because of natural contributions.

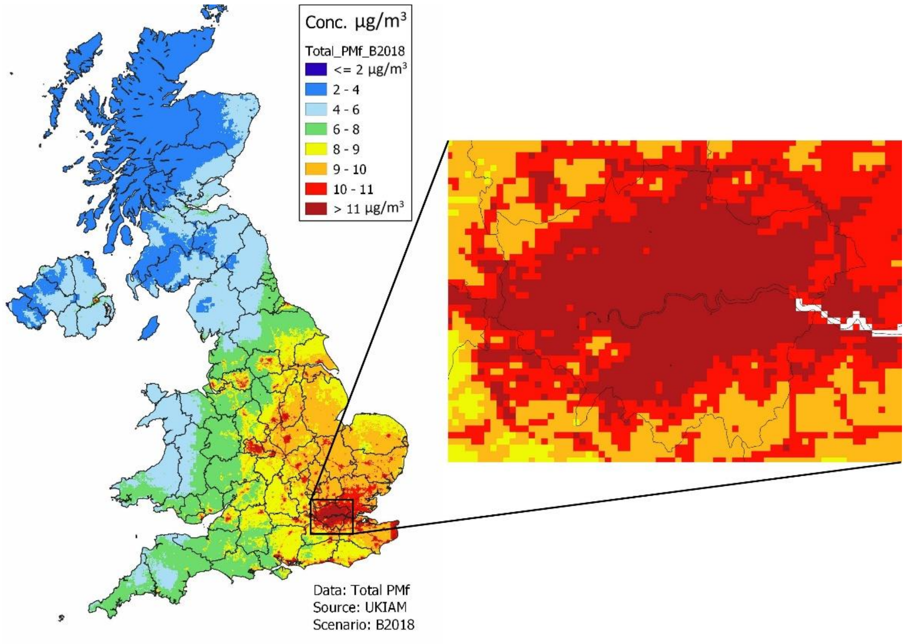

Figure 3. Total modelled $PM_{2.5}$ concentrations (1×1 km resolution) show a gradient from SE to NW, with London showing widespread high concentrations in 2018.

Combining the mapped $PM_{2.5}$ concentrations on a 1×1 km 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. Table 1 shows a breakdown of contributions to total concentrations, distinguishing primary from secondary $PM_{2.5}$, transboundary contributions, shipping, and natural sources. Concentrations are given nationally, for devolved regions, and distinguish urban and rural areas. London is shown separately, as this is where the highest $PM_{2.5}$ concentrations are evident.

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

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

For policy applications, it is also useful to provide source apportionment to quantify the relative importance of different sources, which is easily generated by the UKIAM modelling framework [1]. A breakdown providing source apportionment of different contributions to the nationally averaged population-weighted mean concentration in 2018 of 9.2 $\mu g\ m^{-3}$ (see Table 1) is shown 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 0.2 $\mu g\ m^{-3}$ primary $PM_{2.5}$ contributed by transboundary sources and shipping and the remainder being secondary, the total SIA exceeds 3.5 $\mu g\ m^{-3}$. 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 the SNAP sector highlighting the difference in contributions between rural and urban areas and between contributions to the UK and London has been illustrated elsewhere [1].

The reduction of both primary and secondary contributions to exposure is the focus of policy and pollution abatement measures, thereby reducing emissions from different sectors. In addition, there is the contribution from natural sources, which is not reducible, and from secondary organic aerosol (SOA), which has been calculated by the NAME model [17] and remains static in the UKIAM, where biogenic emissions play an important role but scientific understanding is still evolving. This is consistent with modelling by EMEP4UK, which shows little change in the anthropogenic contribution to SOA, with uncertainties in the contributions of iVOCs with intermediate volatility [9].

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 (excl. London)	Scotland	Wales	Northern Ireland
UK Primary $PM_{2.5}$	2.21	2.51	1.18	3.68	2.38	1.13	1.53	1.76
UK SIA	2.08	2.12	1.93	2.57	2.23	1.04	1.79	1.09
Europe (p$PM_{2.5}$ & SIA)	1.22	1.22	1.20	1.62	1.27	0.71	1.22	1.24
Shipping	0.70	0.71	0.69	0.88	0.74	0.39	0.77	0.48
Natural/Other	2.95	2.99	2.84	3.58	3.09	2.18	2.63	1.87
TOTAL	9.16	9.54	7.84	12.34	9.71	5.45	7.93	6.44

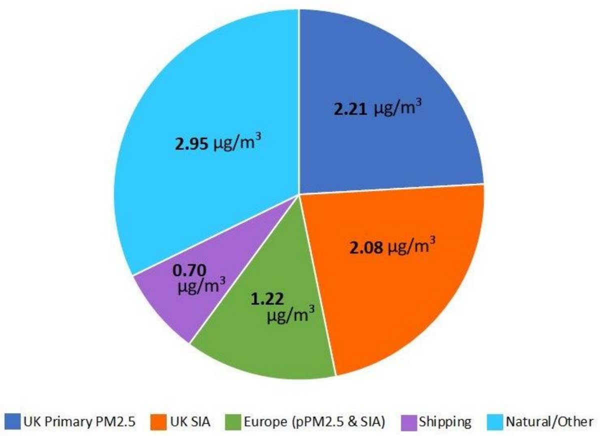

Figure 4. Contribution of national (UK), transboundary, and natural sources towards UK population-weighted mean concentrations of $PM_{2.5}$ in the UK in 2018. See Table 1 for contributions to devolved regions.

