Analysis of abatement options to reduce $PM_{2.5}$ concentrations

Defra contract report: SNAPCS project

Support for National Air Pollution Control Strategies

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Executive summary

The purpose of the work undertaken for this report has been to support Defra in setting targets for reducing exposure in England to fine particulate air pollution, $PM_{2.5}$, by modelling a range of future scenarios up to 2050 for the UK. These scenarios reflect different levels of effort and ambition in reducing pollutant emissions; and include some consideration of co-benefits of climate measures to reach net zero. The targets to be set in the Environment Act are aimed at reducing overall population exposure and associated health impacts; and providing a limit on the maximum concentrations to address improvements for those with the highest levels of exposure.

The measures contained within the modelled scenarios and sector sensitivity analysis are hypothetical and do not in any way constitute current or planned government policy. Any views in the report reflect the opinions and interpretation of the authors, they should not be taken to be the views of Defra or other government departments.

The central model used for this scenario analysis is the UK Integrated Assessment Model, UKIAM, developed at Imperial College with assistance from the UK Centre for Ecology and Hydrology. This has been linked to the Scenario Modelling Tool, SMT of Defra based on National Atmospheric Emission Inventory, NAEI, emissions. 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. 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, as well as a detailed break-down for UK sources distinguishing contributions from the different devolved administrations and London.

In the first part of the report UKIAM is described with illustration of concentrations in 2018 as the base year with corresponding emissions from the NAEI, and the substantial improvements expected by 2030 assuming a business as usual scenario. In addition to changes in UK emissions this includes anticipated changes in emissions in other countries; and from shipping, which is an important source currently generating about 660kt of NO_x in sea areas round the UK (which is considerably larger than the ceiling set for all UK emissions of NO_x in 2030 under the National Emissions Ceilings Regulations).

As input to setting targets for reduction of $PM_{2.5}$ UKIAM calculates population weighted mean concentration, PWMC, in different regions; which is combined with population data as an estimate of population exposure used in assessment of the benefits of reducing emissions in the different scenarios. Towards the setting of limit values on the maximum concentrations

UKIAM also calculates the population weighted mean exceedance of different threshold levels across the map areas of different regions.

UKIAM inevitably includes some simplifications and assumptions, particularly with regard to atmospheric chemistry; and hence we have included comparison with the detailed model EMEP4UK with full chemistry and detailed meteorology, as well as with available measurements. This shows that UKIAM agrees well with current measurements with little bias, but tends to be a bit more conservative in estimating improvements in the longer range secondary inorganic aerosol component compared with EMEP4UK. However, UKIAM, with higher resolution than EMEP4UK, gives sharper urban peaks from local primary sources in urban areas. The EMEP4UK modelling illustrates that interannual variability with meteorology can lead to differences of around 2 $ug.m^{-3}$ in average $PM_{2.5}$ concentrations, whereas in more average years differences between the models are less than ~ 1 $ug.m^{-3}$.

With respect to setting limits on maximum concentrations of $PM_{2.5}$, it should be noted that UKIAM produces background concentrations averaged over 1x1 km grid-squares, corresponding to the resolution of emissions in the NAEI inventory; and within such grid squares there will be spatial variability. To explore this limitation we have investigated modelling undertaken for London using a 10x10 m grid with the ADMS model, illustrating much higher concentrations close to the busiest major roads within a few 1x1 km grid-squares, and explaining outliers in scatter plots comparing UKIAM with monitoring data. Other sources may also give local hot-spots, but current modelling is limited by the lack of sufficiently detailed emission data as well as the complexities of urban topography. It was concluded that the 1x1 km resolution used in UKIAM is sufficient for estimating overall population exposure, but that care is needed in defining where limit values apply and in interpreting the representativeness of monitoring locations. Comparison of population exposure in agglomerations outside London, based on monitoring station data from each agglomeration, and as calculated with UKIAM, gave encouraging agreement; but insufficient measurement data was available for London or for identifying exceedance of potential limit values.

There are many other uncertainties that have complicated this project and the setting of targets for $PM_{2.5}$. Some of these, such as uncertainties in emissions had already been addressed in previous work; and other simplifications are inherent, such as the adoption of $PM_{2.5}$ mass in estimating health impacts ignoring potential differences in toxicity of different components. Before undertaking analysis of future scenarios we have undertaken studies of individual sectors to identify the major sources and key factors affecting future $PM_{2.5}$ concentrations and exposure, and followed these up with sensitivity studies- for example with respect to domestic wood-burning as an important source but with very large uncertainties affecting future predictions.

<u>Sectoral studies</u>

There is a large reduction in projected NO_x emissions from road transport which gives substantial improvements in air quality, reducing both NO_2 and secondary $PM_{2.5}$. This is driven initially by improved emissions from new diesel vehicles post RDE testing, and reinforced by electrification of the fleet. 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, although there may be some reduction from regenerative braking. Apart from some potential measures such as better wheel alignment to reduce tyre wear and possible future technologies to reduce non-exhaust emissions, further improvements ultimately depend on reducing kilometres driven especially in London and 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 like road charging, as well as local action in urban conurbations and by local authorities. Sensitivity studies have been undertaken in subsequent analysis of scenarios to explore the difference when percentage reductions in kilometres driven are widely applied in all urban areas, or restricted to major agglomerations and populated areas in London. This will be relevant to urban planning requiring more detailed investigation for specific situations.

For the domestic sector, climate measures to cut out use of coal and oil and reduce emissions from 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 NO_x emissions and may even enhance them, 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. We had already explored the large uncertainties in emissions from wood, including the proportion of wet wood and the mode of combustion or type of stove, as also reported by the Air Quality Expert Group, AQEG: and Defra has commissioned further investigation to improve estimates. Meanwhile we adopted the NAEI emissions giving a high contribution to primary $PM_{2.5}$ concentrations in urban areas, and potential for corresponding reduction with appropriate measures. However, it was noted that the NAEI emissions seemed high compared with other independent estimates; and during the course of this work, as recently reported by DUKES in 2021, the estimated amount of wood burned has been revised downwards by two thirds compared with the NAEI data. 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 below.

Another consideration is missing sources of $PM_{2.5}$ in the NAEI, illustrated in the domestic sector by domestic and commercial cooking, and the focus of a previous study indicating its potential importance in urban areas. This topic of missing sources is considered further with respect to London.

The agricultural sector is important as the dominant source of ammonia as a precursor of the chemical formation of secondary inorganic aerosol in combination with NO_x and SO_2 emissions. Because of the dispersed nature of emissions from livestock wastes and fertiliser use, abatement measures are of limited efficiency, and complicated by the pathway of emissions from livestock wastes through housing, storage and spreading on the land. Future changes in agricultural production and land-use, and in dietary demand as proposed in climate measures to reduce greenhouse gases, may also lead to lower ammonia emissions and further investigation is recommended. The scenarios modelled to reduce ammonia emissions for this sector illustrate both the importance for secondary particulate contributions to $PM_{2.5}$ concentrations, and for helping protection of natural ecosystems by reducing nitrogen deposition and eutrophication for which ambitious targets have been set.

Emissions from the power sector and industrial use of energy have both reduced over recent years from the reduced use of fossil fuels and stronger regulation of emissions; and this is expected to continue. As explained in relation to electrification of transport any associated air pollutant emissions will depend on the expansion and timing of enhanced renewables relative to increased electricity demand, or alternatively hydrogen production for the transport sector. Noting that "other industrial combustion" from smaller industries generates a large proportion of $PM_{2.5}$ a potential concern is the use of biomass for these industrial boilers compared with alternative energy sources, especially when located in populated urban areas.

<u>The scenarios</u>

To explore potential improvements in reducing $PM_{2.5}$ to inform the setting of targets, a selection of future emission scenarios up to 2050 has been investigated with different levels of ambition in reducing emissions. The starting point is the baseline scenario based on NAEI emissions and emission projections published in 2018, with some adjustments to allow for more recent estimates such as updated emission factors for new diesel cars. The baseline projections already give big improvements, including by 2030. Medium, high and speculative scenarios have been modelled with successively greater emission reductions applied to the baseline projections. These were provided by Defra using the Scenario Modelling Tool, SMT; with some adjustments agreed with Defra, particularly on road transport to enable use of our more detailed modelling of electrification of the fleet with the BRUTAL sub-model of UKIAM.

Concentrations of $PM_{2.5}$ have been 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 are given in the report together with maps and other data on exposure. In addition to the medium, high and speculative scenarios an additional scenario was added incorporating climate measures 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 this is without the inclusion of additional air pollution abatement measures and further work is needed on this. A further comparison has been made with a scenario aimed at meeting the UK emissions ceilings, set in the National Emissions Ceilings Regulations, and also assuming the DfT plans for electrification of vehicles. This is an international obligation for the year 2030, where it produces comparable improvements to the high scenario.

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. Additional hybrid scenarios have therefore been investigated superimposing additional abatement in London on nation-wide abatement. This has focused on the medium and high scenarios, first by assuming more ambitious measures within London, and then by considering additional localised action in the more polluted areas illustrated by further reduction of car use within the expanded ULEZ area. These scenarios clearly show the benefits of combining greater effort to reduce emissions in

London including behavioural change, with broader measures in England and the rest of the UK. However, they also emphasize the importance of uncertainties in urban emissions, especially missing sources in the NAEI such as cooking.

Towards the setting of targets

Comparison of the scenarios above with the baseline in 2018 is used in section 8 of the report to indicate potential **improvements in population exposure** over different time periods, particularly up to 2030 and 2040, with greater uncertainties for 2050. Percentage reductions in population exposure are suggested as an appropriate indicator for improvement, giving more consistent reductions across London with the highest concentrations, and the rest of England.

In addition to discussion of model uncertainties, where it is suggested that a safety margin of 1 $ug.m^{-3}$ should be allowed for modelling uncertainties (except in years with adverse meteorology when this can be up to 2 $ug.m^{-3}$), a sensitivity study has been undertaken to the major contribution from wood-burning. As indicated there has been substantial revision of quantities of wood burned by up to 2/3rds published in the recent DUKES 2021, and further work is in progress for Defra to improve assessment of emissions which may partially counteract this change. As an extreme case we have considered how the assumption of reducing emissions from wood-burning in line with the DUKES 2021 report, with corresponding reduction of improvements in $PM_{2.5}$ concentrations from abatement measures in the scenario analysis, would affect the potential reductions in population exposure to $PM_{2.5}$. This assumes that missing sources such as cooking make up for the reduction in wood-burning emissions, retaining the agreement between the modelled total concentrations and measurements; although such sources could also be subject to abatement and hence this sensitivity study may be pessimistic. This sensitivity study makes a significant difference of 3 to 7 % in the potential improvements in population exposure, and also to exceedance of thresholds for the population with the highest exposure.

Table 1 below summarises the percentage reductions relative to 2018 in population exposure to $PM_{2.5}$ in England, and broken down for London and the rest of England for each scenario. The numbers in italics correspond to the sensitivity study assuming less wood-burning emissions. Results for additional scenarios and sensitivity studies are provided in the main text, together with additional sensitivity studies.

Taking the estimates in bold from the original calculations and ignoring the more pessimistic sensitivity study based on wood-burning, for 2030 the reductions from the medium to speculative scenarios lie between 25% and 33%. The high scenario in the middle achieves a 28% reduction, increasing to 33% for the London area when stronger measures are superimposed there. Even for the sensitivity study figures in italics which are likely to be on the pessimistic side, an average reduction of 24% is achieved both across London and England-London by 2030 in the high scenario. This increases to 26% for the higher exposure in London with additional measures there. Overall our model results suggest that **a reduction**

of around 24 to 25% in population exposure would be achievable by 2030 even for these more pessimistic assumptions.

For the original calculations higher percentage reductions of between 30% and 40% are shown for 2040, increasing again to between 34% and 42% in 2050, though predictions that far ahead are very uncertain. For 2040 the high scenario shows estimated improvements of around 35% relative to 2018 for both London and the rest of England. Even for the more pessimistic assumptions in the sensitivity study **a 30% reduction in population exposure is achieved in 2040** with the high scenario plus additional measures in London.

Table 1. Percentage reductions in PWMC relative to 2018 for the different scenarios.

2030	England	*less wood*	Eng-Lon	*less wood*	London	*less wood*
baseline	22.9%	*20.4%*	23.1%	*20.7%*	22.2%	*19.4%*
medium2030	25.6%	*22.6%*	25.7%	*22.8%*	25.5%	*22.2%*
high 2030	28.4%	*24.2%*	28.4%	*24.3%*	28.5%	*23.9%*
spec 2030	33.4%	*27.3%*	33.3%	*27.4%*	33.8%	*27.0%*
M2030LH	26.3%	*23.1%*	26.0%	*23.0%*	27.8%	*23.4%*
M2030LS	27.3%	*23.7%*	26.3%	*23.3%*	31.4%	*25.3%*
M2030 LSC	27.4%	*23.8%*	26.3%	*23.3%*	32.1%	*26.0%*
H2030LS	29.3%	*24.8%*	28.6%	*24.6%*	32.1%	*25.7%*
H2030LSC	29.5%	*24.9%*	28.7%	*24.6%*	32.8%	*26.4%*
2040						
baseline	24.9%	*22.5%*	25.2%	*22.9%*	23.8%	*21.1%*
medium 2040	30.7%	*27.1%*	30.8%	*27.4%*	30.3%	*26.3%*
high 2040	34.9%	*29.5%*	34.9%	*29.7%*	34.9%	*28.8%*
spec 2040	39.2%	*33.0%*	39.2%	*33.1%*	39.5%	*32.5%*
M2040LH	31.8%	*27.8%*	31.3%	*27.7%*	33.8%	*28.2%*
M2040LS	32.5%	*28.4%*	31.7%	*28.1%*	36.0%	*29.6%*
M2040LSC	32.6%	*28.5%*	31.7%	*28.1%*	36.4%	*30.1%*
H2040LS	35.6%	*30.1%*	35.3%	*30.0%*	37.0%	*30.3%*
H2040LSC	35.7%	*30.2%*	35.3%	*30.0%*	37.4%	*30.7%*
2050						
baseline	24.8%	*22.4%*	25.1%	*22.7%*	23.6%	*20.9%*
medium 2050	34.0%	*29.9%*	33.9%	*29.9%*	34.2%	*29.6%*
high 2050	37.5%	*32.1%*	37.4%	*32.1%*	38.2%	*32.1%*
spec 2050	41.4%	*35.2%*	41.1%	*35.1%*	42.7%	*35.8%*

A scenario name starting M or H indicates a medium or high scenario nationally. A name ending in LH or LS indicates that for London stronger measures in the High or Speculative *scenarios have been imposed for London. If the final letter is C this indicates that additional reductions in car km have been introduced within the extended London ULEZ. Absolute values of the underlying population weighted mean concentrations are given in figure 8.1 in the main text.*

Towards the setting of **limit values** we have estimated population weighted mean exceedance of different threshold values from 8 to 12 $ug.m^{-3}$ for both London with the highest concentrations and the rest of England. These have been tabulated in a traffic light format, with different levels of exceedance from red for high exceedance to green for zero or negligible exceedance for the different scenarios and years- see table 2. In applying these data to selection of limit values, the suggested safety margin of $1ug.m^{-3}$ for model uncertainty, means that modelled concentrations between 9 and 10 $ug.m^{-3}$ could be above 10 $ug.m^{-3}$, so that estimated negligible non-exceedance of 9 $ug.m^{-3}$ becomes the criterion for attainment of a limit value of 10 $ug.m^{-3}$; and similarly for other possible limit values. In addition, we have undertaken a similar sensitivity study as assumed above for reduction of population exposure, with more adverse assumptions concerning the improvement attributable to abatement of domestic wood-burning. The resulting exceedance values are compared with the original estimates for selected scenarios in table 2, giving significant increases for the sensitivity study. The table illustrates the higher levels of exceedance in London, and the improvements when additional measures including behavioural change and traffic reduction are taken to reduce concentrations there. Again, results for additional scenarios and sensitivity studies are given in the main text.

Our modelling results suggest that, even with the more adverse assumptions in the sensitivity study, for the high scenario with additional measures in London including behavioural change and traffic reduction, concentrations below a limit of 10 $ug.m^{-3}$ could be achieved by 2040 except close to major roads and other localised hot-spots. Outside London, or with more favourable assumptions this could be achieved earlier by 2030.

Although the medium scenario coupled with stronger measures in London is also effective towards attainment of a limit value of $10ug.m^{-3}$, it gives less improvement than the high in population exposure and associated health impacts reflected in the monetised benefits below.

Table 2. Population weighted mean exceedance PWME (ng.m-3).

Numbers in bold are original estimates based on NAEI, and in italics for the wood sensitivity study

England											
ug/m3	B2018	Med2030	*less wood*	M2030LH	*less wood*	M2030LSC	*less wood*	High 2030	*less wood*	H2030LSC	*less wood*
8	1902	213	*336*	166	*305*	90	*250*	133	*273*	62	*220*
9	1136	55	*113*	29	*93*	6	*55*	21	*83*	2	*47*
10	591	3	*19*	1	*12*	1	*6*	1	*9*	0	*4*
11	278	0	*2*	0	*1*	0	*1*	0	*0*	0	*0*
12	112	0	*0*	0	*0*	0	*0*	0	*0*	0	*0*
		Med2040	*less wood*	M2040LH	*less wood*	M2040LSC	*less wood*	High 2040	*less wood*	H2040LSC	*less wood*
		91	184	43	*146*	*17*	*110*	28	*124*	7	*90*
		9	47	2	*27*	*1*	*13*	1	*20*	0	*8*
		1	5	1	*3*	*1*	*2*	0	*1*	0	*0*
		0	1	0	*1*	*0*	*1*	0	*0*	0	*0*
		0	0	0	*0*	*0*	*0*	0	*0*	0	*0*

England outside London											
		Med2030	*less wood*	M2030LH	*less wood*	M2030LSC	*less wood*	High 2030	*less wood*	H2030LSC	*less wood*
8	1455	53	*126*	48	*118*	42	*109*	21	*90*	18	*83*
9	732	7	*22*	6	*20*	5	*19*	2	*15*	1	*14*
10	269	1	*6*	1	*5*	1	*5*	0	*4*	0	*4*
11	73	0	*2*	0	*1*	0	*1*	0	*1*	0	*1*
12	18	0	*0*	0	*0*	0	*0*	0	*0*	0	*0*
		Med2040	*less wood*	M2040LH	*less wood*	M240LSC	*less wood*	High 2040	*less wood*	H2040LSC	*less wood*
8		10	43	9	*38*	*8*	*33*	1	*22*	1	*19*
9		2	9	1	*8*	*1*	*8*	0	*4*	0	*4*
10		1	3	1	*3*	*1*	*2*	0	*1*	0	*0*
11		1	1	1	*1*	*0*	*1*	0	*0*	0	*0*
12		0	0	0	*0*	*0*	*0*	0	*0*	0	*0*

London											
		M2030	*less wood*	M2030LH	*less wood*	M2030LSC	*less wood*	High 2030	*less wood*	H2030LSC	*less wood*
8	4334	1078	*1476*	809	*1320*	350	*1015*	739	*1271*	299	*968*
9	3334	318	*611*	155	*487*	7	*253*	124	*453*	5	*226*
10	2338	14	*89*	3	*47*	0	*8*	2	*40*	0	*6*
11	1394	0	*3*	0	*1*	0	*0*	0	*1*	0	*0*
12	620	0	*0*	0	*0*	0	*0*	0	*0*	0	*0*
		M2040	*less wood*	M2040LH	*less wood*	M2040LSC	*less wood*	High 2040	*less wood*	H2040LSC	*less wood*
8		529	948	231	*735*	69	528	174	*676*	41	*475*
9		51	253	4	*129*	0	44	0	*104*	0	*33*
10		1	15	0	*3*	0	0	0	*2*	0	*0*
11		0	1	0	*0*	0	0	0	*0*	0	*0*
12		0	0	0	*0*	0	0	0	*0*	0	*0*

Monetised benefits

The assessment of monetised benefits of abatement scenarios compared with the baseline indicates substantial amounts. This is illustrated in table 3 where health benefits have been estimated reflecting recommendations of the Committee on Medical Effects of Air Pollution, COMEAP. For the high scenario the net present value for the total benefits, including other benefits as well as health over the period 2023 to 2030, is estimated at almost £10 billion, increasing to £38 billion over the extended period to 2040. Most of this benefit is attributable to the health benefit of reduction in $PM_{2.5}$ exposure of the population. Additional work is in progress with Defra to compare these benefits with the costs of abatement, taking into account corresponding reductions in greenhouse gases to be reported in the Impact Assessment of the proposed targets. It is suggested that further work should consider how the abatement scenarios could be made more cost-effective as some measures are included that have little impact on PM2.5 emissions but have a high cost.

Table 3. Net present value of benefits relative to the Baseline scenario for the periods 2023 to 2030, 2023 to 2040 and 2023 to 2050. Units, £million.

Total estimates of benefits by scenario			
	2023-2030	**2023-2040**	**2023-2050**
Medium	6,380	23,150	51,163
High	9,930	37,891	76,887
Speculative	16,174	59,611	110,196
Benefits associated with reduced $PM_{2.5}$ exposure			
	2023-2030	**2023-2040**	**2023-2050**
Medium	5,378	18,229	38,005
High	8,690	31,780	61,478
Speculative	14,123	50,434	90,618
Net zero	448	8,488	24,105

Other benefits

Use of the deprivation index has illustrated that the benefits are not uniformly distributed, but suggest convergence between exposure in some of the more deprived areas and the least deprived areas, reflecting reductions in primary $PM_{2.5}$ emissions in more polluted urban areas including traffic. However, this ignores localised spatial variation such as higher exposure close to major roads, which needs further investigation.

In addition to reducing $PM_{2.5}$ concentrations the scenarios modelled also have other benefits, such as reducing nitrogen deposition towards improved protection of ecosystems from eutrophication, where future changes in agriculture including land-use change and climate measures will also be important.

Uncertainties and further work

Throughout the report many uncertainties have been identified, with investigation where possible including model intercomparison and sensitivity studies, and suggestions for further work to refine the scenario assessment undertaken. 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 is likely to be difficult with respect to both modelling and measurements.