There are other significant and uncertain sources that contribute to total concentrations of $PM_{2.5}$ that 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 [3,18], notably, emissions from cooking, which are not included in the NAEI but have been found to have a significant impact on exposure to $PM_{2.5}$ [19], and the non-linear response of SIA to changes in pre-cursor emissions [9].

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 5 μg m^{-3} [1], indicating the difficulty of reaching the recently revised WHO guideline of 5 μg m^{-3} in these areas, even with all anthropogenic emissions removed.

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 S2 for 2018. There is some scatter, but the overall agreement is good, with only a very small negative bias [9]. Here, it is important to remember the uncertainties, including the additional interannual variability between years, whereas the UKIAM is based on annual average meteorological data.

A comprehensive evaluation of the UKIAM has been reported elsewhere [9], which includes a direct comparison against the complex Eulerian EMEP4UK model for selected core scenarios reported here. This is important because the UKIAM is a reduced-form model that can evaluate multiple scenarios quickly, whereas EMEP4UK is a complex ACTM with full chemistry that has been tested widely against measurement data [20–28] and shows good performance. Using both models in combination for policy support facilitates the analysis of multiple alternative policy strategies at the same time as quantifying the potential effects of interannual variability in meteorology and non-linear atmospheric chemistry.

Modelling with EMEP4UK also illustrates the interannual variability with population-weighted mean concentrations. The modelling uncertainties noted above and elsewhere [3] are estimated to have effects on population-weighted mean concentrations within the $\pm 1\ \mu g\ m^{-3}$ range. Interannual variations in meteorology, however, suggest an uncertainty margin of $2\ \mu g\ m^{-3}$ may be more suitable to account 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 (accessed on 1 February 2023)), with some adjustments to allow for more recent estimates such as updated emission factors for new diesel cars (https://www.emisia.com/utilities/copert/ (accessed on 1 February 2023)). The baseline projections show large improvements in air quality, expected by 2030 as a result of existing measures/trends. Medium, high, and speculative scenarios are 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 the 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, optimistic uptake rates, and implementation timescales.

The scenarios are based on hypothetical measures identified through stakeholder engagement and a literature review by Wood Plc [29], with an overview of the key assumptions noted in Box S1. The emissions describing these scenarios were calculated by the scenario modelling tool (SMT) developed by Ricardo Plc for Defra. In the case of road transport, a more detailed modelling of electrification of the fleet with the BRUTAL sub-model of the UKIAM [14,15] is used, based upon projections of the uptake of electric vehicles specified by DfT [30].

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/ (accessed on 1 February 2023)), 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 and Figure 3). Additional hybrid scenarios were, therefore, also investigated by superimposing additional abatement in London on top of nationwide abatement, clearly showing the potential benefits of combining greater efforts 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, obtained by the DDM energy model for the 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 (accessed on 1 February 2023)). This is similar to the core scenario developed by the Climate Change Committee, CCC [31], 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 to be phased out with replacement by electric vehicles. The air pollutant emissions were obtained 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 the BEIS does not include actions to reduce domestic wood-burning emissions, which therefore were retained as the emissions officially reported in the NAEI, although because of more recent evidence that these were overestimated, sensitivity runs were undertaken for 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. Only with business-as-usual is there a reduction of approx. 30 kt $PM_{2.5}$, evident in the 2040 baseline, relative to 2018. A further 7 kt reduction is suggested in the medium scenario, another 12 kt in the high scenario, and up to 20 kt in the speculative scenario.

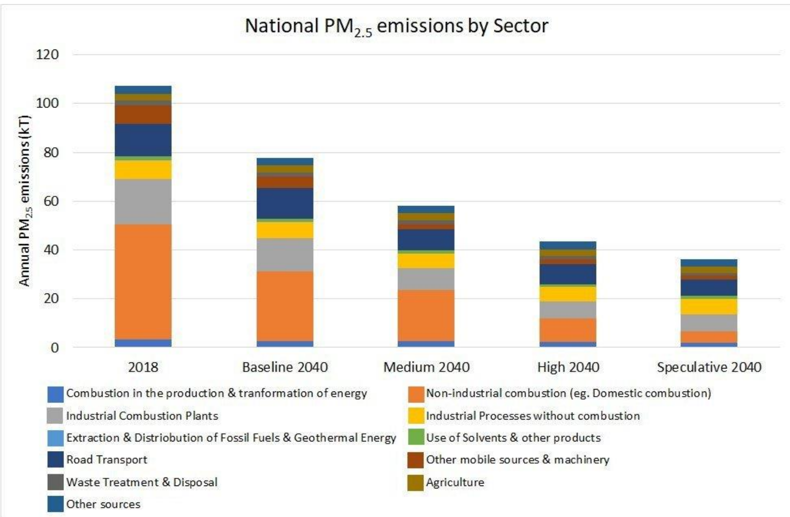

Figure 5. The reduction in emissions in different SNAP sectors is clear for scenarios in 2040, relative to 2018, with progressively greater reductions with higher ambition.