Particularly important will be more detailed investigation of synergies between climate measures air quality improvements including $PM_{2,5}$, and how air pollution measures can best be combined with net zero scenarios. This needs to consider potential future changes not only in energy generation and use, but also future agricultural change.

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Glossary

ADMS: ADMS is a pollution model for tackling air pollution problems in cities and towns, developed by Cambridge Environmental Research Consultants, https://www.cerc.co.uk/

AGANET: UK Acid Gases and Aerosols Monitoring Network

AIS: Automatic Identification System

AN: Ammonium Nitrate

ASAM: Abatement Strategies Assessment Model (ApSimon et al., 1994; Warren and ApSimon 1999, 2000)

ASOA/BSOA: Anthropogenic Secondary Organic Aerosol/Biogenic Secondary Organic Aerosol

AURN: Automatic Urban and Rural Network

BAT: Best Available Technology

BAU: Business-As-Usual

BEIS: Department for Business, Energy and Industrial Strategy.

BEV: Battery Electric Vehicle

BRUTAL: Background, Roads and Urban Transport: modelling of Air quality and Limit values – sub-model of the UKIAM

BVOC: Biogenic Volatile Organic Compounds

CAS: Clean Air Strategy

CCC: Climate Change Committee

CCS: Carbon Capture and Storage

CEH: Centre for Ecology and Hydrology, https://www.ceh.ac.uk/

CIAM: Centre for Integrated Assessment Modelling https://iiasa.ac.at/web/home/research/researchPrograms/air/policy/CLRTAP---EMEP---CIAM.en.html

CLE: current legislation

CLRTAP: Convention on Long-Range Transboundary Air Pollution, https://unece.org/environment-policy/air

CMAQ: Community Multi-scale Air Quality modelling system, https://www.cmascenter.org/cmaq/

CO_2: Carbon Dioxide

COMEAP: Committee on the Medical Effects of Air Pollutants

COPERT: COmputer Program to calculate Emissions from Road Transport

CORINAIR: EMEP Core Inventory of Air Emissions

DALY: Disability Adjusted Life Years

Defra: Department of Environment, Food and Rural Affairs, https://www.gov.uk/government/organisations/department-for-environment-food-rural-affairs

EB: Executive Body

EC: European Commission

EC4MACS: European Consortium for Modelling of Air pollution and Climate Strategies, funded by the EU-LIFE Programme, Contract LIFE06/PREP/A/000006, https://ec4macs.eu/

EMEP: (1) Cooperative Programme for Monitoring and Evaluation of the Long-range Transmission of Air Pollutants in Europe (1984, Geneva Protocol) https://www.emep.int/
(2) Unified EMEP Eulerian model https://www.emep.int/models.html

EMEP4UK: National-scale implementation of the EMEP model, https://eip.ceh.ac.uk/apps/atmospheric

EPCAC: Expert Panel on Clean Air in Cities

ESP: electrostatic precipitators

FRAME: Fine Resolution Atmospheric Multi-species Exchange model (Fournier et al., 2004)

FGD: Flue Gas Desulphurisation

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://iiasa.ac.at/models-and-data/greenhouse-gas-and-air-pollution-interactions-and-synergies

GFS: Global Forecast System

GHGs: Greenhouse Gases

HARM: Hull Acid Rain Model

HGV/LGV: Heavy Goods Vehicle/Light Goods Vehicle

IAM: integrated assessment model(ling)

iAQEG: Defra International Air Quality Expert Group

ICP: International Cooperative Program

ICP Veg: International Cooperative Program on Effects of Air Pollution on Natural Vegetation and Crops

IIASA: International Institute for Applied Systems Analysis, Laxenburg, Austria https://www.iiasa.ac.at/

iMOVE: integrated Model Of Vehicle Emissions (Valiantis, 2007)

IMD: Index of Multiple Deprivation

IMO: International Maritime Organisation

IVOC/SVOC: Intermediate Volatile Organic Compounds/Semi Volatile Organic Compounds

LSOA: Lower-layer Super Output Areas

LV: air quality limit value specified by the EU Framework Directive 96/62/EC on ambient air quality, and 1st Daughter Directive (1999/30/EC) relating to NO_x, SO_2 and PM_{10}.

MARPOL: International Convention for the Prevention of Pollution from Ships, https://www.imo.org/

MB: mean bias

MFR: maximum feasible reduction assuming current technology

MPMD: Multi-Pollution Measures Database

MSW: Municipal Solid Waste

N_2O: Nitrous oxide

NAEI: National Atmospheric Emissions Inventory, https://naei.beis.gov.uk/

NAME: The Met Office's Numerical Atmospheric dispersion Modelling Environment (NAME), used to model a wide range of atmospheric dispersion events. https://www.metoffice.gov.uk/research/modelling-systems/

NAPCP: National Air Pollution Control Program

NCAR: National Centre for Atmospheric Research

NCEP: US National Centre for Environmental Prediction

NEBEI: Network of Experts on Benefits and Economic Instruments

NECR: National Emissions Ceilings Directive (NECD) 2001/81/EC adopted into UK law as NECR

NECA: Nitrogen Emission Control Areas

NMSE: normalised mean square error

NO_x: nitrogen oxides, mainly comprising NO, nitric oxide and NO_2 nitrogen dioxide

NWP: Numerical weather prediction

OA: Organic Aerosol

PCM: The Pollution Climate Mapping (PCM) model

PHEV: Plug-in Hybrid Electric Vehicle

PM_{10}: airborne particulate matter less than 10 µm in diameter

$PM_{2.5}$: airborne particulate matter less than 2.5 µm in diameter

PPM: (1) primary particulate matter; (2) Primary Particulates Model

PRIMES: a Partial Equilibrium Energy Model proscribed by EU for use in policy impact assessments https://ec.europa.eu/clima/eu-action/climate-strategies-targets/economic-analysis/modelling-tools-eu-analysis_en#PRIMES (see also https://ec4macs.eu/)

PWMC: population weighted mean concentration (μg m^{-3}) of an air pollutant, calculated as the sum of all exposures divided by the total population

RDE: (1) Real Driving Emissions; (2) relative directive error

RMSE: root mean square error

SCR/SNCR: selective (non-)catalytic reduction

SECA: Sulphur Emissions Control Areas, applicable to shipping under the revised MARPOL Annex VI (y)

SIA: secondary inorganic aerosols (i.e., NH_4, SO_4 and NO_3).

SNAP: Selected Nomenclature for sources of Air Pollution (http://www.eea.europa.eu/publications/EMEPCORINAIR4/BNPA_v3.1.pdf)

SMMT: Society of Motor Manufacturers and Traders

SMT: Scenario Modelling Tool

SO_2: Sulphur Dioxide

SOA: secondary organic aerosols

SRM: source–receptor matrices calculated by atmospheric dispersion models (e.g., FRAME or EMEP) and used by integrated assessment models to define impact footprints of emission sources

TFEIP: Task Force on Emissions Inventories and Projections

TFIAM: Task Force on Integrated Assessment Modelling.

TSAP: EU Thematic Strategy on Air Pollution, COM(2005)446

UKEAP: UK Eutrophying and Acidifying Pollutants network (https://uk-air.defra.gov.uk/networks/network-info?view=ukeap)

UKIAM: UK Integrated Assessment Model

UNEA: United Nations Environment Assembly

UNECE: United Nations/Economic Cooperation in Europe (UN/ECE), https://www.unece.org/

UNFCCC: United Nations Framework Convention on Climate Change, https://unfccc.int/

VOCs: volatile organic compounds

WGSR: World Group on Strategies and Review

WHO: World Health Organisation

WRF: Weather Research Forecast

Scenarios

	Abbreviation	Definition
2018		
	Baseline adj	adjusted baseline 2018
2030		
	Baseline adj	adjusted baseline 2030
	Medium	medium national
	High	high national
	Speculative	speculative national
	Net zero	net zero scenario +EVs
	NECR+EV	National Emission Ceilings Regs +EVs
	M2030LH	medium national but London high
	M2030LS	medium national but London speculative
	M2030LSC	medium National but London Spec+ Car reduction in ULEZ
	H2030LS	high national + London speculative
	H2030LSC	high national + London spec + car reduction in ULEZ
2040		
	Baseline adj	adjusted baseline 2040
	Medium	medium national
	High	high national
	Speculative	speculative national
	Net Zero	net zero + EVs
	M2040LH	medium national but London high
	M2040LS	medium national but London speculative
	M2040LSC	medium National but London Spec+ Car reduction in ULEZ
	H2040LS	high national + London speculative
	H2040LSC	high national + London spec + car reduction in ULEZ
2050		
	Baseline adj	adjusted baseline 2050
	Medium	medium national
	High	high national
	Speculative	speculative national
	Net Zero	net zero + EVs

Analysis of abatement options to reduce $PM_{2.5}$ concentrations

Part 1: The Modelling approach

1. Introduction

Defra has the responsibility for setting targets for reducing exposure to $PM_{2.5}$ in England in the forthcoming Environment Act, this being the pollutant responsible for a large proportion of current health impacts of air pollution. This requires reductions in overall human exposure that are both ambitious and attainable; and also addressing those areas with the highest concentrations and greatest health impacts. This report describes work undertaken to support Defra in this task, which has involved modelling a wide range of potential future scenarios up to 2050, with different levels of ambition in abating emissions and influence of climate measures. **The measures contained within the modelled scenarios and sector sensitivity analysis are hypothetical and do not in any way constitute current or planned government policy. Any views in the report reflect the opinions and interpretation of the authors, they should not be taken to be the views of Defra or other government departments.**

The aim has been to investigate reduction of population exposure to $PM_{2.5}$, with associated health benefits, and to explore the maximum outdoor concentrations of $PM_{2.5}$ to which people may be exposed with regard to setting limit values. The report is in three parts, the first describing the modelling approach and the atmospheric models used in the project, including model intercomparisons. The second part describes the scenario analysis undertaken, including sectoral studies as well as the different scenarios analysed; and additional studies for London where $PM_{2.5}$ concentrations are highest. The third part draws on the results to provide a framework for setting targets, recognising the associated uncertainties, and complemented by assessment of the health and other environmental benefits and cost-effectiveness, as well as exposure of more deprived communities and other environmental co-benefits.

The modelling approach is described in part 1. The analysis of a large number of scenarios required a model that is fast to run and that could represent total primary and secondary $PM_{2.5}$ concentrations spanning atmospheric transport over European to local scales. This was necessary in order to combine the imported contributions from other countries and from international shipping, with more detailed consideration of UK emissions and enhanced concentrations in urban areas. This has been undertaken using the UK integrated assessment model, UKIAM, as described below in section 2, coupled with economic analysis of health benefits for cost benefit analysis. Inevitably, there are many assumptions and uncertainties right through the process, from emissions to atmospheric dispersion to impacts on health and the environment, which need to be recognised to inform robust policy decisions.

In parallel with the simplified modelling with UKIAM by Imperial College, the far more sophisticated EMEP4UK model, developed by UKCEH, has also been used to model selected scenarios to compare with UKIAM, and to investigate sensitivity studies such as the interannual variability in response to meteorological difference between years. This complements validation studies against measurements for UKIAM, and further intercomparison with urban modelling results for London at a detailed spatial scale.

Part 2 starts with an exploration of the contributions of individual sectors, identifying key sources and uncertainties, and the way in which climate measures may complement air quality measures. This includes the road transport sector and effects of electrification of the fleet, the domestic sector with important but uncertain sources like wood-burning, the agricultural sector as the main source of NH_3, and energy and industry dependant on future energy generation.

This is followed by exploration of a range of scenarios provided by Defra using the Scenario Modelling Tool, SMT, developed by Ricardo, which we have interfaced with UKIAM. These cover medium and high ambition scenarios, together with a scenario including more speculative additional measures. In addition, we consider a climate policy scenario aimed at attainment of net zero. These scenarios emphasize the particular challenge of London, where the concentrations of $PM_{2.5}$ are highest. Additional modelling has been undertaken of hybrid scenarios with higher levels of abatement in London, as compared with the rest of England.

The results from these scenarios are used in part 3, in setting a framework for selecting targets. This includes the reductions achievable in population weighted mean concentrations, and development of a "traffic light" system for identifying what limits might be set for the highest concentrations in different years, according to the different scenarios. In this process, it is important to recognise the uncertainties and consider error margins. Further consideration is given to the benefits of the different scenarios, especially for health, but also covering other aspects including improvements for those in deprived areas and co-benefits for natural ecosystems. The measures in the scenarios are not part of government policy but were developed through stakeholder engagement and literature review by Wood Plc on behalf of Defra. Further attention to the cost effectiveness of individual measures and their feasibility is required. The final summary stresses the uncertainties, and the need for further work to refine the scenarios.

2. The modelling approach: the UKIAM model and associated assessment of health benefits

To assess and compare future scenarios to explore setting targets for overall reduction of exposure of the UK population to fine particulate $PM_{2.5}$ and associated health impacts, while also paying particular attention to those areas with higher concentrations, a flexible model was required that could model total $PM_{2.5}$ concentrations across the UK with at least a 1 km x 1 km grid resolution. This requires bringing together projected UK emissions up to 2050 and potential measures to abate them, their subsequent atmospheric dispersion superimposed on contributions from outside the UK and natural contributions to give total $PM_{2.5}$ concentrations; and producing metrics representing the exposure of different population groups in the UK, to link to health impacts and the monetised benefits of their reduction.

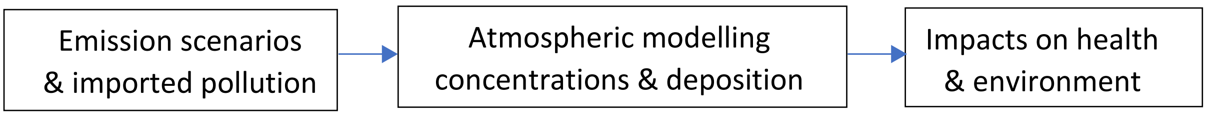


Figure 2.1. Modelling approach.

The UK Integrated Assessment Model, UKIAM, has been developed as a scenario modelling tool to fulfil this requirement, and can run a scenario in under an hour once the required input data has been assembled. It was originally developed as a tool to investigate abatement strategies for reducing UK emissions to comply with national emission ceilings. These were set for the UK in the Gothenburg protocols to reduce transboundary air pollution, and in the National Emissions Ceilings Directive of the EC, NECD, now adopted in UK law. This required assessing the benefits of reducing emissions of SO_2, NO_x, NH_3, $PM_{2.5}$ and VOCs, both in the UK and the rest of Europe, both for human health and protection of ecosystems. UKIAM was originally developed to predict concentration changes, rather than absolute concentrations, but for this work is now required to simulate total $PM_{2.5}$ concentrations. Such calculation of total $PM_{2.5}$ introduces additional complexities with additional contributions from other sources, together with the need to address the spatial variability in concentrations and exposure. Moreover, we needed to distinguish different regions of the UK, and so developed a new version of UKIAM that could treat England, Wales, Scotland and Northern Ireland independently and also distinguish London, owing to its uniquely higher concentrations. Abatement strategies are normally applied at UK level, but this regional approach allows us to separate out England as the region addressed in the Environment Act.

2.1 Emissions

In UKIAM, UK emissions 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. 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 (this is explained in more detail in the section on road transport and electrification of the fleet in Section 5.1). Alternative scenarios and abatement strategies, together with sensitivity studies and exploration of uncertainties, are undertaken by adjusting the emissions. UKIAM has been linked to the Scenario Modelling Tool, SMT, as a tool for assembling such scenarios developed by Defra, reflecting future emissions dependent on forecast energy, transport and agricultural projections and including climate measures. UKIAM can also be used for independent investigation of particular sources, and detailed source apportionment calculations.

As an example, Figure 2.2 gives a simplified summary of UK emissions, broken down by SNAP sector, for 2018 and the baseline for projected emissions in 2030 reflecting measures in current legislation and to which the UK is already committed.

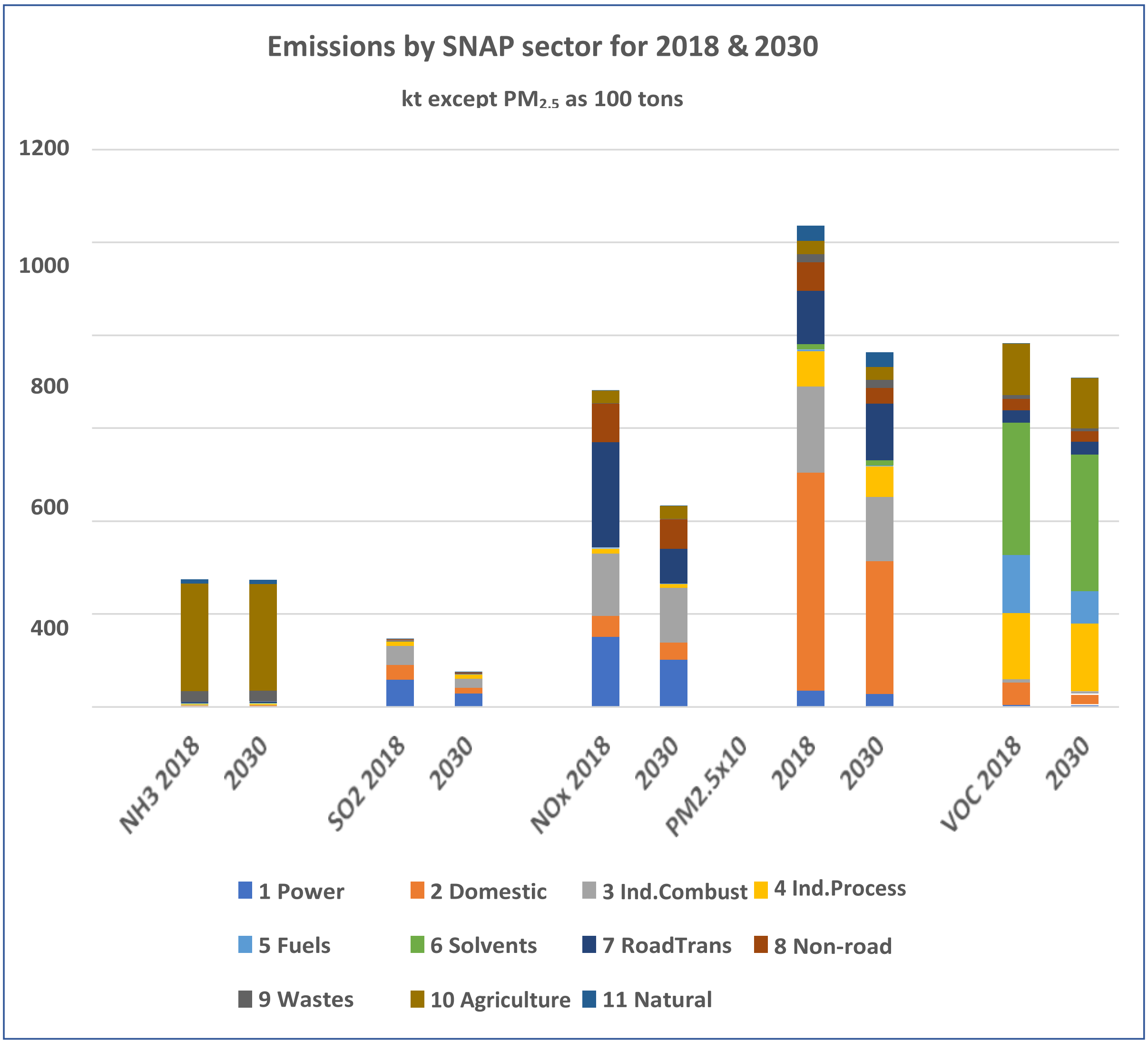


Figure 2.2. Emissions by SNAP sector.

To assess imported contributions from sources outside the UK, a study by IIASA has been used, which developed different future EU emission scenarios to support development of the EU's Second Clean Air Outlook, CAO2. This study used the GAINS model to develop a range of future scenarios, linked to energy projections from the PRIMES energy model, with different degrees of climate ambition up to 2050. We are grateful to IIASA for making the resulting national emissions available and have used results from two of the scenarios in our current studies with UKIAM. These are the With-Additional-Measures, WAM, scenario incorporating some additional national measures from NAPCP reporting superimposed on a baseline scenario matching the latest EU-wide legislation and already adopted national measures. IIASA have also considered scenarios with more ambitious emission reductions from which we have selected the Mix55 scenario reflecting the EC's 2020 proposal for stronger commitments towards reducing emissions. These scenarios are described in full in an IIASA report (IIASA, 2020*).*

Table 2.1. Emissions from EU27 (kt) for IIASA WAM & MIX55 scenarios.

		2005	2020	2025	2030	2040	2050
NH_3							
	WAM	3790	3467	3245	3054	3029	3031
	MIX55	3788	3415	3233	3009	2957	2943
SO_2							
	WAM	6803	1677	1411	1045	798	700
	MIX55	6803	1594	1160	872	671	668
NO_x							
	WAM	10160	5628	4341	3383	2601	2430
	MIX55	10163	5570	4100	3032	2172	2095
$PM_{2.5}$							
	WAM	1665	1224	953	643	514	478
	MIX55	1665	1176	898	676	566	551

The IIASA modelling also gives projected emissions for the European sea areas, which are also used in UKIAM, except for sea areas immediately surrounding the UK. The contributions from shipping in the seas round the UK are modelled in more detail because the NO_x emissions from international shipping give an important contribution to $PM_{2.5}$ in the UK, and also contribute to nitrogen deposition with respect to eutrophication of UK ecosystems. International shipping has been divided into shipping leaving or arriving at a UK port, and in transit without visiting a UK port; with UK shipping defined as leaving and returning to a UK port. There is separate treatment of all in-port emissions. Shipping emissions are based on detailed AIS data from the Maritime and Coastguard Agency, as analysed by Ricardo (2017). These have been mapped distinguishing the Emission Control Area, ECA, through the English Channel and into the North Sea, where legislation to limit emissions is in place; and non-ECA areas including the Irish Sea and shipping up the western side of the UK and round the north of Scotland. Emission projections have been extrapolated out to 2050 reflecting the current ECA controls, although there are substantial uncertainties including the growth of different categories of shipping. This is described in a separate Defra contract report (ApSimon et al., 2019), together with the resulting contributions to secondary $PM_{2.5}$ and nitrogen deposition across the UK.