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 [13]. Sectoral studies were 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 provides 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 [15]. With respect to primary $PM_{2.5}$ emissions, electrification was shown to have a small effect because of the dominance of non-exhaust emissions. However, it is likely that the amount and composition of non-exhaust emissions will change due to factors such as regenerative braking reducing brake wear or heavier vehicles increasing tyre wear. Figure 6 highlights how electrification of the fleet in line with current government policies [30] 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.

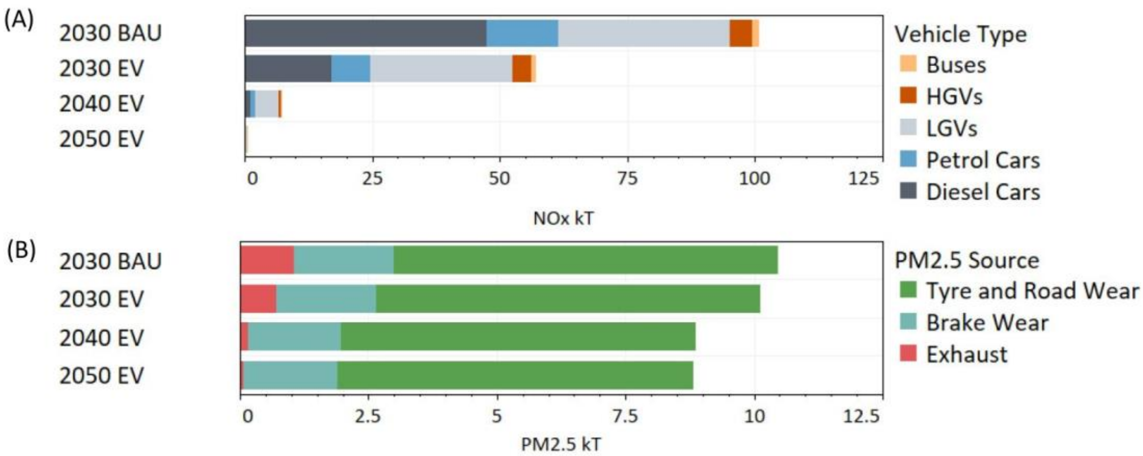

Figure 6. Projected emissions from road transport to 2050 for EV scenario; (**A**) NOx emissions, where colour shows the emissions from each vehicle type; and (**B**) $PM_{2.5}$ emissions where colour shows the emission source. Reproduced from [15].

Apart from some technological measures to reduce non-exhaust emissions still in development [32], further reductions of $PM_{2.5}$ ultimately depend on reducing kilometres driven, especially in London and other densely populated areas. This is dependent on behavioural change rather than technical measures, with associated uncertainties in the extent of implementation influenced by national measures such as road charging, as well as local action in urban conurbations and by local authorities. Reductions in kilometres driven in urban areas or their restriction to major agglomerations and populated areas of London will be relevant to urban planning and will require 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 the use of wood-burning stoves is growing, with emissions of $PM_{2.5}$ from domestic wood burning having increased by 124% in the decade to 2021 [33].

It should be noted that there are very large uncertainties in $PM_{2.5}$ emissions from wood burning, as emphasized by [34] and reported elsewhere by [18]. These reflect not only uncertainties in the quantities of wood burned, the type of wood, and whether wet or dry, but also in how it is burned, whether in open grates or stoves with different efficiencies and modes of operation. Moreover, past estimates of the domestic combustion of wood may have been overestimated [35], 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 [36].

The scenarios discussed here adopted the NAEI2018 emissions, giving a high contribution to primary $PM_{2.5}$ concentrations in urban areas and with the potential for a corresponding reduction in emissions with appropriate measures. More recent estimates [37] show the amount of wood burned has been revised downwards significantly, compared with the NAEI 2018 data, as a result of a 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].

5. Results & Discussion

The UKIAM was applied to the scenarios above to derive mapped concentrations of $PM_{2.5}$ on a 1×1 km grid across the UK. Figures 7 and 8 (and Figure S3) 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 10 $\mu g\ m^{-3}$ but also in the orange area between 9 and 10 $\mu g\ m^{-3}$ and eventually in the yellow area between 8 and 9 $\mu g\ m^{-3}$. In this context, allowing for model uncertainties [18], the areas in orange are clearly at risk of exceeding 10 $\mu g\ m^{-3}$; 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.

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 Tables 1 and S3). As expected, there are successive improvements in population exposure with increasing levels of abatement from the medium to the speculative scenario and over time. Both the maps and PWM concentrations clearly highlight London as the region with the highest concentrations throughout, suggesting more ambitious strategies may be necessary. The net-zero scenario (see Table S3) gives reductions similar to the medium scenario by 2040, 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 S3). In particular, the results show the difficulties of eliminating the exceedance of the 2005 WHO guideline of 10 $\mu g\ m^{-3}$ 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 Ultra-Low Emission Zone (ULEZ).

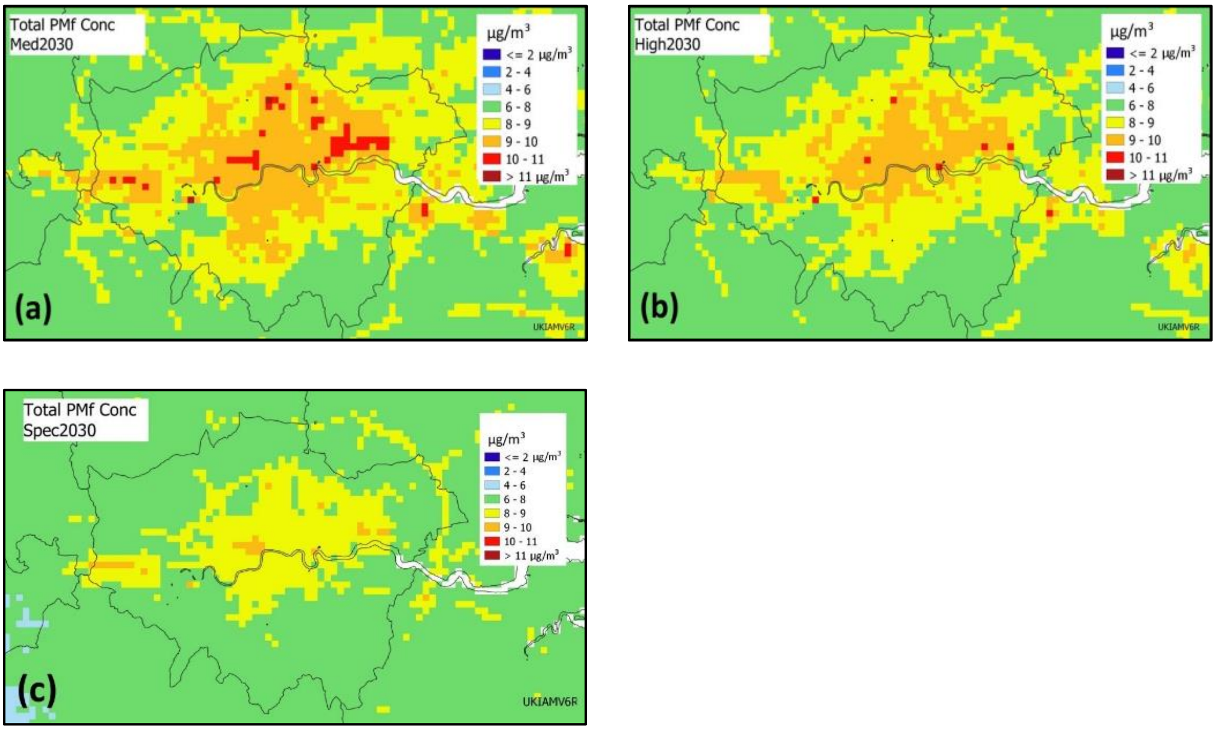

Figure 7. In 2030, there are still large areas at risk of exceeding 10 µg m^{-3}, with (**a**) clear exceedance in the medium scenario, (**b**) much of central London at risk of exceedance in the high scenario, and (**c**) the speculative scenario suggests most of London would only be at risk in an adverse meteorological year.