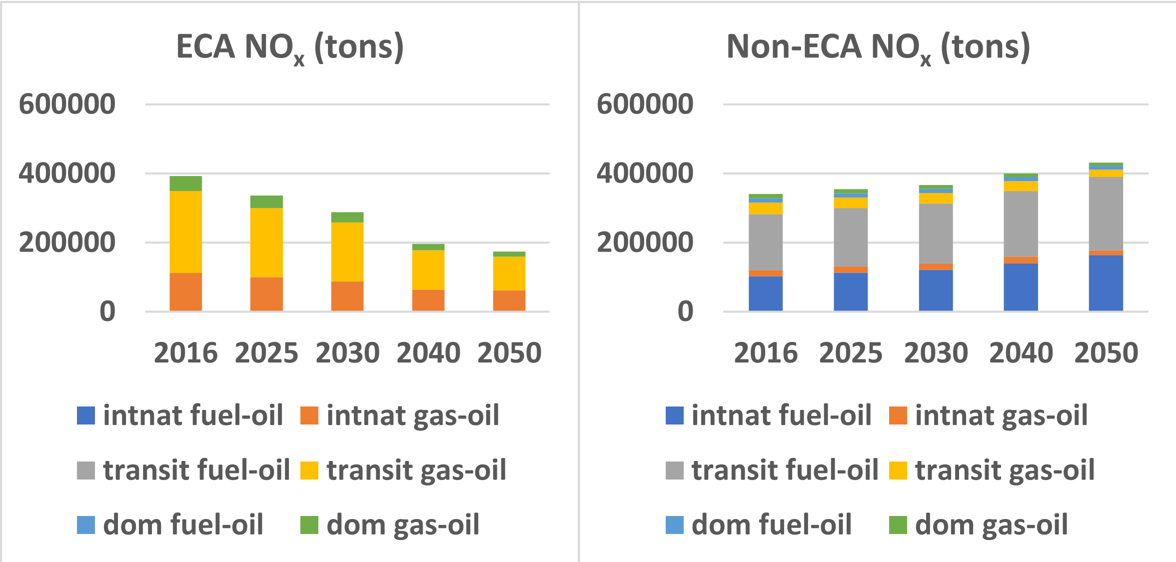


Figure 2.3. Shipping emissions 2018 to 2050 in ECA and non-ECA areas.

2.2 Modelling atmospheric concentrations and deposition

In this section, the treatment of atmospheric dispersion in UKIAM is described, including the underlying atmospheric dispersion models that provide footprints of concentrations and deposition for different sources. These are then adjusted in response to changes in emissions and superimposed to map exposure across the UK. The structure is flexible, with the potential to substitute alternative emissions data or dispersion modelling for selected sources, or to add or remove sources.

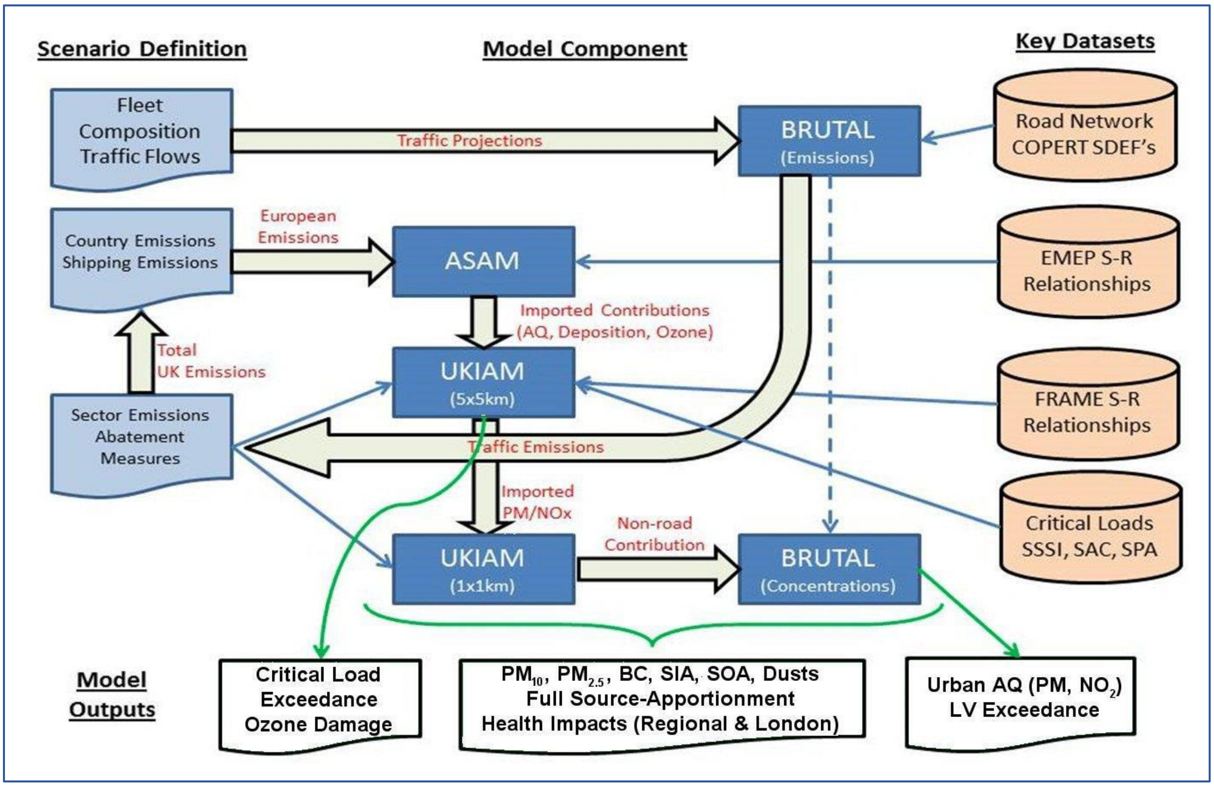


Figure 2.4. Modelling of atmospheric dispersion in the UKIAM model.

Figure 2.4. shows the overall model framework and the different components covering imported contributions from outside the UK area, UK emissions and surrounding international shipping. Road traffic is treated in more detail with the BRUTAL sub-model of the UK road network (Oxley et al., 2009).

The ASAM module covers the imported $PM_{2.5}$ from other countries and sea areas, using the same atmospheric modelling of their individual contributions as in the GAINS model, based on the European Eulerian EMEP model (Simpson et al., 2012). The responses to changes in emissions were derived by reducing individual pollutants from each country or sea area one at a time and examining the effect on concentrations and deposition across Europe. The resulting changes in concentration or deposition across the UK have then been normalised to provide source-receptor matrices, reflecting the response to unit changes in emission of each pollutant from each country or sea area. The central focus here is the secondary inorganic aerosol, SIA, resulting from the emissions of NO_x, SO_2 and NH_3; with primary emissions giving only a small imported contribution.

As indicated in the section on emissions above, UKIAM distinguishes around 90 different sources in each of 5 regions of the UK (London, rest of England, Wales, Scotland and N Ireland). These sources also emit SO_2, NO_x and NH_3, contributing to SIA formation. Changes in SIA concentration are calculated in a similar way as the imported SIA, but using source-receptor matrices across the UK on a 5 x 5 km^2 grid for each source and pollutant as calculated by the FRAME model. The FRAME model (Singles et al., 1998) is fast to run and could undertake the large number of runs required to provide this substantial data set, also producing parallel data on deposition of sulphur and nitrogen used in assessing impacts on ecosystems.

FRAME has also been applied to shipping in the seas surrounding the UK, where international shipping generates substantial NO_x emissions, contributing to SIA concentrations and nitrogen deposition across the UK (ApSimon et al., 2019).

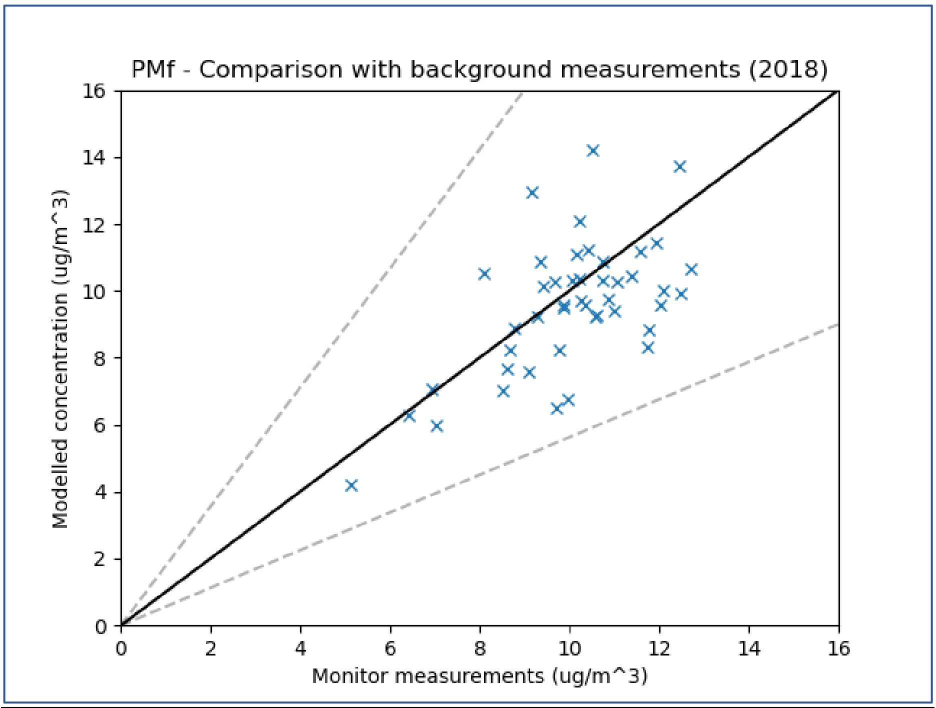
Using linear scaling of the above contributions in accordance with changing emissions, provides a fast way of assessing changes in SIA contributions, but ignores the non-linear behaviour of chemical interactions between pollutants and interactions with changes in the import from outside the UK. This is justified, providing the overall emission reductions do not change the chemical mix too far, but does not provide an estimate of total concentrations starting from zero emissions. To overcome this, initial concentrations of SO_4, NO_3 and NH_4 components are matched to measurements for the current situation, taking an average of 3 years of data from the AGANET measurement network (to allow for interannual variability) and adding an additional mapped contribution across the UK. Intercomparison has been made with independent modelling with the EMEP4UK model incorporating full chemistry (Vieno et al 2016) and further inter-comparison studies are in progress (see later sections 3 and 4) This is the only use of measurements to adjust calculated concentrations.

It should be noted that the formation of SIA from the precursor gas emissions takes time, with subsequent removal on a time scale of a few days involving atmospheric transport over continental scales. The resulting concentration map varies relatively smoothly without localised peaks close to major sources, for example within urban areas. In contrast, primary emissions of $PM_{2.5}$ can give rise to sharp localised peaks in concentration close to the source. In UKIAM this is modelled with the PPM Gaussian model producing concentrations on a 1 x 1 km^2 grid, to match the resolution of the emissions data, and based on annual average wind-rose data. Adjustments are made to reflect source characteristics such as effective release height, and urban effects on dispersion. This results in enhanced urban concentrations and contributes to the higher overall exposure of urban populations to $PM_{2.5}$, especially in the extended city area of London.

The original WHO guideline of 10 μg m^{-3} for annual $PM_{2.5}$ concentrations applies to the total mass of $PM_{2.5}$; and there are other sources contributing to total $PM_{2.5}$ concentrations, both secondary and primary, which need to be taken into account when estimating exceedance. These include secondary organic aerosol, as taken from the NAME model of the UK Met Office and subsequently revised and calibrated to match measurements (to be revised when there is improved understanding of anthropogenic contributions adding to the major influence of biogenic VOCs, and also the role IVOCs, VOCs of intermediate volatility). Contributions from natural dust and sea salt have been provided by Ricardo as used in their Pollution Climate Model, PCM, used for regulatory purposes; and we also add water as included in the EMEP modelling. Apart from some small reduction in water content with SIA concentrations, these additional contributions are currently assumed to remain fixed when considering future scenarios: and when combined are referred to as the "irreducible contribution" for which we do not have abatement options. This becomes a substantial addition amounting to over 3 µg m^{-3} for large parts of England. Clearly, there are large uncertainties, but it is important that this contribution is taken into account when considering exceedance of the WHO guideline, and how much future abatement strategies can reduce this by addressing just the sources that can be controlled.

Total $PM_{2.5}$ concentrations

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 AURN sites in Figure 2.5 for 2018. There is some scatter, but the overall agreement is good with only a very small negative bias. 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. This is discussed further in a later section where the UKIAM model is compared with more sophisticated modelling by the EMEP4UK model with full chemistry.



N	Obs.	Mod.	r	FAC2	FB	NMSE	RMSE
45	10.03	9.54	0.62	1.0	0.05	0.29	1.67

Figure 2.5. Scatter plot of UKIAM $PM_{2.5}$ in 2018 against AURN sites.

Investigation of outliers in the scatter plot shows that the model can overpredict compared with measurements in grid squares with major roads (e.g. the A40 Westway and Euston

Road), which explain the high emissions and modelled concentrations. There will be large spatial variation in such grid squares, so that any measurement will depend crucially on its location. This spatial variability is discussed further in section 4.2. Reciprocally the model may tend to underestimate concentrations in N Ireland (see Derry for example) because of lower quality traffic data, and because of underestimation of the contribution from the neighbouring Republic of Ireland, derived from the EMEP model and diluted over a coarser grid scale.

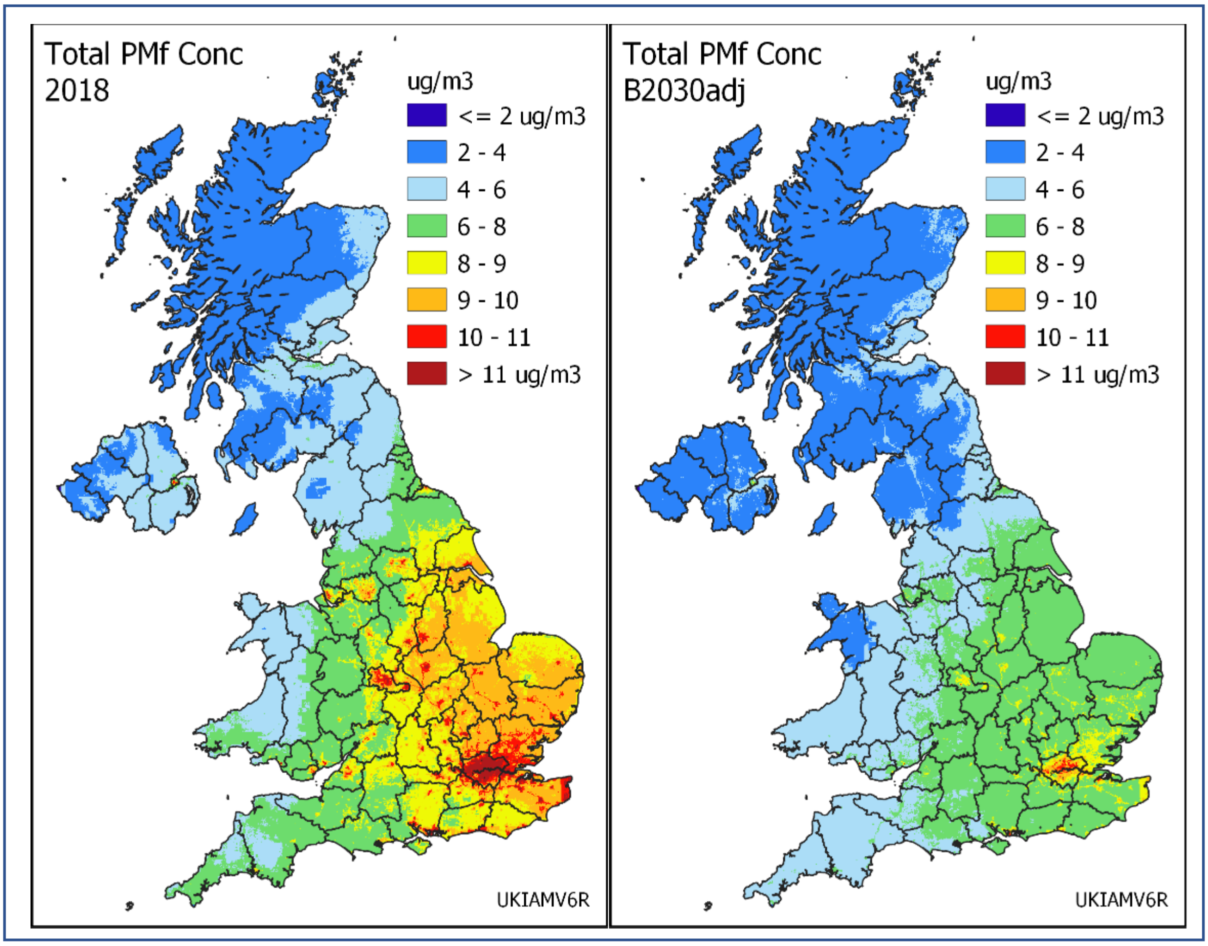


Figure 2.6. Maps of $PM_{2.5}$ for 2018 and the 2030 baseline.

Figure 2.6 shows maps of $PM_{2.5}$ as calculated by UKIAM for both 2018 and the baseline 2030 projections. It is clear that for 2018 large areas of England exceed the WHO guideline of 10 µg m^{-3}, and that there are higher concentrations over the extended urban area of London. Allowing for uncertainties further areas in orange are above 9 µg m^{-3} and at risk of exceedance: and if 2018 had been an extreme meteorological year, even areas in yellow could be considered at risk. But there is a large improvement in the map for the baseline 2030 scenario, with the remaining exceedance of the WHO guideline mainly confined to London and major cities.

2.3 Population exposure and health impacts

The next step is to assess the health effects on the UK population from the mapped distribution of $PM_{2.5}$. Combining the mapped $PM_{2.5}$ concentrations on a 1x1 km2 grid spanning the UK with population data gives an approximate estimate of population exposure, which can be used to assess health impacts. The geographical distribution is based on census data from 2011 and remains fixed, although population growth is allowed for in calculating the health impacts. 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. This is to compare the average outdoor concentration to which people are exposed in different areas or regions.

$$\text{PWMC} = \sum_{i,j} P_{ij} \times C_{ij} / \sum_{i,j} P_{ij}$$

Where the summation is over grid cells i,j in the UK or sub-region with population Pij and concentration Cij.

Table 2.2. PWMC values for national and different areas of the UK for2018 and the 2030 baseline.

	2018							
	National	**Urban**	**Rural**	**London**	**England**	**Scotland**	**Wales**	**Northern Ireland**
Primary $PM_{2.5}$	2.392	2.691	1.356	3.943	2.576	1.206	1.669	1.924
SIA UK sources	1.791	1.845	1.604	2.173	1.971	0.711	1.233	0.705
SIA Europe & Int. Shipping	1.340	1.357	1.279	1.728	1.444	0.582	1.130	0.846
Irreducible	2.953	2.986	2.839	3.584	3.087	2.181	2.627	1.873
NonLinear Adjustment	0.684	0.660	0.764	0.912	0.626	0.771	1.271	1.090
Total $PM_{2.5}$	**9.159**	**9.540**	**7.843**	**12.340**	**9.704**	**5.451**	**7.931**	**6.439**
	B2030adj							
	National	**Urban**	**Rural**	**London**	**England**	**Scotland**	**Wales**	**Northern Ireland**
Primary $PM_{2.5}$	1.660	1.866	0.947	2.762	1.788	0.853	1.146	1.297
SIA UK sources	1.154	1.186	1.046	1.427	1.270	0.457	0.812	0.456
SIA Europe & Int. Shipping	0.997	1.010	0.951	1.289	1.073	0.454	0.834	0.622
Irreducible	2.613	2.636	2.532	3.217	2.725	1.965	2.337	1.708
NonLinear Adjustment	0.684	0.660	0.764	0.912	0.626	0.771	1.271	1.090
Total $PM_{2.5}$	**7.108**	**7.358**	**6.241**	**9.606**	**7.482**	**4.500**	**6.399**	**5.174**

The PWMC value can be used to compare exposure in different parts of the UK. Table 2.2 provides an illustration of this, distinguishing urban and rural areas, and different regions of the UK and London, as well as the overall national picture. This reflects the geographical distribution shown in Figure 2.6, with the highest PWMC for London due to higher long-range contributions to secondary inorganic aerosol, SIA (resulting from emissions in other countries, international shipping and UK emissions) as well as primary $PM_{2.5}$ from local emissions within the city. As expected, the population in urban areas has a higher exposure than in rural areas, with a greater contribution from primary $PM_{2.5}$. Average exposure in England is also higher than in other regions of the UK.

With regard to the imported contributions, these are calculated separately for the sea areas round the UK, and from other countries and more distant sea areas. The main contributing countries are France, Germany, and the Low Countries. These contributions are based as described above on modelling of the With Additional Measures (WAM) scenario of IIASA, with a contrasting scenario Mix 55 for future European emissions used as a sensitivity study. A breakdown of the resulting contributions to national population weighted mean concentrations is given in Table 2.3, noting that these may be a slight underestimate because of the linear scaling assumptions (see section 4). This indicates that there is a modest difference between the WAM and Mix 55 scenarios. A sensitivity experiment to extending the nitrogen emissions control area, NECA, to include the rest of shipping round the UK including the Irish Sea, indicates a reduction to 0.25 µg m^{-3} for the contribution of shipping in 2050. However, there are large uncertainties in shipping projections so far into the future.

Table 2.3. Imported contributions from shipping round the UK, and from other countries and sea areas to national PWMC values (µg m-3).