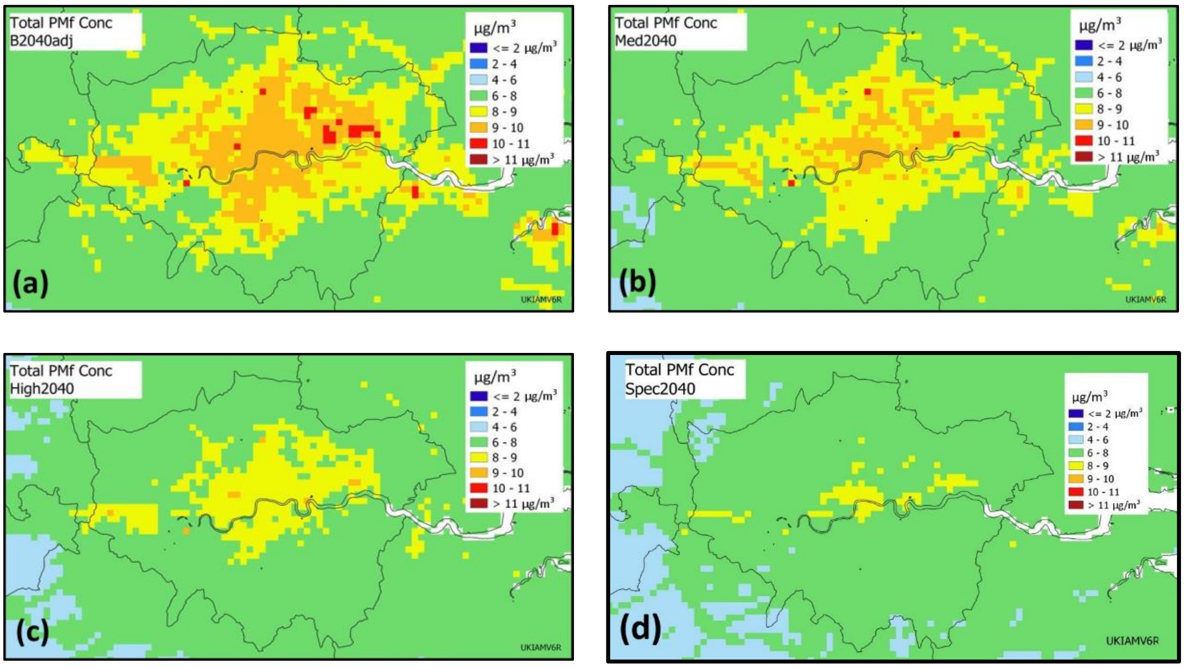

Figure 8. In 2040, (**a**) the baseline and (**b**) the medium scenario show large areas of London remain at risk of exceedance, whereas (**c**) the high ambition and (**d**) the speculative scenario almost remove all areas (orange) at risk of exceeding exceeding 10 µg m^{-3}.

Bearing in mind model uncertainties, the areas in orange, between 9 and 10 µg m^{-3}, are at high risk of exceeding the guideline; 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 10 μg m^{-3}, even in the very ambitious speculative scenario (Figure 7) and by superimposing stronger measures in London in the high scenario. However, further improvements in the high scenario by 2040 almost entirely remove these areas (Figure 8). This is reflected in the process of setting the AMCT target, discussed 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 atop one of the other scenarios. A number of alternative combinations for stronger measures in London were evaluated [3], such as, 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 working towards meeting the WHO interim target of 10 μg m^{-3} [38].

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

5.1. Target Setting

5.1.1. Annual Mean Concentration Target (AMCT)

The purpose of a concentration target is to limit $PM_{2.5}$ concentrations where they are highest to reduce exposure disparities and ensure that no one is exposed to excessive levels. An annual mean concentration target (AMCT) requires that all measured concentrations meet the target level by the target date. This places a greater challenge on modelling as individual measurements at specific locations are more difficult to predict with models than national averages, both because modelling uncertainties have a larger impact and also because individual measurements are subject to greater variation from changes in weather or local conditions which are difficult to replicate.

UKIAM modelling provides the annual average value for a grid square from which the population-weighted mean exceedance (PWME) can be calculated nationally or for different regions. Using these modelled results, the accumulated exceedance of different concentration thresholds across all grid squares can be derived and the risk of exceeding this value assigned. If the concentration of a grid square is close to a threshold, it contributes less to the metric than if it is exceeded by a large degree. The lower the accumulated exceedance across all grid squares, the greater the likelihood that the country will meet a particular target. This approach is not reliant on monitoring site locations and seeks to avoid the risks associated with using individual grid squares; however, it is less intuitive and requires judgment on the level of exposure exceedance, which would align with different subjective risk categories. When assessing whether a concentration can be achieved, it is useful to also consider the achievability of a concentration level 1 μg m^{-3} below, due to modelling uncertainties, and up to 2 μg m^{-3}, below to account for meteorological variations. The accumulated exceedance in London was used as the basis of this assessment, as this is the region where concentrations are highest.

This approach enables a matrix of feasible targets for each scenario and year modelled to be produced (Figure 9). The colours represent the likelihood of all measurements being below the indicated maximum by the given date under different scenarios. For example, where there was no exposure exceedance of a specified concentration, it will show as green. Where there is significant exposure exceedance of a concentration, it will show as red. Orange allows for 1 μg m^{-3} of uncertainty, and yellow allows for 2 μg m^{-3} of uncertainty, appropriate for adverse meteorological years, as noted in Section 2.2.

This "Traffic Light" diagram clearly shows how the 10 μg m^{-3} limit is progressively more likely to be achievable over time; in 2018, 10 μg 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, 10 µg 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 10 µg m^{-3} may be achievable.

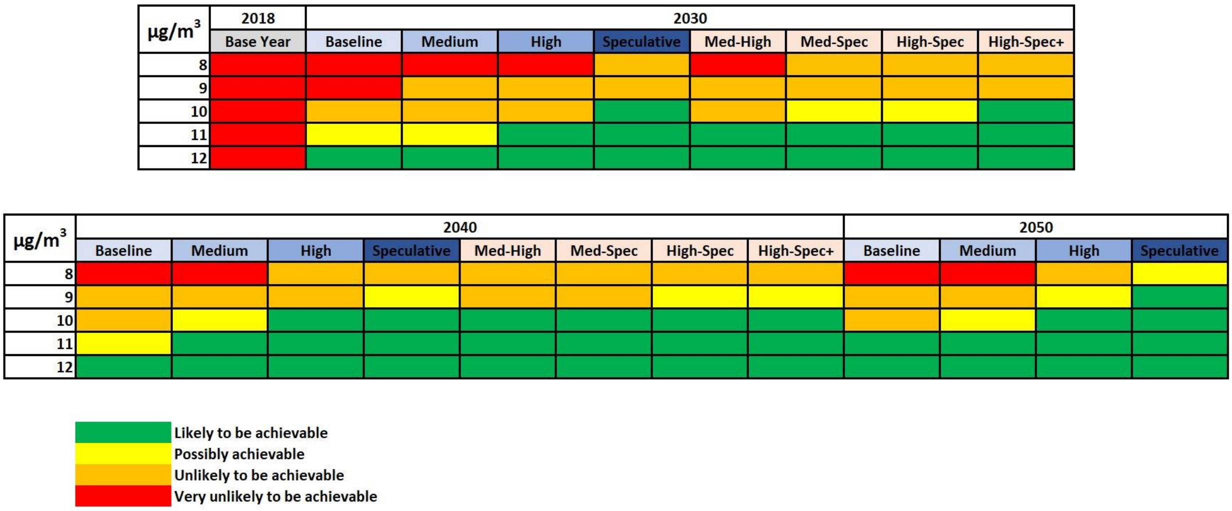

Figure 9. Risk of exceedance Traffic Light Matrix of feasible targets for each scenario and year modelled, highlighting the degree of ambition needed to reach the target concentrations. The base year is shown in grey, the alternative scenarios are shown from light blue (baseline) to dark blue (speculative), and the combined scenarios shown in pink and reflect, for example, for "High-Spec", the high scenario applied nationally with the speculative scenario applied in London.

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

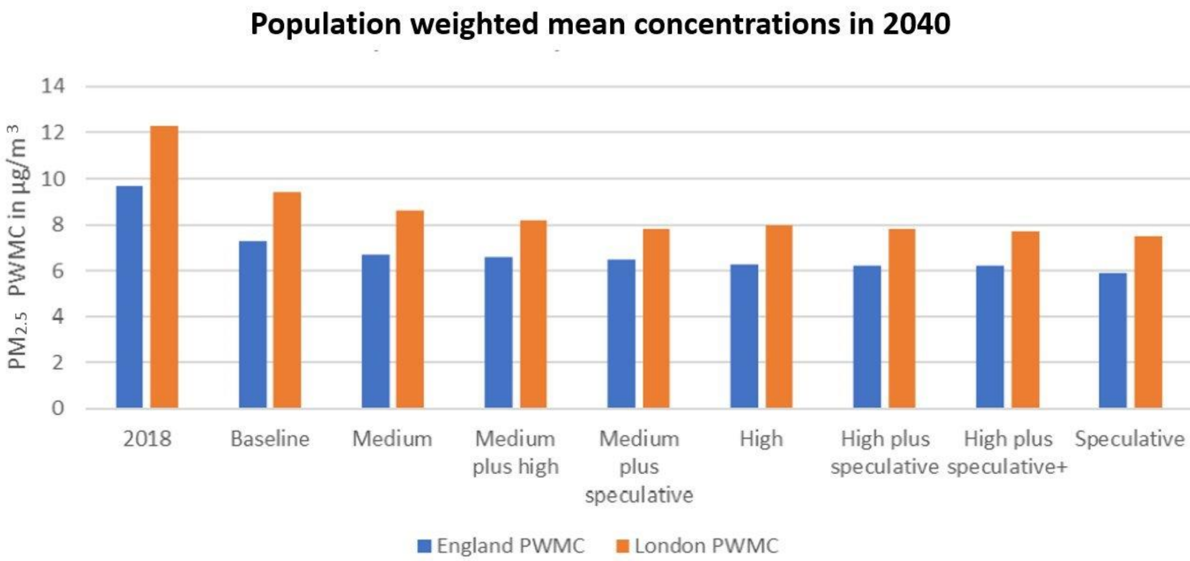

Figure 10. Population-weighted mean concentrations for the different scenarios in 2040; these provide the basis for deriving population health impacts and population exposure reduction targets alongside monitoring data.

The average of the annual mean concentration at all urban background monitoring sites is an indicator of current population exposure. The population-weighted mean concentration (PWMC) is a good indicator of future population exposure that can be obtained from the modelling results enabling projections of future population exposure to be produced. One approach to assessing PERTs is to use the average of the modelled concentrations for each grid square where urban background monitoring sites are located. This may be less robust than using the PWMC, as there may be data artefacts affecting individual grid squares, which could result in anomalies. It is to be expected that the monitoring-based population exposure calculations would be slightly higher than exposures calculated from modelling since monitoring sites tend to be located in areas of higher concentrations, whereas the PWMC includes all grid squares, which is reflected in the comparison shown in Figure S5.

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

5.2. Monetised Benefits

Table S2 shows the total cumulative air quality benefits for England, derived from reduced damage to health, productivity, and ecosystems and reduced soiling of buildings for the medium and high scenarios. Benefits associated with reductions in $PM_{2.5}$ exposure and other air quality co-benefits such as reduction in NO_2 are estimated at GBP 23.2 billion for the medium scenario and GBP 37.9 billion for the high scenario.

Where possible, the relevant cost data was drawn from existing tools and information in previous Defra reports. Where this was not possible, additional research was undertaken by external consultants to identify relevant cost data through several methods, including literature reviews as well as interviews and workshops with stakeholders.

For most measures, there is both a capital cost and an operating cost. For the purposes of comparison, the equivalent annualised cost of measures is calculated by distributing capital costs over the lifetime of the measure and combining them with operational expenditure. This allows for a representative cost per year of the measures to be compared where the lifetimes of costs differ. By setting the monetised benefits against the social costs, summary appraisal statistics can be obtained, such as the Net Present Social Value and benefit–cost ratio, which provide an indication of the net economic impact of the modelled scenarios.