	2018	2030	2040	2050
Shipping round UK	0.58	0.49	0.44	0.45
Imported from elsewhere WAM	1.03	0.69	0.59	0.57
Imported from elsewhere Mix 55	1.03	0.65	0.57	0.58

<u>Exceedance of the WHO guideline</u>

A particular application of UKIAM is to investigate exceedance of relevant thresholds- for example the WHO guideline. This was originally set at 10 µg m^{-3}: but note that WHO have recently issued revised guidelines in September 2021 (WHO 2021) setting a further tightened guideline of 5 µg m^{-3}. The WHO guidance is based on epidemiological evidence related to total $PM_{2.5}$ by mass, which is why it has been important to include the additional, but uncertain, contributions in the "irreducible" fraction. A convenient way of assessing exceedance of any threshold value, t, is to calculate the population weighted mean exceedance, PWME. To calculate this UKIAM adds up the "accumulated exceedance" above the prescribed threshold concentration, t, by adding up the population in each grid cell above the threshold times any excess concentration; and then divides by the summed population to get an average exceedance per person.

$$\text{PWME} = \sum i,j\ Pij\ \times \max(Cij - \text{t}, 0)\ /\ \sum i,j\ Pij$$

The graphs in Figure 2.7 show plots of PWME averaged over the whole UK against different threshold values, t, for 2018 and the 2030 baseline. They illustrate how the threshold value at which PWME converges to zero improves over this period, and also the reduction in exceedance of the current WHO guideline of 10 µg m^{-3}.

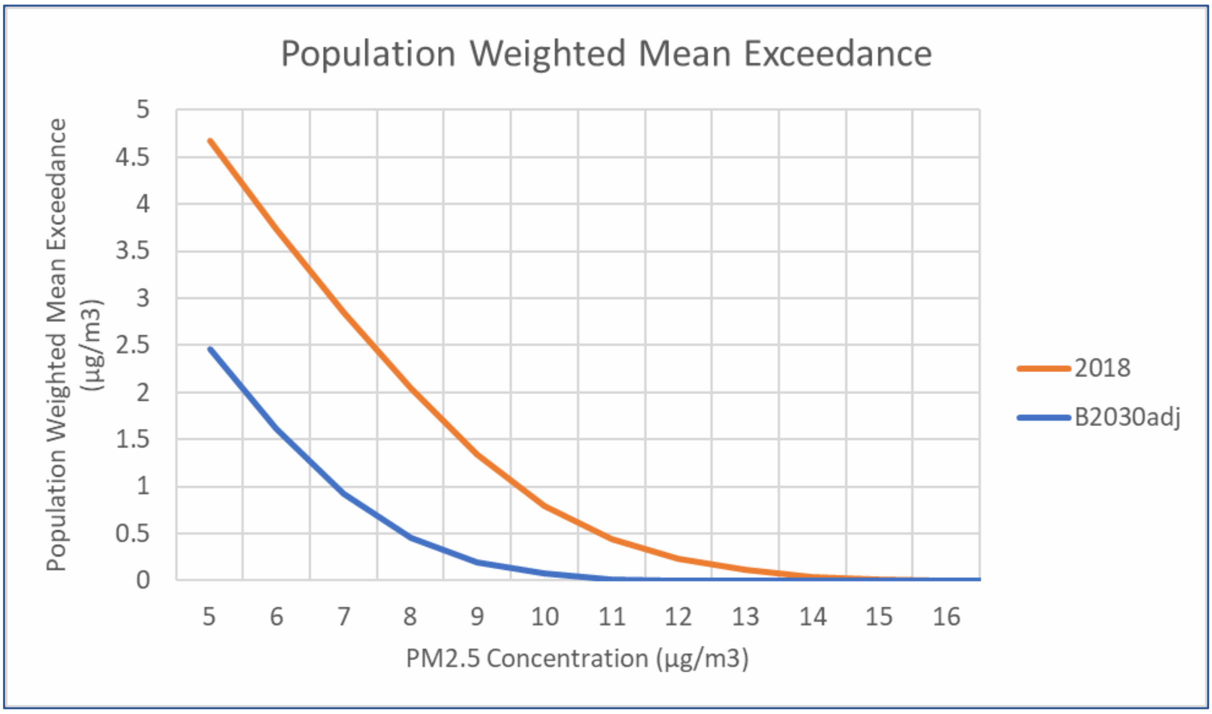


Figure 2.7. Graphs of national PWME against threshold for 2018 and 2030 baseline.

PWME can be used to compare different regions in a similar way to PWMC. To allow for uncertainties with respect to exceedance of the WHO guideline, values of PWME are also calculated for thresholds 1 µg m^{-3} and 2 µg m^{-3} above and below the 10 µg m^{-3} threshold. London has much higher exceedance than the rest of the country, but exceedance of the WHO guideline is small in Wales, Scotland and N Ireland. The higher exceedance in urban areas is largely due to the urban peaks in primary $PM_{2.5}$ concentration, emphasizing the need to address primary $PM_{2.5}$ emissions in reducing exceedance of the WHO guideline.

For policy applications, it is also useful to provide source apportionment to give 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 9.2 µg m^{-3}, is provided in the pie chart in Figure 2.8. It can be seen that the biggest contribution comes from the overall contributions to secondary inorganic aerosol. The primary contribution weighted by the concentration of population in urban areas is also substantial. Reduction of both these contributions to exposure is explored in later sections of this report, looking at emissions from different sectors. In addition, there is the contribution from natural sources, which is not reducible, and from secondary organic aerosol, where biogenic emissions play an important role but scientific understanding is still evolving.

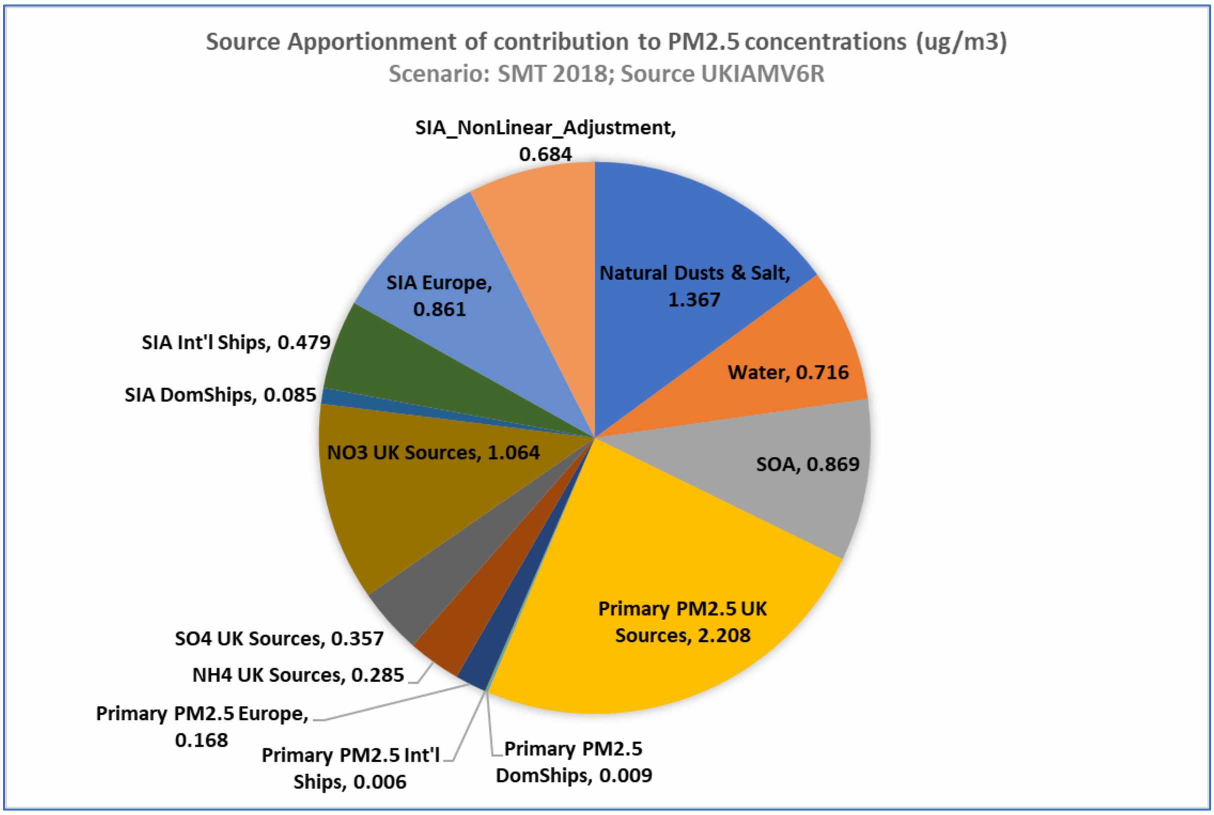


Figure 2.8. Pie chart showing source apportionment of UK national PWMC in 2018.

<u>Monetised benefits of reducing pollutant concentrations</u>

In comparing scenarios for improvement of air quality, it is helpful to assess the health and economic benefits to set against the costs of abatement measures. This is done using damage costs per person for a change of 1 µg m^{-3} in annual concentration, based on tools previously developed for Defra (Ricardo, 2019, 2020) for quantification of damage costs per tonne of pollutant emission and exposure. Use of the damage cost tool ensures full consistency with the positions agreed for quantification by the Interdepartmental Group on Costs and Benefits (IGCB). Following discussion with Defra, two updates have been applied to the positions adopted in the Ricardo work:

- Damage costs are updated to 2020 prices
- The response function for mortality linked to $PM_{2.5}$ exposure has been increased from a relative risk of 1.06 per 10ug.m^{-3} $PM_{2.5}$ to 1.08 following recommendations made recently by the Committee on the Medical Effects of Air Pollutants (COMEAP, 2022), drawing on a major systematic review by Chen and Hoek (2021) carried out to inform development of the revised Air Quality Guidelines from the World Health Organisation (WHO, 2021).

For $PM_{2.5}$, the updated central estimate of the damage costs is £62.7 per person per µg m^{-3} (range £16.9 to £178.2 indicating the uncertainties). These damage costs are then combined with population exposure to give a monetised impact for each scenario. For example, the improvement of 2 µg m^{-3} in population weighted mean concentration in Table 2.2 between 2018 and 2030 for the 67 million people in the UK corresponds to an annual benefit of ~£8.4 billion for 2020 prices (range £2.2 to £24 billion). In comparing scenarios such benefits can be accumulated over time using economic data such as discount factors as undertaken in section 8.2 of this report. Where relevant, we also consider any side benefits in reducing NO_2 exposure for which the corresponding damage costs of NO_2 exposure is £7.02 per person per µg m^{-3} (range £0.53 to £27.67, and allowing for the difficulties of distinguishing the additional effects of NO_2 in a mixture of pollutants). The uncertainties in quantifying health impacts and assigning monetised benefits are in addition to those in assessing concentrations and exposure.

2.4 Uncertainties

Clearly, there are many uncertainties in the modelling described above, which ongoing work is addressing with emphasis on $PM_{2.5}$. This includes emissions where many of the important sources identified in the source apportionment, such as wood-burning and non-exhaust emissions, are highly uncertain. There are also significant sources such as cooking not yet included in the National Atmospheric Emission Inventory, NAEI, used to define the baseline UK emissions in UKIAM. Also, there may be additional contributions from IVOCs with intermediate volatility, which are still very much at the fundamental research stage.

There are also assumptions and uncertainties in the atmospheric modelling. The effects of non-linearity in the chemistry can be significant, but are less than other uncertainties; and further inter-comparison has been undertaken with more complex Eulerian modelling of SIA (where we have not wanted to overestimate future improvements due to emission reductions - see section 4). In urban areas, there are also many uncertainties in the way pollution disperses in and between streets, which are difficult to resolve even with very detailed CFD models (e.g. Woodward et al., 2019). Within 1x1 km^2 grid cells there will be local peaks not resolved by the model, and the microscale complexities of hot-spots would be a very serious difficulty if the WHO guideline was applied as a limit value in an analogous way to the limit value for NO_2. This is another reason for our dual emphasis on PWMC and PWME as indicators for reducing both human exposure and health impacts, and making improvements for those urban areas with higher exposure rather than focusing on hot-spots.

In applying to future scenarios, additional uncertainties arise in emission projections, and the effectiveness of abatement strategies, both for the UK and imported contributions. The breakdown of concentrations into different contributions shown above indicates the relative importance of UK and imported contributions, and draws attention to those additional components currently kept constant in the “irreducible fraction”. This is a substantial and very uncertain contribution to total $PM_{2.5}$ concentrations by mass and includes secondary organic aerosol.

2.5 Linking modelling and measurements

In addition to comparing modelling results with measurements, initial steps have been taken to assess the potential for monitoring data to be used to evaluate progress towards meeting targets for reducing concentrations. To this end, we have calculated population exposure for different agglomerations, using modelling results which capture the variation in concentrations across an agglomeration, and comparing these with exposures derived using available measurements as a proxy for concentrations across the agglomeration, as has been used in assessing compliance with EU legislation on $PM_{2.5}$.

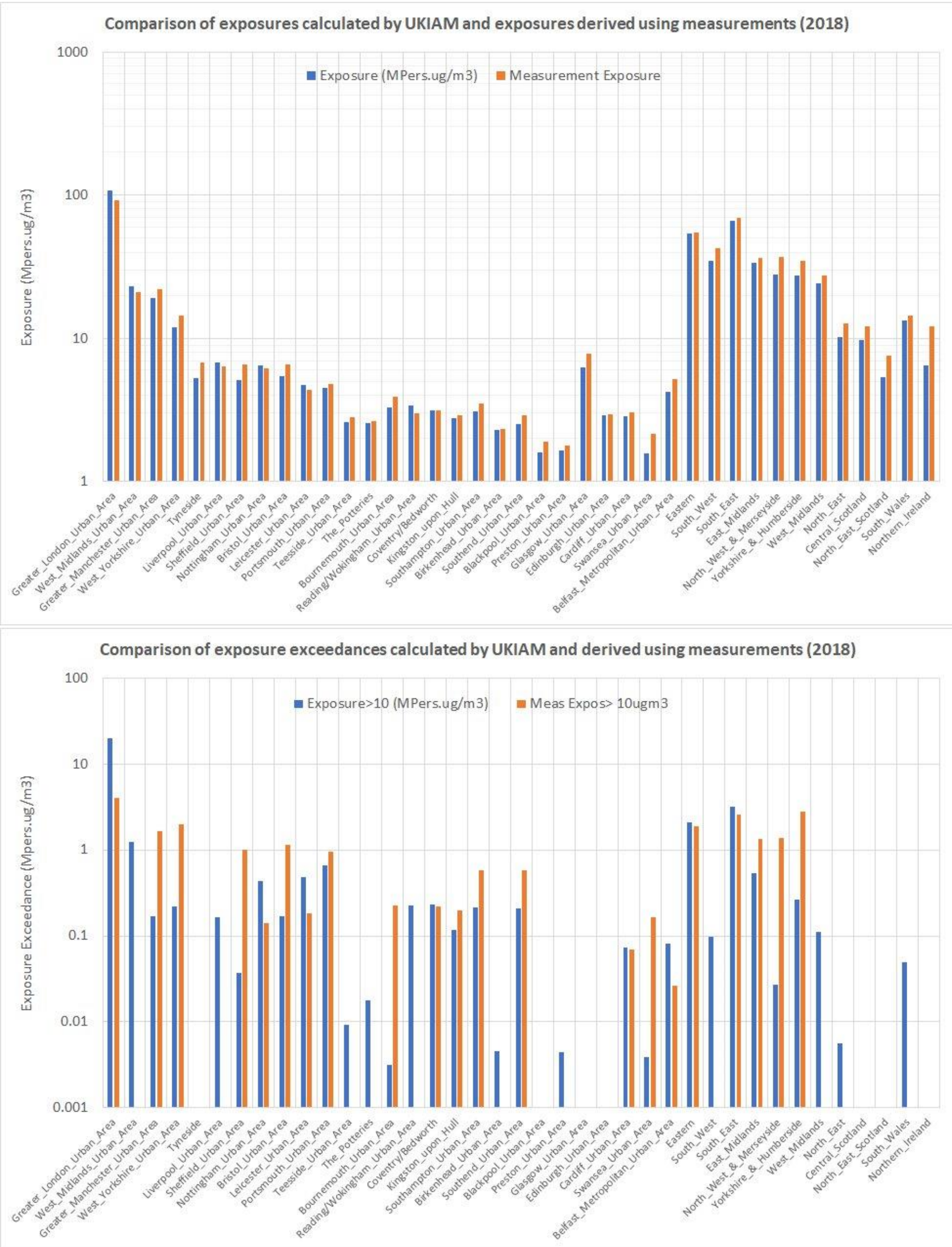


Figure 2.9. Comparison of population exposure based upon measurements and modelling for different agglomerations (a) total $PM_{2.5}$ concentrations, (b) exceedance of 10 µg m-3.

For the limited number of measurements of background concentrations available away from roads and local sources, we found that there was reasonable agreement of total population exposure, suggesting that the measurements appear to be fairly representative of concentrations across the given agglomeration (see Figure 2.9(a)).

It should be noted in these preliminary results that for larger agglomerations there may be multiple measurement sites, in which case these have been averaged to provide the measurement proxy for the whole agglomeration. This is less than adequate for very large urban agglomerations, such as London, where there are high emissions, large populations, and significant spatial variability in concentrations. The agreement between modelling and measurements of total population exposure thus diverges in these agglomerations. Further measurements will be necessary to evaluate the representativeness of measurements for smaller areas, such as individual London boroughs.

Importantly, however, even where the measurements may be able to provide a reasonable proxy for representative concentrations of total $PM_{2.5}$ across an entire agglomeration, the measurements are not able to capture the concentrations and population exposure *above a threshold concentration* such as 10 µg m^{-3}. This is highlighted in Figure 2.9b, where the exposure exceedances calculated by the modelling diverge considerably from exposure exceedances based on measurements. The reason for this is straight forward, inasmuch as if the measurement is below the threshold then there can never be exposure exceedance ; whereas even if the PWM concentration calculated by the model is below the threshold at the measurement site any modelled higher peaks above the threshold in that agglomeration will be captured and exposure exceedance quantified; see, for example, South Wales, North East, or Preston where the PWMC and the measurements are below the threshold but where exposure exceedance is still evident (Figure 2.9) because of hotspots within the agglomeration which have not been picked up by the measurements. Furthermore, as discussed in section 4.2, concentrations will be enhanced locally close to major roads or other concentrated sources, which is not represented in modelling at a 1x1km^2 resolution.

Thus, measurements could be used to evaluate progress towards concentration reductions of total $PM_{2.5}$ at least outside London. However, for the present, modelling can be useful to capture and assess progress towards overall reduction in exposure exceedance in relation to any specified threshold concentration. Further analysis is needed, using additional measurements from other monitoring networks, to both validate this combined measurement and modelling approach to assessing progress towards reductions in concentrations. Analysis is also needed to identify suitable locations for additional monitoring to be implemented, in order to provide more complete spatial coverage of measurements- see also section 4.2.

In this context it is also helpful to consider a break down of the total population exposure in England, as shown in Figure 2.10, giving the relative contributions from London and the urban areas covered by the other agglomerations compared with the exposure in the remaining rural areas and towns by zone. It is clear that these areas outside major towns are responsible for a substantial proportion of the total population exposure in the UK, emphasizing the benefit of reducing concentrations in these areas as well as in the major cities. This will tend to be more dependent on the longer range contribution of secondary inorganic aerosol rather than the primary sources which are concentrated more in cities.

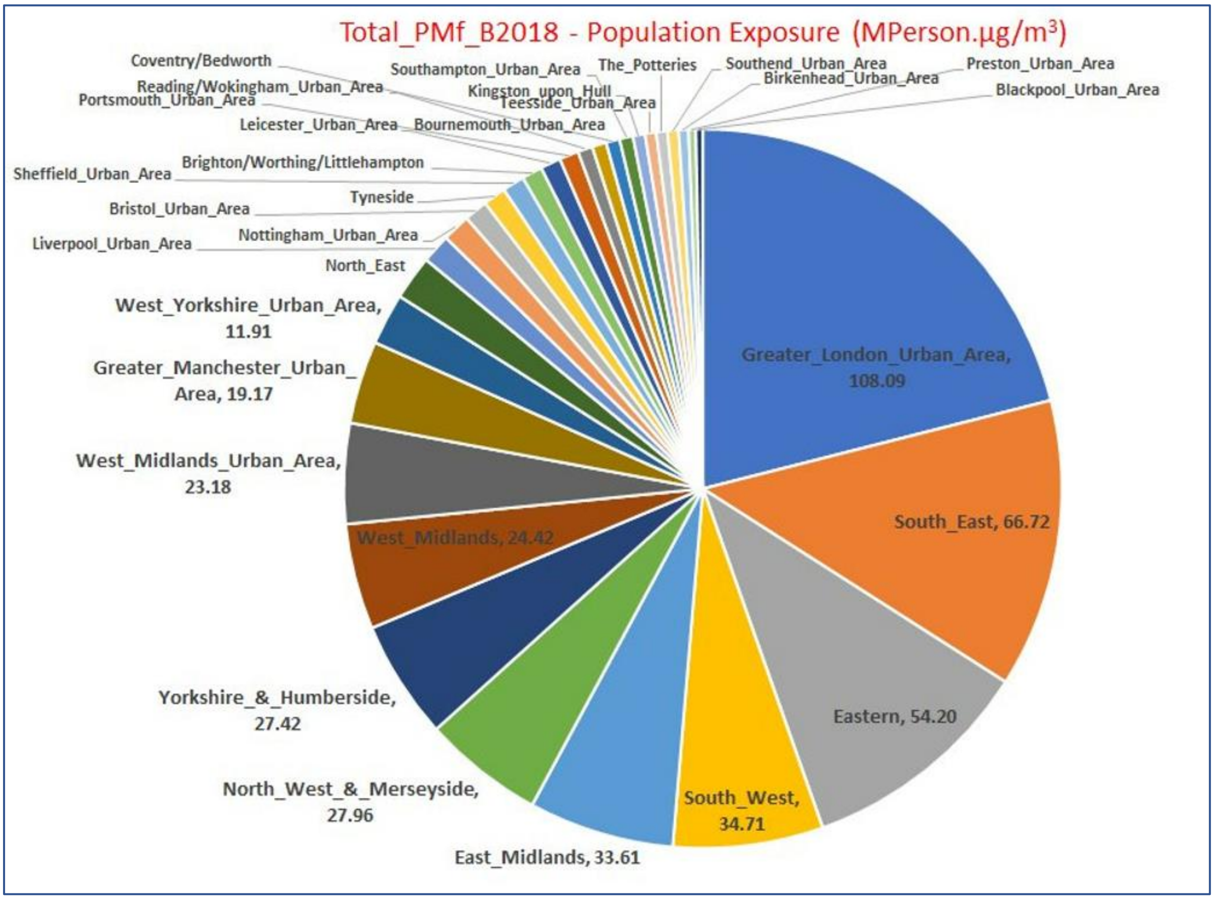


Figure 2.10. Spatial distribution of population exposure in England.