Table 2 outlines summary results for the medium and high scenarios under central sensitivity assumptions. It is clear from the evidence in this table that the pathways are likely to achieve good value for money, with benefits outweighing costs. Further detailed analysis of the economic costs and benefits is reported elsewhere [3].

Table 2. Summary cost–benefit analysis results for the medium and high scenarios, 2023–2040, discounted at 3.5% (2020 prices, GBP m).

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

5.3. Social Impacts & Deprivation

Mean population exposure is generally used 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 as a whole and within London [39–42]. The work presented here uses an 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 (accessed on 1 February 2023)). A map of the IMD by Lower-Layer Super Output Area (LSOA) is given in the Supplementary Material (Figure S4). 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 [43]. Figure S4 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, the 1×1 km^2 map of $PM_{2.5}$ concentrations for each scenario is overlaid with the IMD map and the population-weighted mean exposure for each IMD decile is obtained, sorted from most deprived (1) to least deprived (10). Figure 11a 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, for example, as demonstrated by Ferguson et al. [42] for London and as reflected in English Housing Survey statistics [44], where concentrations are higher due to traffic emissions [45]. 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 is not sufficient to resolve the effect of elevated concentrations near roads.

While Figure 11a 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, the mean PWMC is subtracted from the decile PWMC. Figure 11b shows the relation of the Delta PWMC (defined as the decile PWMC, or 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 S6a,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 in 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 in these scenarios. The 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.

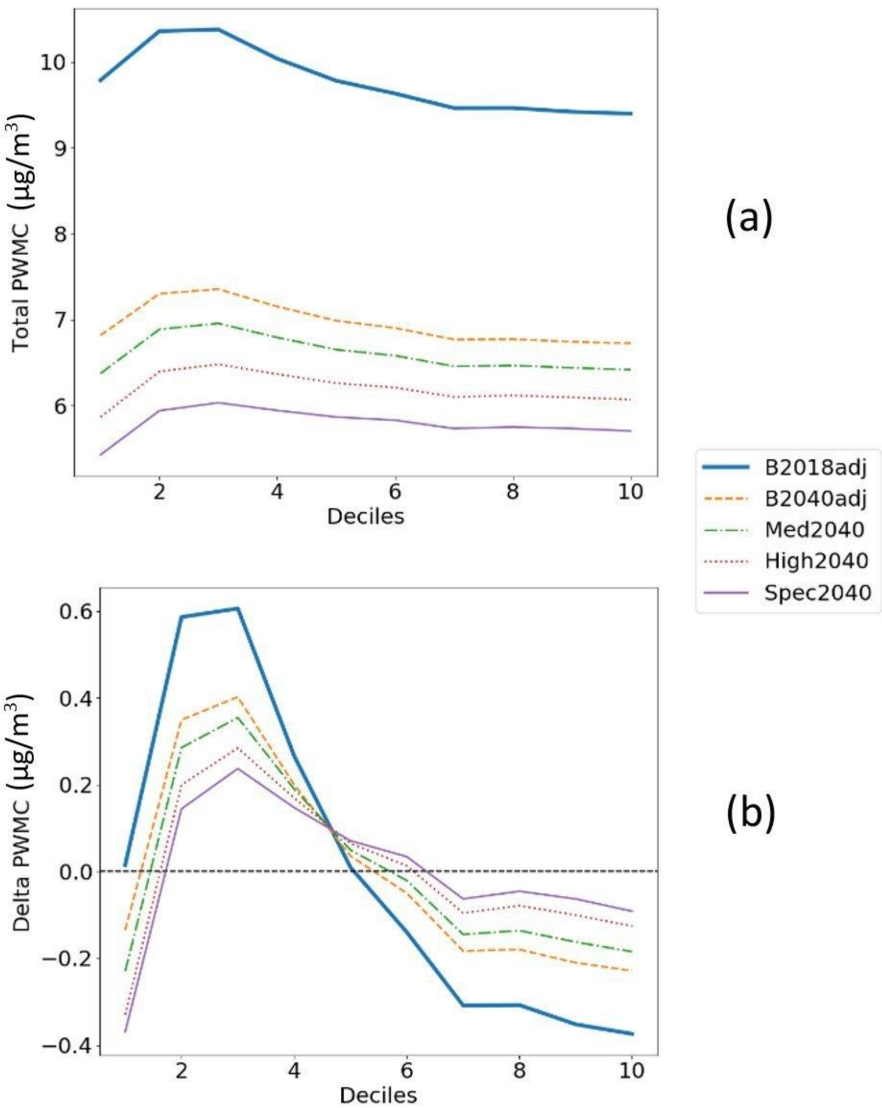

Figure 11. (**a**) PWMC for each deprivation decile and (**b**) the Delta PWMC for England for each deprivation decile for B2018adj and 2040 scenarios.

6. Uncertainties

Throughout this work, many uncertainties have been identified, with investigations where possible including model intercomparisons [9] and sensitivity studies and with 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.