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3. The EMEP4UK Model

3.1 Model description

EMEP4UK is a full Eulerian atmospheric chemistry and transport model which simulates the emissions, transport, chemical transformations and deposition of a wide range of pollutants and provides hourly outputs (Vieno et al., 2009; Vieno et al., 2010; Vieno et al., 2014; Ots et al., 2016; Vieno et al., 2016a; Vieno et al., 2016b; Ots et al., 2018; Aleksankina et al., 2019; Carnell et al., 2019). It is a UK high-spatial resolution implementation of the European EMEP MSC-W model (Simpson et al., 2012; https://github.com/metno/emep-ctm), which is used within the framework of the UNECE Convention on Long-range Transboundary Air Pollution (CLRTAP) to assess country-to-country transport of air pollutants, the exceedance of critical loads thresholds for ecosystems and underpins the setting of European emission ceilings. The model simulates the various processes more mechanistically, whilst still with a simplicity that makes it applicable for multi-year, full-country simulations.

For the simulations here, EMEP4UK was based on EMEP model version rv4.36 and run at a resolution of about 3 × 3 km^2 over the British Isles, nested within a European domain with a horizontal resolution of 27 × 27 km^2. Fixed boundary concentrations were prescribed for the perimeter of the European domain, independent of scenario or year. The meteorological input data was generated with the Weather Research Forecast (WRF) model version 4.2.2 (Skamarock et al., 2008; www.wrf-model.org) which included data assimilation (Newtonian nudging) of the coarse-scale numerical weather prediction (NWP) model meteorological reanalysis with the US National Center for Environmental Prediction (NCEP) / National Center for Atmospheric Research (NCAR) Global Forecast System (GFS) at 1º resolution, every 6 hours (Saha et al., 2013).

Compared with UKIAM, the EMEP4UK-WRF system is much more mechanistic and meteorologically explicit (Table 3.1). It therefore provides additional insights into the performance and robustness of the UKIAM. In particular, it provides:

1. An assessment of whether UKIAM reasonably reflects the non-linear response of secondary inorganic aerosol (SIA) components to changes in precursor emissions, especially in the more extreme emission reduction scenarios.
2. An indication of the change expected in the secondary organic aerosol (SOA) component, formed from biogenic and anthropogenic volatile organic compounds. This is kept constant in the UKIAM and therefore does not capture its response to emission changes.
3. A quantification of the additional $PM_{2.5}$ that may be expected in years with particularly unfavourable meteorology.

The EMEP4UK-WRF modelling system has been tested widely against measurement data (Vieno et al., 2009; Vieno et al., 2010; Vieno et al., 2014; Ots et al., 2016; Vieno et al., 2016a; Vieno et al., 2016b; Ots et al., 2018; Aleksankina et al., 2019; Carnell et al., 2019) and shows good performance, except for roadside sites where the 3 km resolution is inadequate to capture the local enhancement.

Table 3.1. Summary of the characteristics and representation of various processes in EMEP4UK-WRF compared with UKIAM.

Characteristics / process	**EMEP4UK-WRF**	**UKIAM**
Horizontal resolution	3×3 km^2	1×1 km^2
Meteorology	Explicitly using meteorological conditions for individual years	Long-term annual average
Response of secondary inorganic aerosol to emission changes and meteorology (NH_4^+, NO_3^-, SO_4^{2-})	Calculated explicitly via the thermodynamic equilibrium with gas-phase precursors	Scaling of source-receptor matrix contributions based on EMEP and FRAME
Representation of organic aerosol	Representation of SOA formation from biogenic and anthropogenic VOCs, but incomplete and does not carry IVOC/SVOC (not in emissions inventory) or their contribution to SOA; a constant background of 0.4 µg m^{-3} represents additional OA not explicitly included in the emissions (e.g. oceanic OA, primary biological material) (Bergström et al., 2012; Bergström et al., 2014)	Based on NAME model with empirical scaling and remains fixed over time
Continuous natural sources	Emissions of biogenic VOC, soil NO_x, seasalt, Dimethyl Sulphide , mineral dust and road-dust driven by meteorology	Sea-salt, natural rural and urban dusts, water (adjusted with SIA)
Sporadic natural sources	Volcano emissions as per meteorological year; fire emissions turned off	-
Non-European contributions	Prescribed boundary concentrations, independent of year and emission scenario; prescribed CH_4 field	As in EMEP model
European contributions	Explicitly accounted for via emission, transport and transformations	Based on EMEP as in the GAINS model

Characteristics / process	EMEP4UK-WRF	UKIAM
Shipping	Some inconsistencies between international and domestic shipping emissions	Domestic, international and in-transit emission in sea area round the UK based on AIS data from Ricardo and modelling of ECA and non-ECA areas over time
UK emissions	Rescaling of the 2018 emissions field of each SNAP sector to match the total emission of each scenario	Broken down for each region into ~90 different source categories from NAEI and NFR codes in the SMT. Detailed modelling of the road transport sector on a bottom-up basis from the road network

Here the UKIAM model, run at 1 km, is expected to perform better. Although, it will still not capture the true roadside increment. To demonstrate the skill in EMEP4UK-WRF to reflect concentrations and trends in SIA components, Figure 3.1 shows a comparison of modelled trends and site-specific model predictions against the measurements of the UK AGANET network, for a slightly older model version (rv4.17). The model reproduces the measurements well both spatially and temporally, but there is a tendency for the model to underestimate the trend and to overestimate concentrations after 2010. This would indicate that EMEP4UK is, if anything, conservative in predicting the SIA reductions that may be achievable through reductions in precursor gas emissions (NH_3, NO_x, SO_2). This assessment is only indicative, however, as the model / measurement comparison heavily relies on the trend in the emissions to be correctly represented in the historic and current emissions inventories. Analysis of satellite observations, for example, has suggested that the NAEI may underestimate NH_3 emissions by 30% (Marais et al., 2021), although the uncertainties in this independent approach are likely no smaller than in the NAEI itself. The impact of meteorology on agricultural emissions of NH_3 and soil emissions of NO_x is also not reflected in the NAEI and its trend (Sutton et al., 2013).

The EMEP4UK-WRF modelling system was run for the meteorological year of 2018 (to match the year of the baseline emissions) and, for comparison, 2003. The year of 2003 was selected because the meteorology led to higher-than-usual concentrations in $PM_{2.5}$ as can, for example, be seen in the peaks in the measured and modelled time-series of SO_4^{2-} and especially of NO_3^- (Figure 3.1a & c). Vieno et al. (2014) analysed the reason for the elevated concentrations and showed that these were linked to extended periods of enhanced transport from continental Europe during February to April, which coincided with cool temperatures to favour the formation of ammonium nitrate (AN). There is no reason to believe that 2003 was an entirely unusual year, and whilst high ammonium nitrate episodes tend to dominate regional high $PM_{2.5}$ events in the UK (Yin and Harrison, 2008), other sources such as wildfires and volcano eruptions could also lead to elevated concentrations in particular years. The relative importance of AN could change in the future as its precursor emissions decrease, and other meteorological features could be more controlling for $PM_{2.5}$.

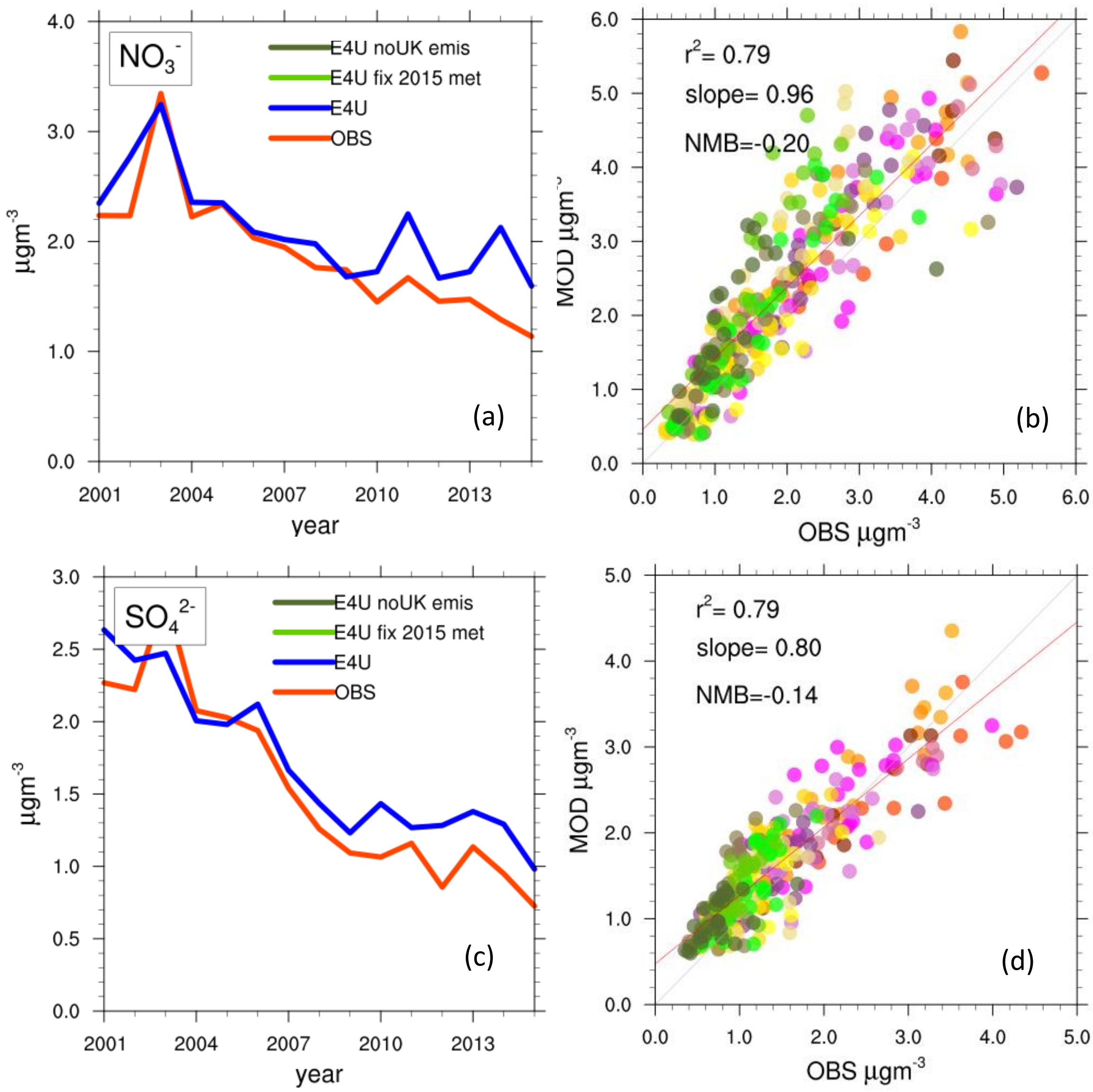

Figure 3.1. Comparison of modelled and measured concentrations of NO_3^- and SO_4^{2-} across the AGANET network sites. (a) Measured (OBS, red) and modelled (E4U, blue) trends of annual NO_3^- concentrations averaged across the AGANET sites. (b) Site-specific comparison of annual average model results (MOD) against the AGANET measurements (OBS) for NO_3^-. Each data point is an annual average for a single site and the colours refer to different years. (c) and (d) show the equivalent results for SO_4^{2-}. Data from EMEP v4.17/WRF 3.9.1.1 at ~5 km x 5km. Compared with the data on UKAIR, the AGANET aerosol concentrations have been adjusted to account for reduced particle retention prior to 2016 (Tang et al., 2015), by a factor of 1.25 for NO_3^- and 1.5 for SO_4^{2-}.

3.2 Inter-annual variability

The model was run to investigate the impact of meteorology on a total of 7 scenarios, which were a baseline scenario for 2018, 2030, 2040 and 2050 as well as the high reduction scenario for 2030 and 2040, and the speculative scenario for 2040 (Figure 3.2). Note that the baseline 2040 and 2050 used here were not quite the same as those used in a slightly revised baseline later in this report, which give smaller emissions reductions in the transport sector. For the baseline year of the baseline run (2018 emissions), it is predicted that the adverse meteorology of 2003 would have resulted in a mean increase in average annual $PM_{2.5}$ concentrations of about 1 µg m^{-3}, with areas in Yorkshire and Cumbria exceeding this value (Figure 3.3). For future scenarios, as emissions and thus average concentrations decrease, the difference stays < 1 µg m^{-3} at the national average and, as demonstrated for this 2040 baseline scenario (Figure 3.3) for all of England.

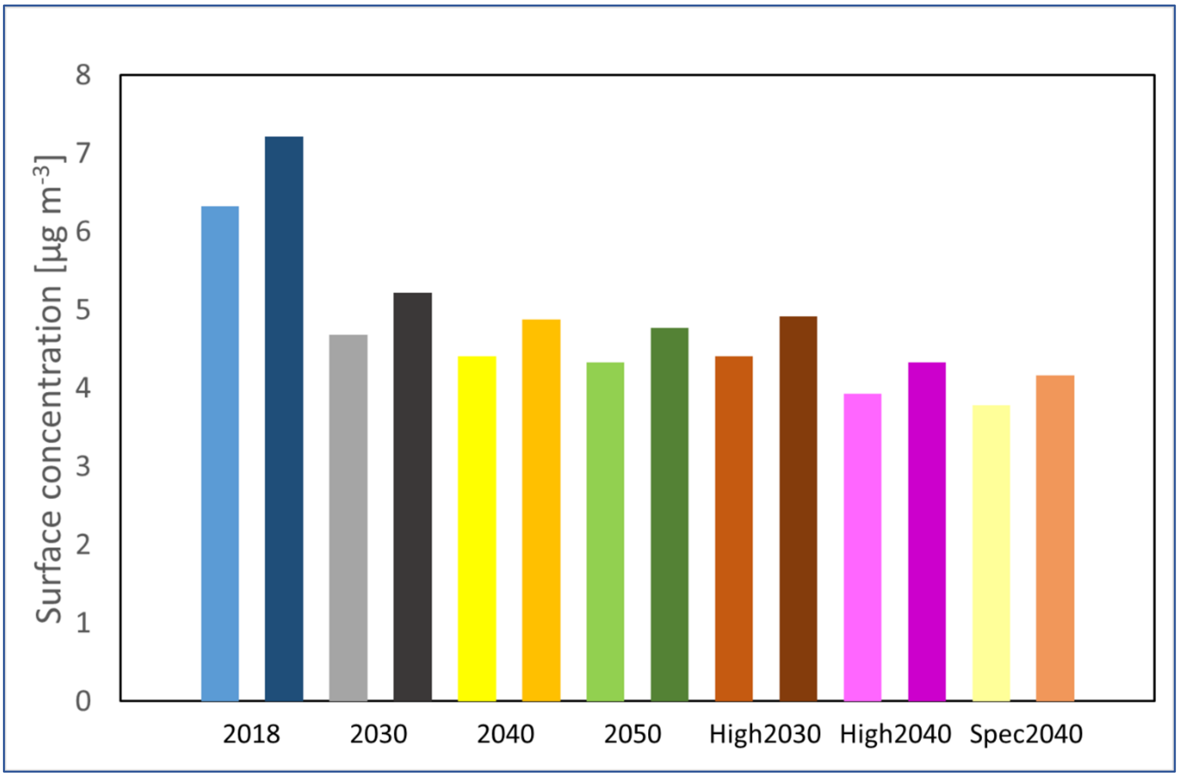

Figure 3.2. Summary of UK spatially average $PM_{2.5}$ concentrations for different emission scenarios, based on 2018 meteorology (lighter colour) and 2003 meteorology (darker colour).

Thus, whilst this is not a comprehensive analysis, and 2003 may not be the most adverse year imaginable, these results suggest that allowance should be made for an increase in average concentrations of the order of 1 µg m^{-3} to account for less favourable meteorology.

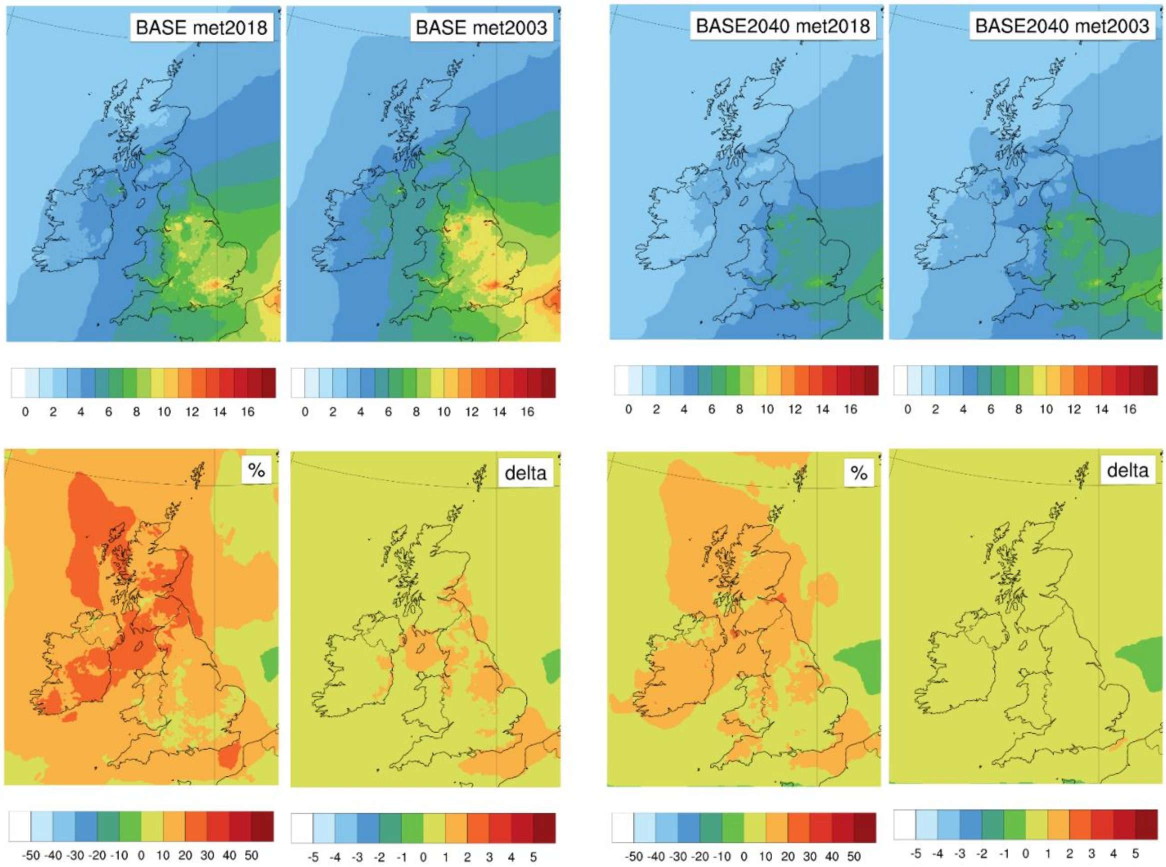

Figure 3.3. Spatial pattern of the increase in concentrations under 2003 meteorological conditions compared with 2018 meteorology for baseline emission scenarios for 2018 and 2040. Shown are the average surface concentration fields as well as the absolute and relative changes due to meteorology.

3.3 Response of secondary organic aerosol to future emission changes

As described before, EMEP4UK-WRF predicts secondary organic aerosol formation from biogenic and anthropogenic volatile organic compounds (BSOA and ASOA, respectively) and includes a constant background contribution to organic aerosol which reflects component emissions which are not captured by the emissions inventories, such as marine OA and biological particles. This component is set fixed at 0.4 µg m^{-3} and does not change with emissions scenario of meteorology (grey bars in Fig. 3.4). Biogenic secondary organic aerosol (BSOA) formation changes with oxidant levels and emissions of biogenic volatile organic compounds, which in return depend on meteorology and land cover. For 2003 meteorology, which includes the 2003 summer heat wave with elevated BVOC emissions, slightly higher BSOA concentrations are predicted. The effect of potential change in land-cover between 2018 and 2050 is uncertain and not represented in the model. If tree species are chosen unwisely, large-scale afforestation planned as one of the NetZero measures could increase BVOC emissions (Royal Society, 2021). ASOA formation is governed by anthropogenic emissions and oxidant availability. This component, although small, is predicted to decrease marginally under future emission scenarios (Fig. 3.4). All this amounts to a very small decrease of the organic aerosol under future emissions and a small increase under 2003 meteorology compared with 2018.

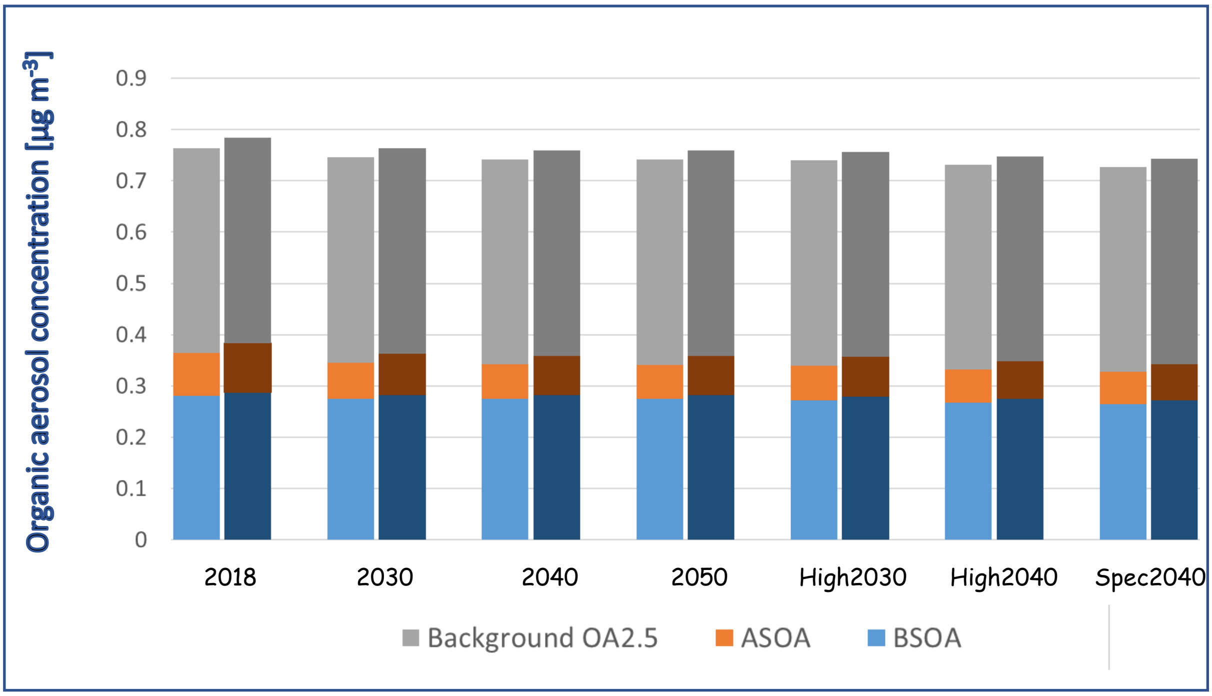

Figure 3.4. UK average concentrations of organic aerosol components predicted by the EMEP4UK-WRF system for 2018 meteorology (lighter colour bars) and 2003 meteorology (darker colour bars).

Overall, the EMEP4UK-WRF results suggest that the use of a constant OA contribution in UKIAM does not increase a major uncertainty and is broadly justified. There are some uncertainties, however, around organic precursors not currently included in the emissions inventories: in particular, as previously mentioned, the representation of OA in the standard EMEP4UK model does not include OA formation from IVOC/SVOCs. Ots et al. (2016) explored the contribution of OA generated from emissions of these compounds associated with diesel engines for 2012 and concluded that ~30% of the SOA in and around London could be due to diesel-related IVOC emissions, increasing the ASO component by approximately a factor of 4. This component would likely decrease as the UK's vehicle fleet is electrified. There may therefore be a deficit in both the EMEP4UK and UKIAM model results of on average possibly 0.4 µg m^{-3} (but locally larger) which would decrease over time. Some of this contribution may already be captured by the background $PM_{2.5}$ OA concentration, which is derived by comparing predicted OA to selected measurements, but whilst this background concentration is constant across England (and the UK), the contribution of IVOC-derived SOA is not.

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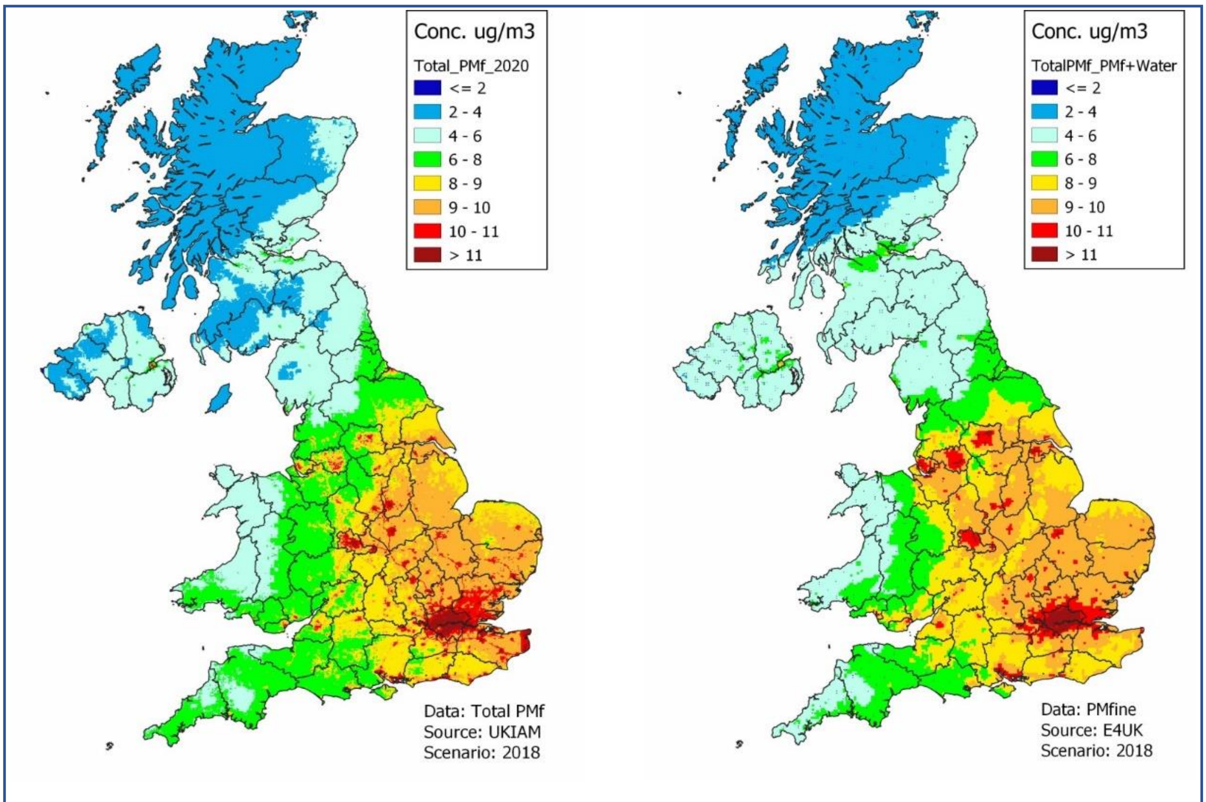
4. Model intercomparisons

In this section, we compare results between the UKIAM model and the EMEP4UK model described in the previous section: and also investigate finer scale variability using modelling for London with the ADMS model.

4.1 Comparison of EMEP4UK and UKIAM

In this section we compare modelling results from the UKIAM model, used for extensive scenario analysis in this study, with those produced from the advanced Eulerian model EMEP4UK, described in the previous section. UKIAM uses fixed annual average meteorology, whereas in the preceding section EMEP4UK has clearly illustrated the effect of interannual variations in meteorology, which are another source of uncertainty in forecasting future concentrations. In the comparisons shown below, the same emission data for equivalent scenarios have been used as far as possible, based on NAEI emissions for the UK, but broken down into the sources differentiated by UKIAM, and by SNAP sector for EMEP4UK. The same emissions have been used for other countries, but there are differences in the shipping emissions, which are represented differently in the 2 models. We compare results for the baseline situation in 2018, and for a future scenario with much lower emissions in 2040.

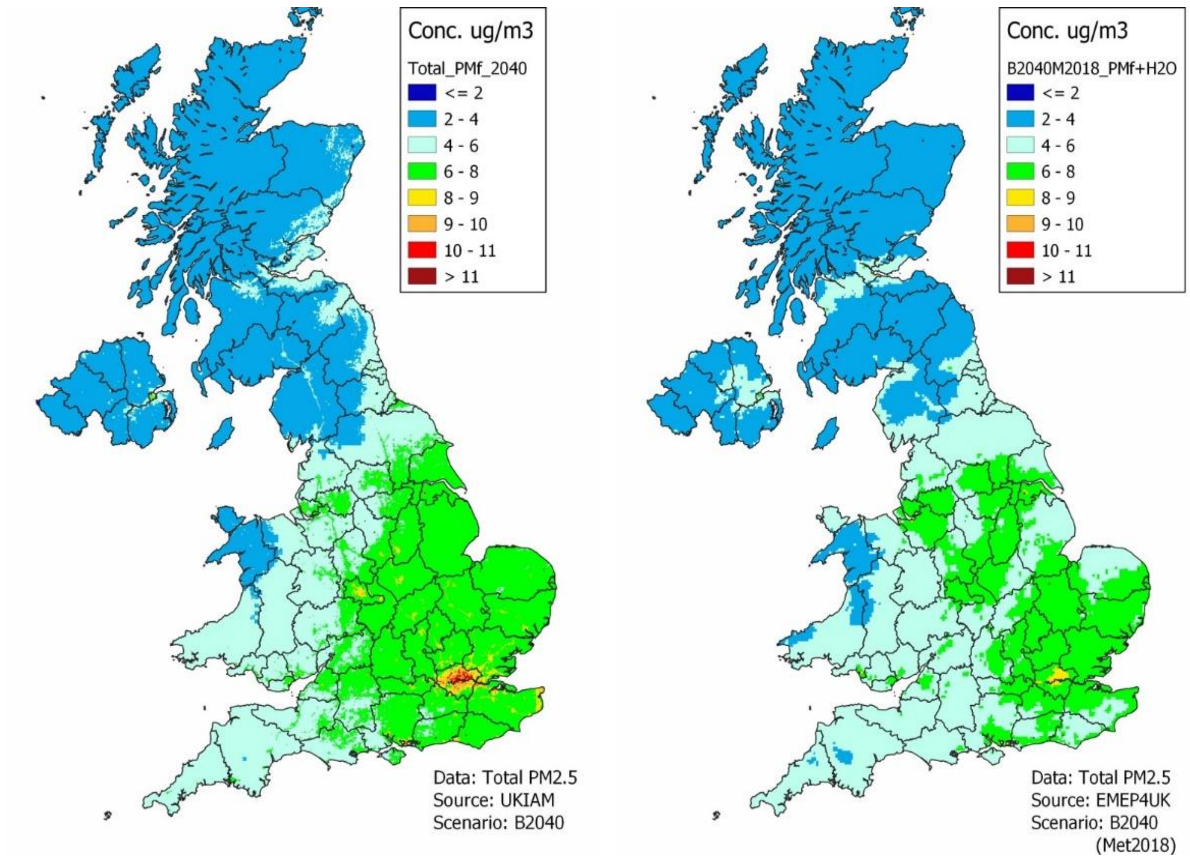


Total $PM_{2.5}$ Concentration UKIAM 2018 *EMEP4UK*

Figure 4.1. Comparison of UKIAM results with EMEP4UK for 2018 emissions.

Figures 4.1 and 4.2 show maps comparing $PM_{2.5}$ concentrations from the 2 models for the baseline scenario in 2018 and 2040 respectively, with EMEP4UK using 2018 meteorology. The first maps for 2018 in Figure 4.1 show very similar concentrations, both corresponding to the same population weighted mean concentration of 9.2 µg m^{-3}, although if 2003 meteorology had been used with EMEP4UK the value would have been almost one µg m^{-3} higher at 10.1 µg m^{-3}.

In Figure 4.2, with an equivalent comparison for 2040 using the same 2018 meteorology, both models show a large improvement. But the EMEP4UK concentrations of total $PM_{2.5}$ are overall a little lower than UKIAM, giving a population weighted mean concentration of 6.2 µg m^{-3} as compared with 6.8 µg m^{-3} from UKIAM. This implies that UKIAM tends to show a smaller improvement than EMEP4UK, which is what might be expected from the simplified, linear approximation plus non-linear adjustment in UKIAM. However, using the more severe 2003 meteorology in EMEP4UK gives higher concentrations equivalent to a population weighted mean concentration of 6.7 µg m^{-3}, almost the same as UKIAM. Hence the difference between UKIAM and EMEP4UK is within the general range of uncertainty due to variations in meteorology.



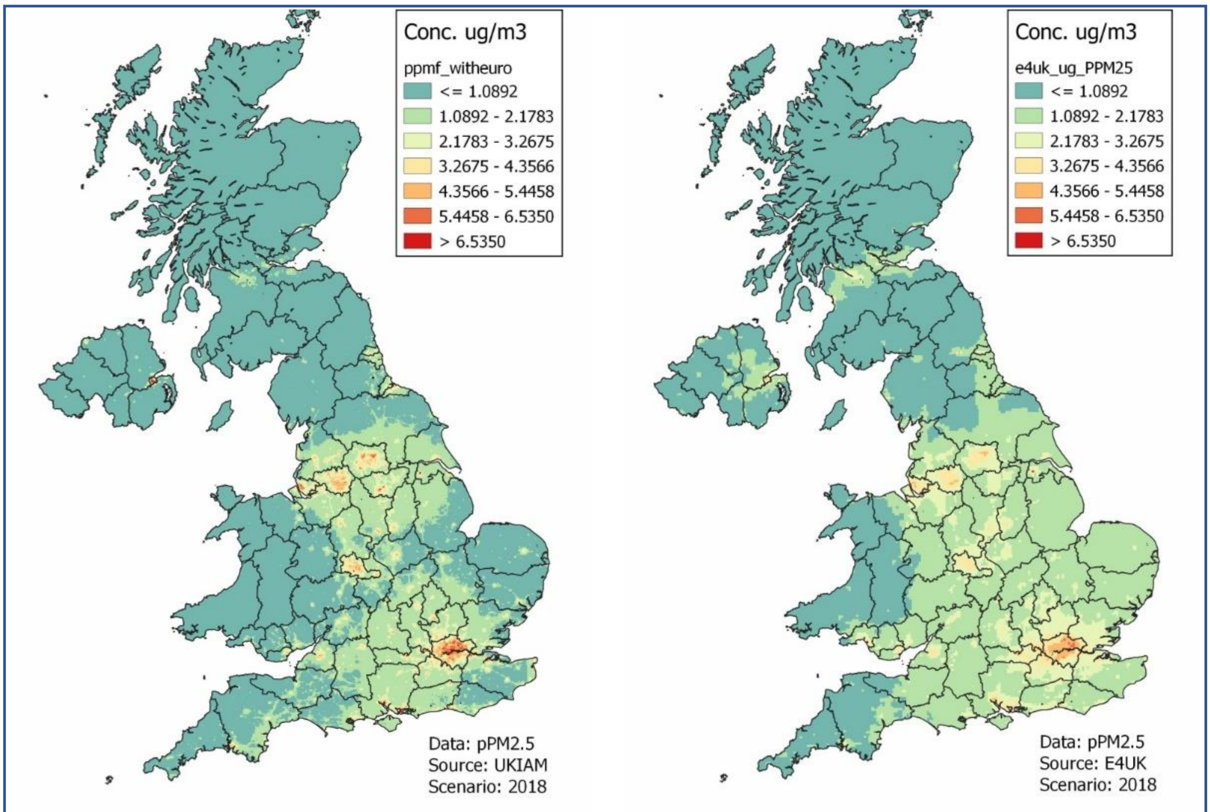
Total $PM_{2.5}$ Concentration UKIAM B2040 ***EMEP4UK***

Figure 4.2. Comparison of UKIAM results with EMEP 4UK for 2040 baseline emissions.

The next question is how the models compare with respect to individual components, in particular the primary $PM_{2.5}$ concentrations and the secondary inorganic aerosol, SIA, as the two components responding to the different emissions and their abatement in the scenarios analysed later. Figure 4.3 shows a comparison of the primary $PM_{2.5}$ concentrations, as modelled by UKIAM and EMEP4UK for 2018, where local emissions and urban areas generate a large spatial variability. These show that UKIAM tends to give slightly higher concentrations in urban areas, and slightly lower values in rural areas- which may be at least partially explained by the finer 1x1 km^2 grid resolution in UKIAM. Table 4.1 gives a comparison of PWMC values showing close agreement, although the higher grid resolution in UKIAM may make more difference in producing some grid cells with concentrated emissions and higher concentrations which could affect estimates of exceedance and PWME.

Table 4.1. Comparison of UKIAM and EMEP4UK for primary $PM_{2.5}$ concentrations in 2018.

PWMC µg m^{-3}	National	London	Urban	Rural
UKIAM	2.8	4.9	3.2	1.5
EMEP4UK	2.7	4.6	2.9	1.9

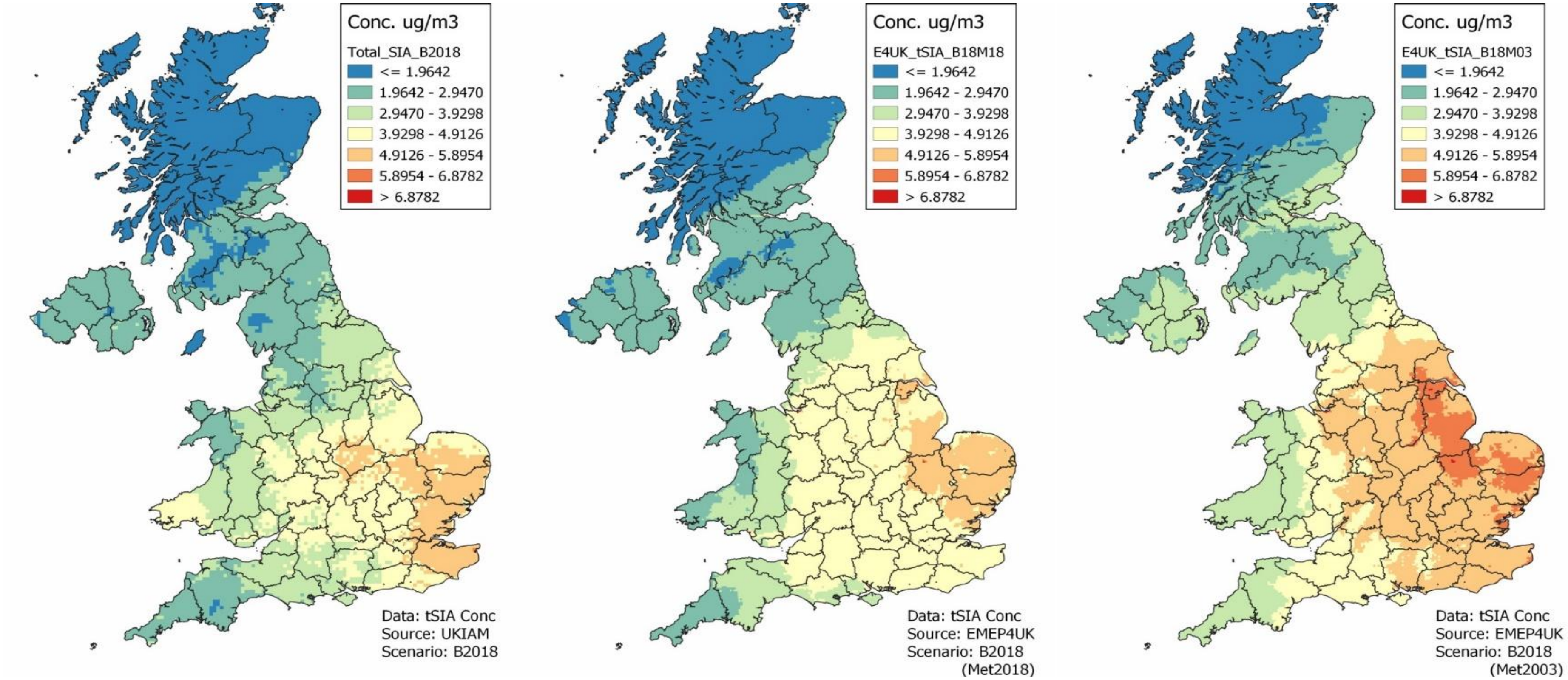


Primary $PM_{2.5}$ Concentration UKIAM ***EMEP4UK***

Figure 4.3. Comparison of UKIAM and EMEP4UK for primary $PM_{2.5}$ concentrations in 2018.

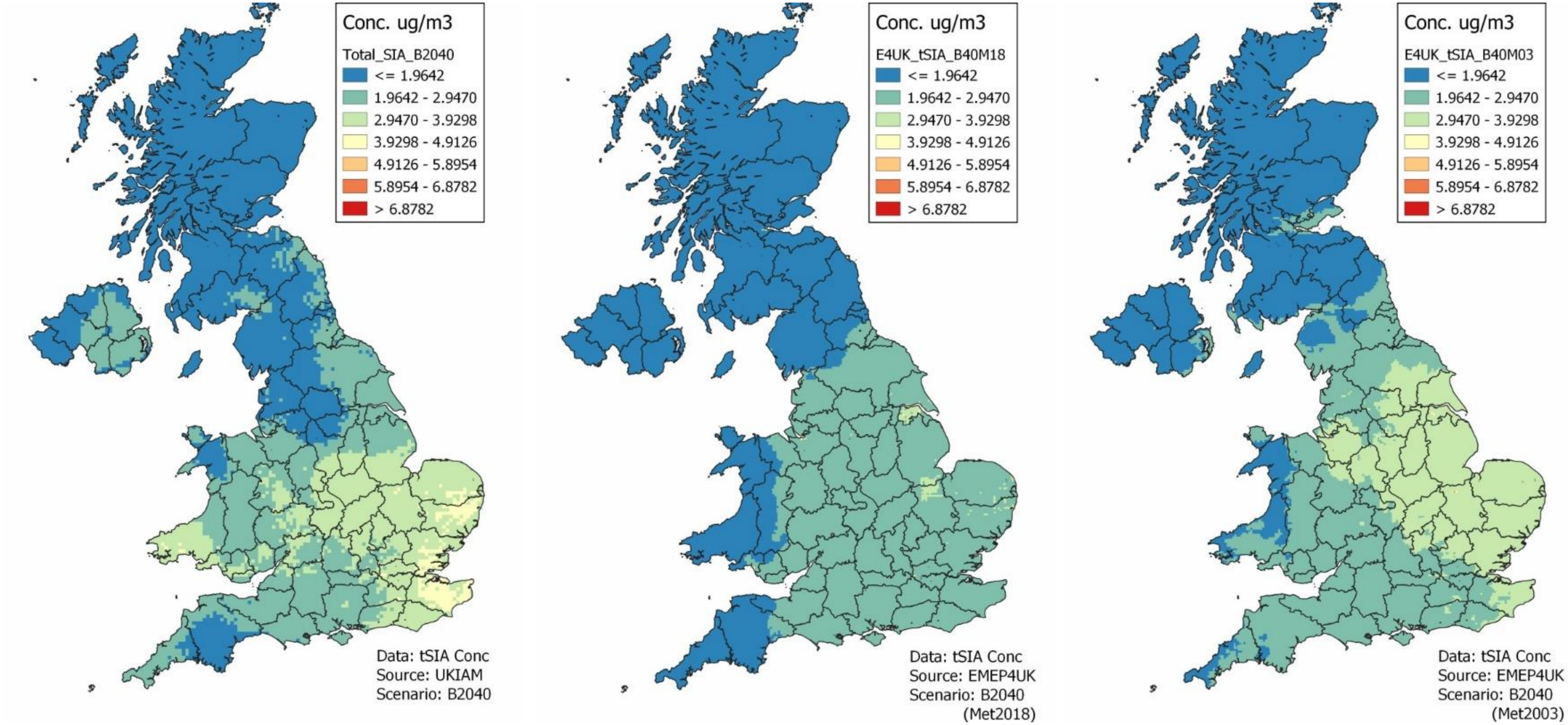
The comparison of modelled SIA concentrations is particularly important because of the complex chemistry, and the simplified linear approach in UKIAM based on source-receptor matrices with a non-linearity adjustment as described in section 2.1. Figures 4.4 and 4.5 provide a comparison of total SIA for the baseline scenario in 2018 and 2040 respectively, with the EMEP4UK concentrations calculated using both the 2018 meteorology and the 2003 meteorology, leading to higher concentrations as discussed in section 3 of this report.