A wide range of uncertainties and assumptions have been identified related to the projected emissions and their abatement, the atmospheric modelling, and the resulting population exposure and its impacts on health and the environment [3,18]. 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 the improvement of air quality. Comparisons with measurements suggest that the modelling bias is small, and allowances for model uncertainty of the order of 1 μg m^{-3} should be made when assessing concentrations but up to 2 μg m^{-3} when allowing for adverse meteorological years.

Uncertainties may be evident in the modelling; in the quantification of imported contributions—transboundary or shipping—which are outside UK control; in the 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 the improvement of air quality.

7. Conclusions

This paper illustrates 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 was 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, an assessment of monetised benefits was undertaken, showing that, for the selected scenarios to achieve the targets, these justify the costs of abatement. Moreover, a preliminary investigation of the deprivation index showed that the disparity between higher exposure of more deprived communities and lower exposure of less deprived communities narrows over time and with the 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 also illustrates 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 being undertaken to better understand net-zero scenarios, including the production and use of hydrogen as a fuel, through linking the UKIAM with a TIMES model addressing future energy projections. 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 is also being used to explore the implication for nitrogen pollution and eutrophication of ecosystems for a wide range of agricultural scenarios, including the effects of climate measures and dietary change.

Supplementary Materials: The following information can be downloaded at: https://www.mdpi.com/article/10.3390/atmos14030525/s1, Figure S1: NOx emissions from international and in-transit shipping in sea areas surrounding the United Kingdom; Figure S2: Comparison of modelled concentrations against AURN measurements for 2018; Figure S3: Maps of total $PM_{2.5}$ concentrations for 2040; Figure S4: Map of the Index of Multiple Deprivation (IMD) at the LSOA level; Figure S5: Comparison of modelled PWMC and PWMC derived from monitoring data for 2018; Figure S6: PWMC and delta PWMC for each deprivation decile across London; Table S1: Statistical comparison at monitoring locations; Table S2: Cumulative (2023-2040) air quality benefits in England from reduced damage to health, productivity, ecosystems and soiling of buildings; Table S3: Population weighted mean concentrations of $PM_{2.5}$ for all target setting scenarios up to 2050; Box S1: Summary of key assumptions in the medium, high and speculative scenarios.

Author Contributions: Conceptualization, H.A.; data curation, T.O. and H.W.; investigation, T.O.; methodology, H.A., T.O., H.W. and M.H.; software, T.O., H.W. and D.M.; writing—original draft, T.O.; writing—review & editing, H.A. and S.R. All authors have read and agreed to the published version of the manuscript.

Funding: This work has been supported by the Department of Environment, Food and Rural Affairs (Defra) under Contract ECM-53210: Support for national air pollution control strategies.

Data Availability Statement: Data relevant to this study can be made available upon request to the corresponding author.

Acknowledgments: This work reflects the personal views of the authors. Although the modelling work has been supported by the UK Department of Environment, Food and Rural Affairs, the findings and recommendations discussed here are those of the authors and do not necessarily represent the views of Defra.

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

Glossary

ACTM	Atmospheric Chemical Transport Model (e.g., EMEP4UK)
AQEG	Air Quality Expert Group, https://uk-air.defra.gov.uk/research/aqeg/ (accessed on 1 February 2023)
AURN	Automatic Urban and Rural Network of monitoring stations, https://uk-air.defra.gov.uk/networks/network-info?view=aurn (accessed on 1 February 2023)
BRUTAL	Road Transport sub-model of the UKIAM [14]
CLRTAP	UNECE Convention on Long-Range Transboundary Air Pollution; renamed as the Air Convention https://unece.org/environment-policy/air (accessed on 1 February 2023)
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/ (accessed on 1 February 2023) (2) Unified EMEP Eulerian model [8]
EMEP4UK	EMEP4UK model [20–28]
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/ (accessed on 1 February 2023)
ICE	Internal Combustion Engine
IIASA	International Institute of Applied Systems Analysis, https://iiasa.ac.at/ (accessed on 1 February 2023)
IMO	International Maritime Organisation, https://www.imo.org/ (accessed on 1 February 2023)
IMD	Index of Multiple Deprivation, https://www.gov.uk/government/statistics/english-indices-of-deprivation-2019 (accessed on 1 February 2023)
NAEI	National Atmospheric Emissions Inventory (http://naei.beis.gov.uk (accessed on 1 February 2023))
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 (<2.5 µm) NO_{3^-})
NOx	Nitrogen Oxides comprised mainly of NO (Nitric Oxide) and NO_2 (Nitrogen Dioxide)
$PM_{2.5}$	Particulate Matter < 2.5 µm 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/ (accessed on 1 February 2023))
SNAP	Selected Nomenclature for Air Pollutants (https://en.eustat.eus/documentos/elem_13173/definicion.html (accessed on 1 February 2023))
SOA	Secondary Organic Aerosol, influenced by both biogenic and anthropogenic emissions
SO_2	Sulphur Dioxide
SO_4^{2-}	Sulphate Aerosol
UKIAM	UK Integrated Assessment Model, developed by Imperial College London [1,2]
ULEZ	Ultra-Low Emission Zone (https://tfl.gov.uk/modes/driving/ultra-low-emission-zone (accessed on 1 February 2023))
VOC	Volatile Organic Compounds

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