Figure 4.4. Comparison of SIA concentrations: 2018 emissions.



UKIAM (annual ave. met)	*EMEP4UK 2018 met*	*EMEP4UK 2003 met*

Figure 4.5. Comparison of SIA concentrations: 2040 emissions.



UKIAM (annual ave. met)	EMEP4UK 2018 met	EMEP4UK 2003 met

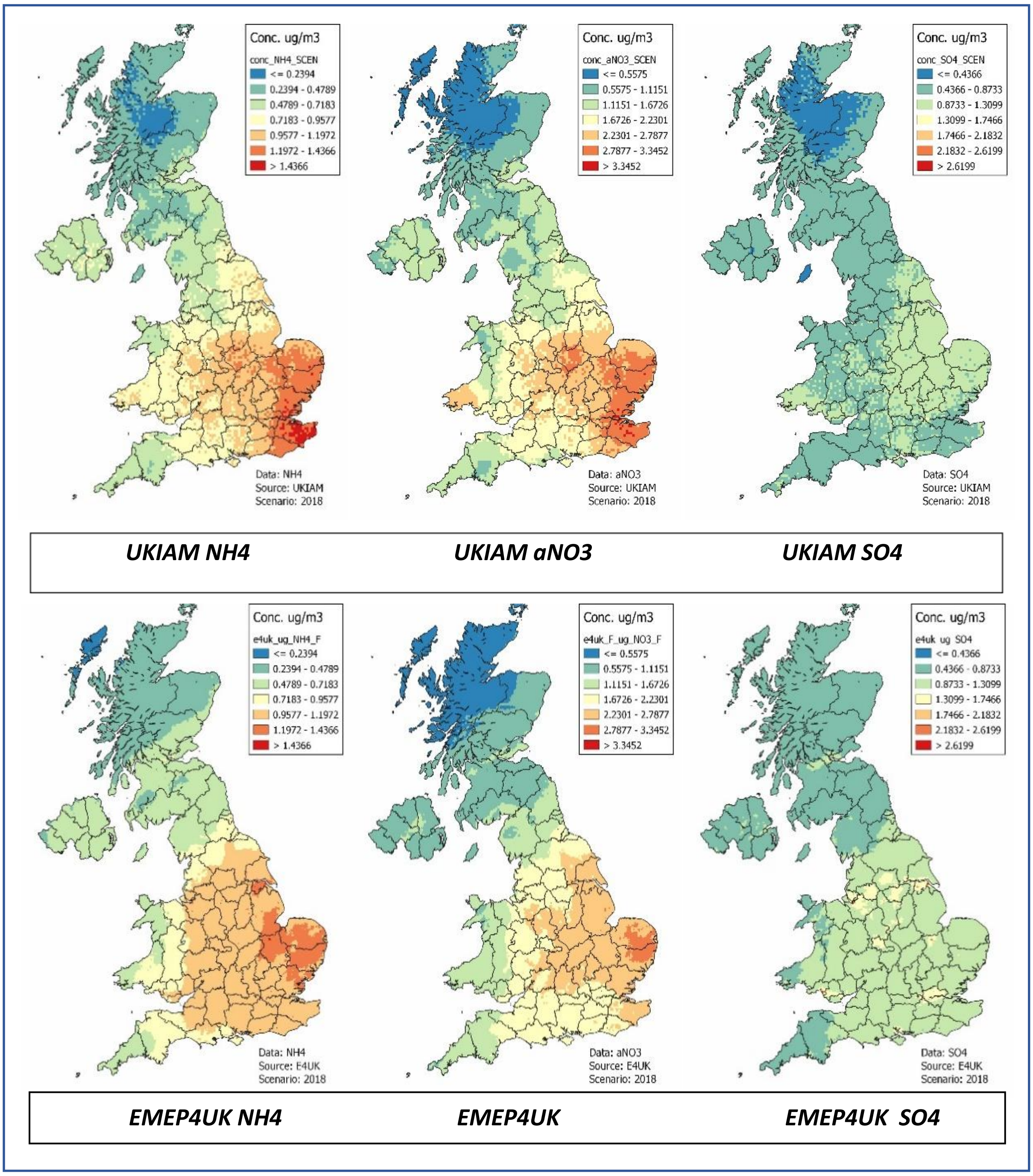


Figure 4.6. Comparison of SIA components for 2018.

The maps show that, in 2018, the UKIAM SIA concentrations are close to the EMEP4UK concentrations using the 2018 meteorology, with a slightly lower population weighted mean concentration of 3.8 µg m^{-3} for UKIAM as compared with 4.1 µg m^{-3} for EMEP4UK. In 2040, when emissions are considerably lower, the UKIAM values have reduced less than with EMEP4UK, and are now closer to the EMEP4UK concentrations calculated for the less favourable meteorology of 2003. This is what was expected with the linear approximation used in UKIAM and no change in the non-linear adjustment. This means that UKIAM errs on the conservative side, but still within the uncertainty range due to interannual variability in meteorology. Figure 4.6 shows comparison of the individual SIA components, NH_4, NO_3 aerosol, and SO_4 (with the EMEP concentrations based on 2018 meteorology).

Further work is planned to compare other components, including SOA - where the calculations of concentrations with EMEP4UK in section 3 show little change in the anthropogenic component. This is consistent with the assumption in UKIAM that SOA remains constant. But there are further questions, such as the role of IVOCs, to be addressed as the scientific understanding advances. Large uncertainties also arise in the contribution of other sources, including natural dusts. These other contributions are important, as together with the water content they add up to between 3 and 4 µg m^{-3} in some areas. They will be increasingly significant when considering the recently revised WHO guideline of 5 µg m^{-3} for annual average $PM_{2.5}$ concentrations.

In this report, overall health impacts are estimated from population exposure, with targets related to the way PWMC values change. Table 4.2 provides a summary of PWMC values calculated with UKIAM and EMEP4UK, also showing the effect of different meteorology in 2018 and 2003. The comparison is encouraging, in that differences between the simplified UKIAM modelling based on annual average meteorology, and the more sophisticated EMEP4UK modelling are generally within the interannual variability suggested by EMEP4UK. However, UKIAM tends to give higher peak concentrations in urban areas, reflecting the finer grid resolution of primary $PM_{2.5}$ contributions.

Table 4.2. Comparison of population weighted mean concentrations

PWMC in µg m^{-3}	National	London	Urban	Rural
2018				
UKIAM	9.2	12.3	9.6	7.8
EMEP4UK (2018 meteorology)	9.2	11.7	9.5	8.1
EMEP4UK (2003 meteorology)	10.1	12.7	10.5	9.0
2040				
UKIAM	6.8	9.4	7.1	5.8
EMEP4UK (2018 meteorology)	6.2	7.9	6.4	5.5
EMEP4UK (2003 meteorology	6.7	8.3	6.9	5.9

4.2 Exploration of spatial variability within a 1x1 km^2 grid using ADMS modelling

UKIAM estimates concentrations at a 1 km resolution and uses these concentrations to derive population exposure; and to suggest possible limit values for maximum concentrations, by calculating population weighted mean exceedance of different threshold values. This is done by multiplying the estimated concentration by the population in each 1 km grid square. This simplistic approach is commonly used and assumes that the ambient concentration at a residential address provides a reasonable estimate of annual average exposure. It therefore does not account for daily periods of elevated exposure, for example while commuting along busy roads, which can only be estimated using a higher resolution model.

A substantial proportion of $PM_{2.5}$ in the air is due to long range transport, for example SIA where precursor emissions can originate hundreds of miles away. However, primary emissions of $PM_{2.5}$ can lead to areas of elevated concentrations or local hotspots which are not captured at 1 km resolution. The location of these hotspots depends on a number of local factors such as the spatial distribution and height of emission sources, and the topography of surrounding streets and buildings. Resolving these small areas of elevated concentrations is therefore very difficult when modelling at national or city-wide scale and requires detailed, high resolution inputs to the model.

Here, we compare the UKIAM concentrations in London with those of a higher resolution model and investigate how representative the UKIAM 1 km resolution concentrations are when compared to a higher resolution map, and to demonstrate the difficulty in estimating population exposure from a small number of fixed monitoring sites.

The higher resolution concentrations used are those generated by Cambridge Environmental Research Consultants (CERC), using their Gaussian plume model ADMS-Urban as part of the Breathe London project, convened by Environmental Defense Fund. ADMS-Urban was used to model the concentrations due to primary emissions originating within Greater London, while values from monitors in areas surrounding London were used to estimate the non-London contribution. The details of the CERC modelling analysis are documented in a report for Breathe London; https://www.globalcleanair.org/files/2021/02/BL-CERC-Final-Report.pdf. The modelling results were provided by the Environmental Defense Fund and an online version of the map with source apportionment is available at https://www.globalcleanair.org/solutions-and-resources/london-pollution-sources-map/.

We have not attempted a direct model comparison, since the CERC modelling uses projections for 2019 based on an earlier version of the LAEI (LAEI2013), and differences would be greatly dependent on the different emissions used. Instead, we have used the very high 10x10 m^2 grid resolution to investigate small-scale variability within 1x1 km^2 grid squares. Because ADMS-Urban is able to estimate concentrations at 10 m resolution, it can resolve the elevated concentrations along roads and railways. However, it is important to note that other than road and rail emissions and a number of major point sources, all other LAEI emissions used have a 1x1 km^2 resolution. The effective resolution of the concentrations for the majority of sources is therefore 1x1 km^2, with higher resolution concentrations from a smaller number of sources superimposed. This is a limitation, not of the model, but of the available emissions data. Nonetheless the ADMS-Urban model represents the highest resolution map currently feasible for London. Figure 4.7 shows ADMS modelling of $PM_{2.5}$ at 10 m resolution, compared with these concentrations averaged over a 1x1 km^2 grid.

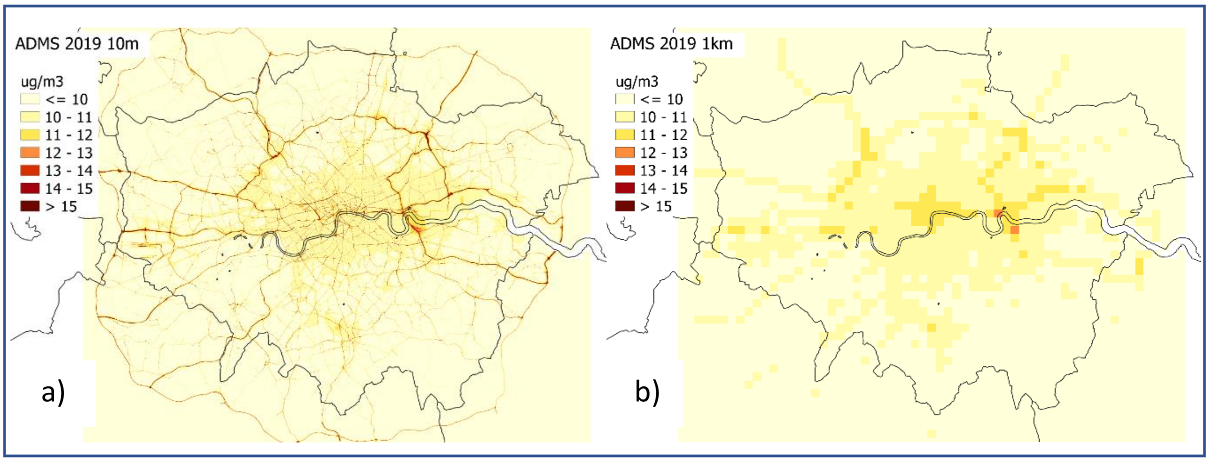


Figure 4.7. a) 2019 $PM_{2.5}$ concentrations at 10m resolution as estimated by CERC using ADMS-Urban, and b) averaged over 1x1 km grid-squares.

We can now use the ADMS-Urban map to investigate how representative 1x1 km^2 mean concentrations are of higher resolution concentrations. Figure 4.8 shows the maximum and the standard deviation of the 10 m concentrations within each 1 km grid square, as a proportion of the 1 km mean. The 10 m concentrations can reach up to 3-4 times the mean 1x1 km^2 concentration: however, these grid squares are mainly those which include main arterial roads. For example, the north circular is clearly visible. A similar picture is seen for the normalised standard deviation, for which the main roads into London are clearly visible. In grid squares which do not contain these arterial roads, the normalised standard deviation is typically within 10% of the mean, however the true variation in concentrations about the mean will be higher as many of the modelled emissions are at 1 km resolution. Other major sources such as domestic and commercial combustion are highly granular point sources and are therefore likely to lead to local hotspots and divergence from the 1x1 km^2 mean.

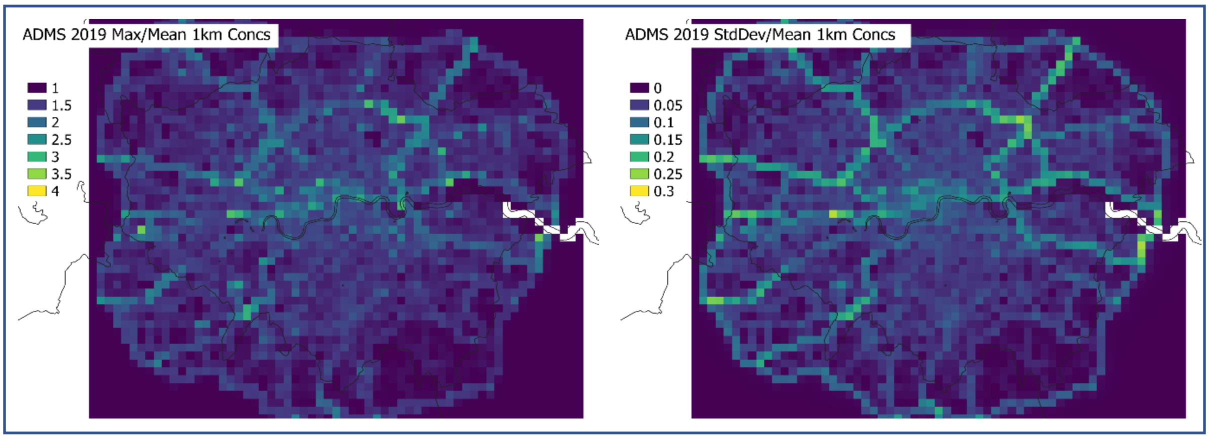


Figure 4.8. The maximum and standard deviation of 10 m concentrations within each 1 km grid square normalised by the 1 km mean.

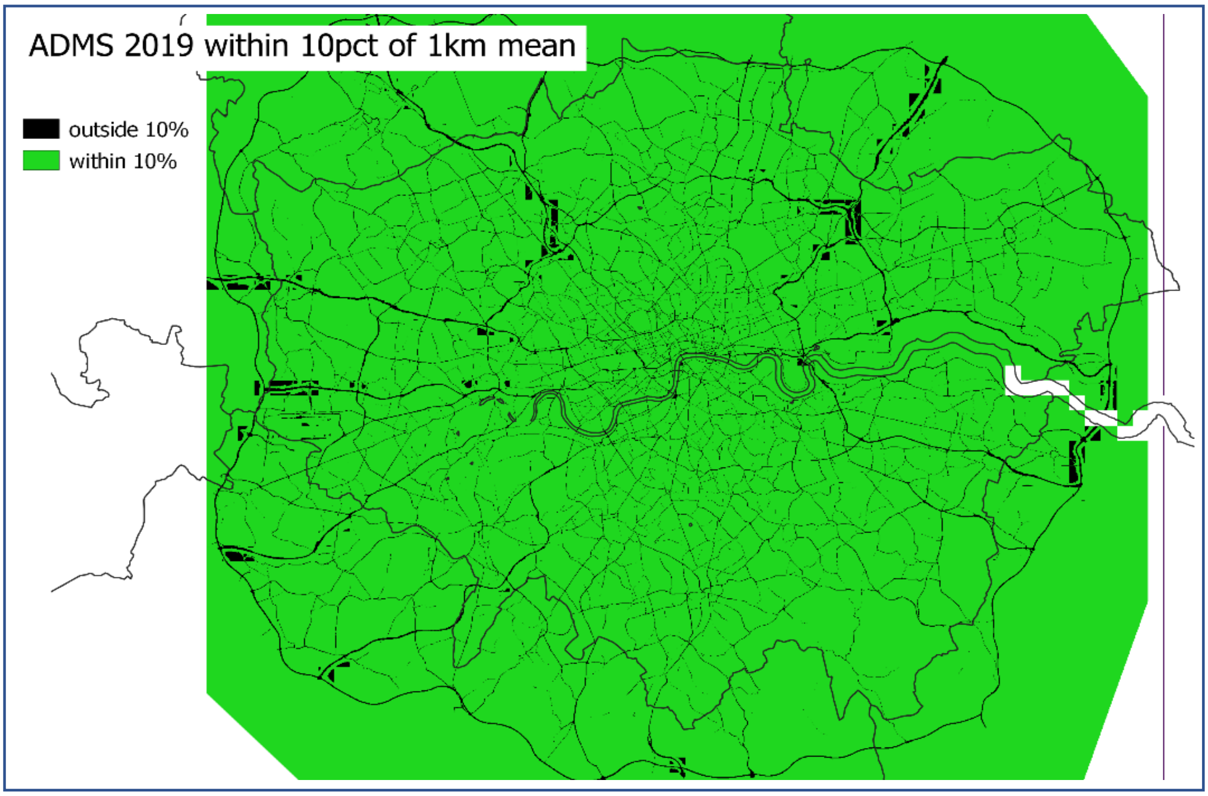


Figure 4.9. 10 m resolution concentrations within 10% of the 1 km mean.

Figure 4.9 shows the area for which the 10 m resolution concentration is within 10% of the 1 km mean. The vast majority of London is within the 10% range, with only the major roads outside of this limit. For grid squares which contain major junctions or particularly busy arterial roads, large proportions of the grid square can lie outside of this limit. This is due to the elevation of the 1 km mean by the higher concentrations along the road, leading to a mean value greater than the surrounding area away from the road. This demonstrates that when higher resolution emissions are used, in this case the roads and railways, the concentrations within the grid square can vary significantly from the 1 km mean value. Despite this, Figure 4.9 shows that the inclusion of roads and railways at higher resolution does not lead to a significant change in the estimated background concentrations away from these sources when compared to the 1 km average. This therefore suggests that a 1 km resolution model provides close to the best estimates (within 10%) of concentrations currently possible for London for background concentrations, which are used for the population exposure calculations.

Figure 4.10 shows the area within 10% of the concentration at the AURN monitor value within each borough. As only 5 AURN sites exist, this calculation is done for 5 boroughs only, with the remainder of London showing the 10x10 m^2 concentrations. On the left is the area of each borough within 10% of the modelled value at the measurement site. Here we see that the vast majority of each borough is well represented by the modelled value. On the right is the area of each borough within 10% of the measured value for 2019. In this case, only two of the boroughs are well represented by the measured value, with the borough in the south west almost entirely outside of the 10% limit.

This highlights the difficulty in comparing population exposures estimated from measured values with those from modelled concentrations. Yet, this also suggests that, provided that measurement sites are carefully chosen and at a sufficiently high density, a reasonable estimate of exposure can be derived from measurement values. However, the right-hand side map also shows that in the case that the measured value does not reflect concentrations elsewhere in the borough, for example if placed near a local source of $PM_{2.5}$, it is easy to derive an inaccurate estimate of the borough-level exposure. For example, the roadside concentrations often reach up to a factor of three greater than the background. Further, as shown in section 2.5, estimating exceedances using fixed measurement sites is a much greater challenge than estimating exposures.

For the purposes of this report, this analysis supports the use of a 1 km resolution model to estimate the population exposure in London using the simplistic approach of multiplying the average concentration by the population density in each 1x1 km grid square. However, this approach does not capture the variation in daily exposure, for example the elevated exposure while travelling along busy roads which can be captured by the higher resolution ADMS-Urban model. It is also important to note that while the ADMS model resolution is at 10 m, major sources such as domestic and commercial combustion were modelled using 1 km resolution emissions and therefore the full variability of concentrations within each 1 km grid square is not captured. Such variability is important in the context of setting limit values for $PM_{2.5}$ in the Environment Act, and in characterising measurement sites to be used in assessing future progress in meeting the targets set.

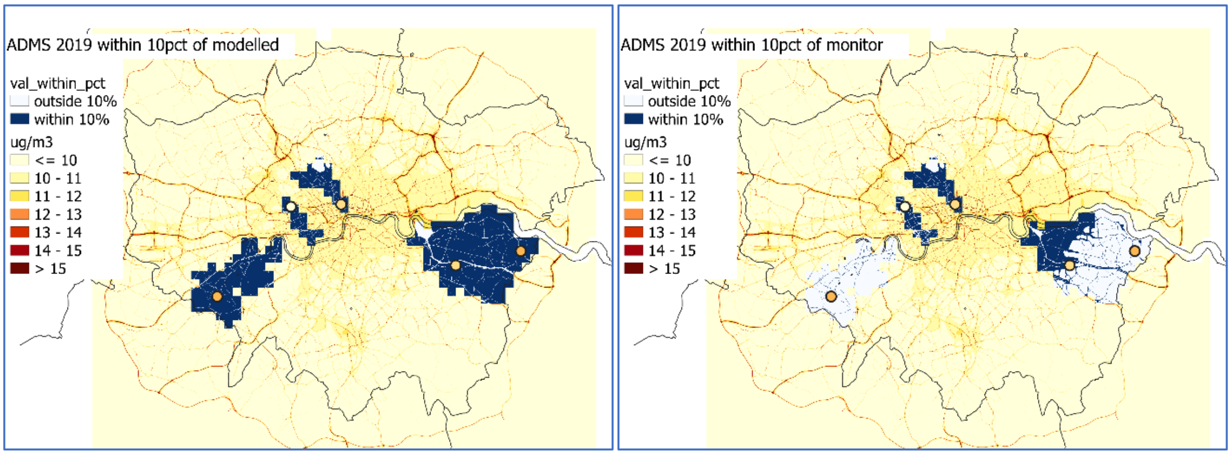


Figure 4.10. 10 m resolution concentrations within 10% of the modelled and measured values at the AURN background monitor sites (5 sites). Concentrations are shown for boroughs without an AURN site.

Analysis of abatement options to reduce $PM_{2.5}$ concentrations

Part 2: Scenario analysis

In this part of the report, we describe analysis of scenarios using UKIAM. There are three sections, the first of which is an investigation of contributions from individual sectors. The second part describes analysis of a range of different scenarios with different levels of ambition up to 2050, applied to the whole country but with emphasis on effects in England. This is followed by a focus on London, where $PM_{2.5}$ concentrations are highest.

5. Sectoral studies

To complement the analysis of a wide range of scenarios between 2018 and 2050, reflecting different levels of ambition and interaction with climate scenarios for greenhouse gas reduction, we have undertaken independent studies of individual sectors. The aim has been to explore the potential contribution to reducing $PM_{2.5}$ exposure, and the combined effect of air quality and climate measures. This has focused on the most important sectors, namely road transport, domestic combustion, agriculture, and a combined look at energy and industrial combustion. The contribution of these sectors to the overall emissions is given in the previous section in Figure 2.2.

5.1 <u>The road transport sector and electrification of the fleet</u>

The focus of this section is to explore future scenarios for electrification of the vehicle fleet; and illustrate the effect on air quality of electrification in line with DfT-proposed plans banning the sale of ICE cars and LDVs, by comparison with a baseline scenario without electrification. Before describing the scenarios, we provide a description of the BRUTAL model within UKIAM for simulation of the road-transport sector.

Modelling of the road transport sector in UKIAM is undertaken with the BRUTAL sub-model, which derives emissions in a bottom-up approach across the UK road network, distinguishing motorways, major roads and other secondary roads in both urban and rural areas with different characteristic average vehicle speeds. The emissions per km on each road depend on the traffic flows and vehicle mix, taking account of the age profile of each vehicle type, and the corresponding speed-dependent emission factors as defined by the COPERT model used in the NAEI 2018 inventory. The COPERT emission factors are parameterised in a sub-model iMOVE, used as input to BRUTAL. Also included are cold-start emissions and allowance for catalyst failure. Total emissions from this bottom-up approach for each vehicle category, together with km driven, have been checked against NAEI national estimates using a top-down approach also based on COPERT, and are closely aligned. Accumulated emissions in each 1x1 km grid square are used to calculate the contribution from road traffic to NO_x and primary $PM_{2.5}$ concentrations in each grid-square, and to derive NO_2 concentrations from NO_x

concentrations. This is based on the proportion of NO_x emissions as primary NO_2 and semi-empirical relationships varying from rural areas to dense urban areas as derived from population density (Oxley et al., 2009).

In addition to exhaust emissions, it is also necessary to calculate non-exhaust emissions, which for primary $PM_{2.5}$ become increasingly important relative to exhaust emissions. This is an important factor when considering electric vehicles, for which 'zero emission' only applies to the exhaust contribution. Non-exhaust emissions are based on Tier 2 emission factors from the EEA guidebook (EMEP/EEA 2019) including contributions from brakes, tyre wear and road abrasion. Unfortunately, these non-exhaust emissions are subject to large uncertainties (e.g. AQEG 2019, OECD 2020), including possible differences for electric vehicles as explored below.

It is not the purpose of UKIAM to calculate concentrations across the road network as is done in the PCM model; however to give an indication of road-side enhancement emission data is retained for the busiest road of each type in each grid-square. These data are used to estimate a potential contribution in each grid square of the selected roads to enhanced concentrations at the road-side relative to the background, with approximate allowance for street canyon effects according to urban density, again based on population density to characterise the street characteristics.

Future scenarios modelled

To explore the effect of electrification we start off with a scenario based on ICE vehicles with little electrification, whilst considering the effect of recent improvements in diesel vehicles following the introduction of real-world emissions testing. We then compare with scenarios for electrification, corresponding to future vehicle sales data and uptake of electric vehicles as defined up to 2050 by the Department for Transport, and matching the current plans in the recent DfT report (Department for Transport 2021). The major emphasis is on $PM_{2.5}$ as the theme of this report, but we also take account of co-benefits in reducing NO_x and NO_2 concentrations which are also important for human health. With respect to primary $PM_{2.5}$ emissions, electric vehicles are not "zero emission" as they still have non-exhaust emissions, which have become increasingly dominant as exhaust emissions for ICE vehicles have been controlled. There are large uncertainties in these non-exhaust emissions and how they may differ for electric vehicles, which we have addressed with sensitivity studies.

Having compared the scenarios with respect to the direct effects of traffic on human exposure and related health impacts, we also consider the indirect effects of fleet electrification on the electricity demand for charging, and the reduced demand for petrol and diesel fuels.

Baseline scenario

The investigation in this section is focused on electrification of the fleet, which is only included to a minimal extent in the baseline scenario derived from 2018 NAEI projections. In this comparison, the base-case considered as the starting point differs from more recent projections in that it does not assume any switching from diesel to petrol in the purchase mix of new vehicles in the period up to 2030. In this context, before exploring how the replacement of ICE vehicles with electric vehicles affects emissions of air quality pollutants, it is important to recognise the improvements in the ICE fleet - in particular the reduction in diesel car emissions of NO_x following the adoption of real-world emissions testing, which affects the projected emissions of NO_x from traffic. This has led to a big improvement in emissions from new diesel cars not yet represented in NAEI emissions, but reflected in COPERT modelling by a 75% reduction in NO_x emissions in post RDE Euro 6d diesel cars (COPERT2021; Emissions Analytics). This results in emissions from new diesel cars being comparable with those from petrol cars, so that irrespective of any switching from diesel to petrol cars there is already a substantial reduction in NO_x by 2030. It is estimated that in the absence of electrification this would reduce NO_x emissions by approximately 23 kt in 2030. It has also been noted that similar improvements are expected in diesel LGVs, which could lead to an additional reduction of up to 12 kt of NO_x in 2030 from road transport, but this has not been included yet in official COPERT estimates. Thus, irrespective of electrification, a substantial reduction in NO_x emissions would be expected by 2030, even without any substitution of new petrol cars instead of new diesel cars.

Electrification scenarios

Scenarios for electrification have been based on DfT projections for km driven and their data for vehicle sales for the UK road transport fleet up to 2050. The main scenario introduces a ban on new internal combustion engine cars and vans (ICE) vehicles in 2030 except for plug in hybrids which are still allowed until 2035. Also introduced are changes for new HGVs from 2040 and for new buses from 2035. As a sensitivity study we also considered a second scenario which delays a ban on ICE vehicles until 2035, and delays changes for buses and HGVs until 2040 and 2045, respectively. The main scenario is in line with current plans as published in the recent DfT report (DfT2021); and has been used as the reference scenario for electrification in this assessment. The second scenario illustrates the effect of delays to electrification yet, apart from a smaller reduction in CO_2 emissions, was found to give only small differences from the reference scenario with respect to air quality, and hence is not the focus here. More details of the way the projected sales data have been used to model evolution of the fleet composition, based on work by Daniel Mehlig as a NERC/DfT funded PhD student, are given in the addendum to this section.

Sensitivity studies have also been undertaken to investigate some of the assumptions, such as projections of kilometres driven and uncertainties in non-exhaust emissions.

Estimated emissions

The clearest effect of vehicle electrification is on NO_x emissions, where Figure 5.1 compares the emissions arising from the scenarios described above up to the year 2030. This is the year most sensitive to the timing of a ban on ICE vehicles.

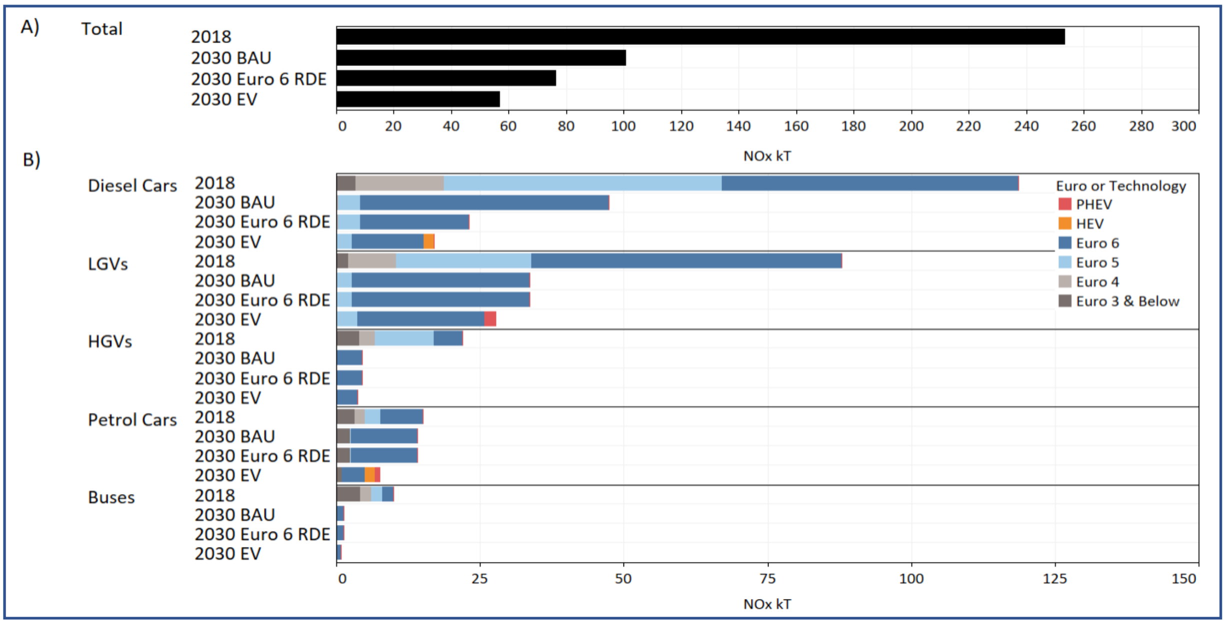


Figure 5.1. Estimated NOx emissions A) Total fleet emissions of NOx for each scenario in 2030. B) NOx emissions given by vehicle type, where colour shows the emissions from each euro standard or fuel type.

The importance of diesel emissions of NO_x from cars and vans in the current fleet is obvious, but there are large improvements by 2030 with the retirement of older Euro 3 to Euro 5 vehicles, and replacement with Euro 6 in the baseline scenario. This is improved further when allowance is made for reduced emissions for new post RDE Euro 6 diesel cars as in the B2030 adjusted scenario. Although not included here, this is likely to apply to diesel LGVs also. Super-imposing the effect of the switch to electric cars up to 2030 gives relatively modest additional reductions, and it is clear that emissions in 2030 will still be dependent on the improvements in emissions from conventional ICE vehicles.

Despite the improvements in emissions by 2030, which should ensure compliance with current limit values of 40 µg m^{-3} for NO_2, there may still be elevated concentrations for short periods at localised hot-spots. In this context, it should be borne in mind that short term exposure can be important for health effects such as asthma, emphasized for example by the Coroner's report on the death of Ella Adoo Kissi-Debrah, which indicated exposure to excessive air pollution as a material contribution to her death (coroner's report 2021). Also, the WHO guideline for annual average NO_2 concentrations has recently been revised downwards from 40 µg m^{-3} to a much lower value of 10 µg m^{-3}, indicating potential effects at lower concentrations.

The corresponding comparison for direct $PM_{2.5}$ emissions is given in Figure 5.2. Here there is a far smaller reduction in emissions. This is due to the increasingly large contribution from non-exhaust emissions relative to exhaust emissions of $PM_{2.5}$, as the latter have become increasingly controlled. In these calculations, non-exhaust emissions from electric vehicles have been assumed to be the same as from the corresponding ICE vehicles, and this important assumption is discussed further below.

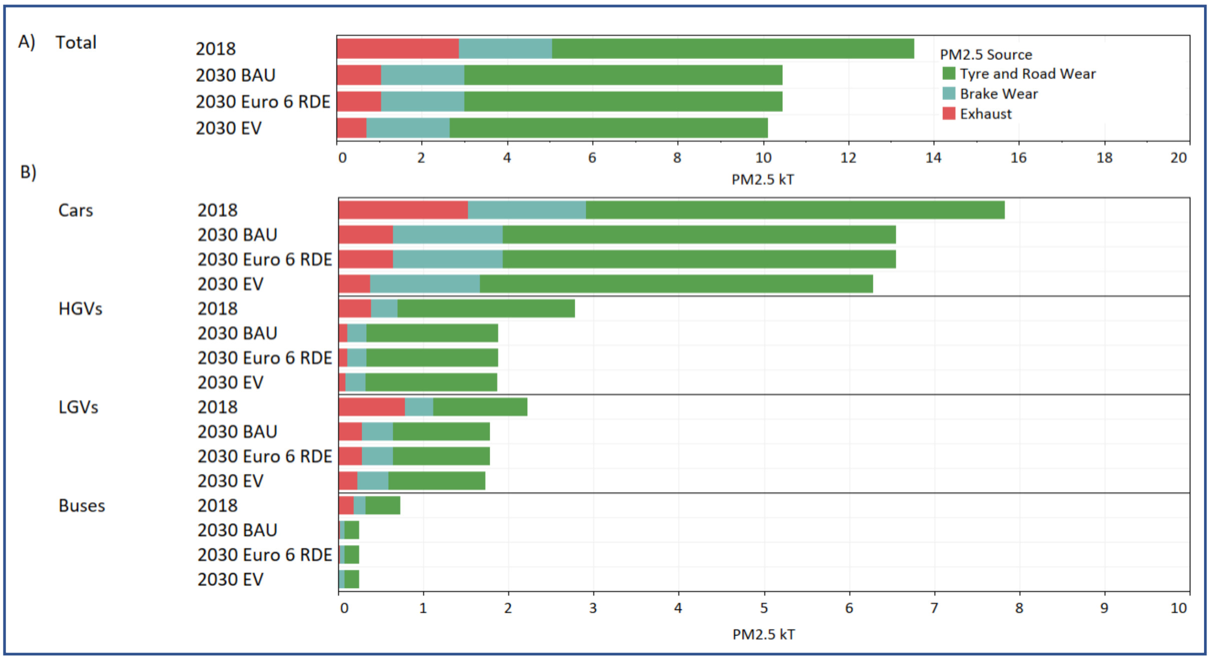


Figure 5.2. Estimated $PM_{2.5}$ emissions A) Total fleet emissions of PM2.5 for each scenario in 2030. B) $PM_{2.5}$ emissions given by vehicle type, where colour shows the emission source: tyre and road wear (categorised together in BRUTAL), brake wear, and exhaust.

Looking further ahead, and assuming the reference electrification scenario, Figure 5.3 shows the longer-term reduction in total NO_x and $PM_{2.5}$ emissions from road transport up to 2050. Here, the effect of electrification on NO_x is very much greater by 2040, when a larger proportion of the fleet has converted, and is effectively zero by 2050, eliminating any remaining traffic contribution to health impacts from NO_2. It is not only the overall reduction in NO_x emissions that is important, but also the spatial change. In this context, emissions from modern ICE vehicles are subject to large transient peaks in emissions with acceleration and changes in engine loading. Electric vehicles will be particularly beneficial at hot-spots of high concentration such as at road junctions, or in congested stop-start flows. Another important benefit is the elimination of cold-start emissions, which can be particularly important in urban areas where a large proportion of trips are short - such as the school-run. A further consideration is that changes in the fleet will not be uniform across the country. For example, new bus replacements in London may result in older buses being transferred to other towns and rural areas.

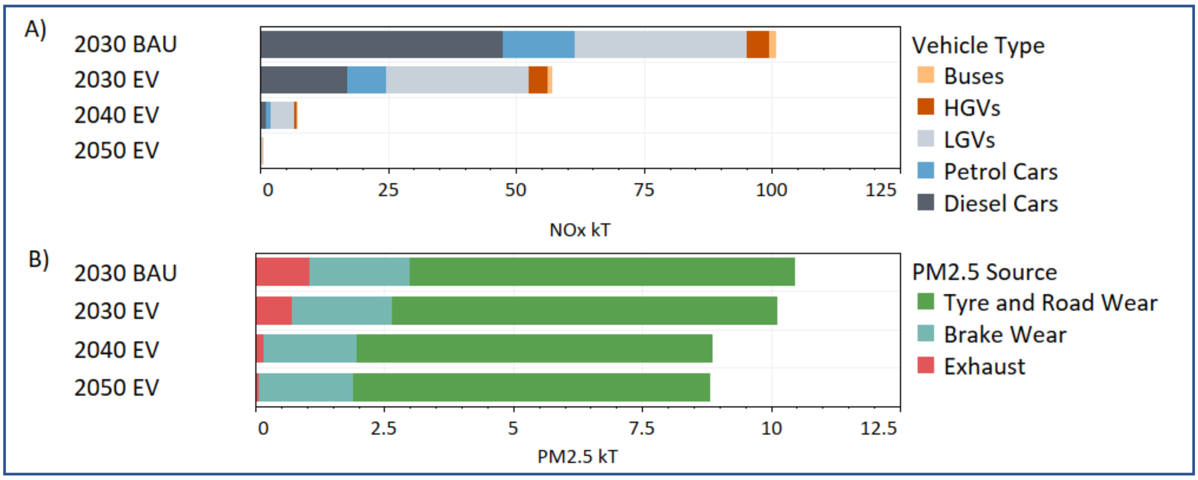


Figure 5.3. Projected emissions from road transport to 2050 for EV scenario. . A) Emissions of NOx, where colour shows the emissions from each vehicle type. B) $PM_{2.5}$ Emissions where colour shows the emission source.

In contrast to NO_x, the electrification of the fleet has a small effect on $PM_{2.5}$ emissions because of the dominance of non-exhaust emissions, as shown in Figure 5.3b. However, this is assuming that electric vehicles will have the same non-exhaust emissions as ICE vehicles.

Unfortunately, there are very large uncertainties in non-exhaust emissions (AQEG 2019) where we have included tyre, brake and road abrasion, but there is also additional resuspension of road dusts. However, there are factors which may systematically increase or decrease the emissions from an electric vehicle relative to a conventional ICE vehicle – see, for example, Beddows and Harrison (2021). First the weight of an electric vehicle is affected by the battery, with increases suggested of up to 25% in overall weight for cars, which we have used for a sensitivity study. We assume a linear increase in emissions from brakes, tyres and road-abrasion. This is simpler but similar to Harrison's plotted variation with weight, and has been applied to all electric cars, LGVs and motorcycles in 2030; resulting in a 9% increase in overall $PM_{2.5}$ emissions from road transport in 2030. Against this, it is also noted that diesel cars have increased in weight with a greater uptake of heavier SUVs; and steps are being taken to reduce the weight of EVs in the vehicle design as well as design smaller cars.

Another factor is regenerative braking, whereby kinetic energy is transferred back to the battery in electric vehicles, and which has been considered to give reductions in brake emissions compared with standard friction braking systems of up to 90% in some circumstances. As a sensitivity study for more general driving conditions, we have assumed a 75% reduction acting on the contribution from brakes for electric cars and LGVs, giving a reduction in overall $PM_{2.5}$ emissions from brakes of 35% in 2030 and a 7% reduction in total $PM_{2.5}$ emissions from road transport. Both these sensitivity studies for increased weight and regenerative braking are well within the range of uncertainty in non-exhaust emissions and will tend to counteract each other.

A different consideration is the km driven, which have been based on DfT reference projections for the electric vehicle scenario in the analysis above, but where cheaper running costs for electric vehicles could encourage more car use. A sensitivity study to a scenario with higher car use provided by DfT, which could be a possible consequence of cheaper running costs for electric vehicles, suggested a modest effect on emissions and concentrations by 2030. However, by 2050, including substantially increased use of LGVs, the higher mileage scenario implies a potential overall increase in emissions of the order of 10% to 15%.

However, there are large uncertainties in such projections to 2050: depending on potential behavioural change and the influence of any future policies such as road charging. Independently of electrification of road transport, improvement of air quality will depend on not only avoiding increased vehicle use and associated problems of congestion, but on overall reduction of traffic especially in urban areas. A key factor here is the replacement of short trips in cars by walking and cycling or public transport. The recent DfT report sets the aim of having half of all journeys in towns and cities being cycled or walked by 2030 (DfT 2021). This is particularly relevant for London and large cities, and is considered in more detail in a later section of this report addressing reduction of $PM_{2.5}$ concentrations in London.

Effects of electrification of road transport on exposure and human health

The effects on human health are related to changes in exposure of the population to $PM_{2.5}$ and NO_2. This is described in more detail in a later section of this report based on advice from COMEAP. However, to put the effects of electrification of road transport in perspective, the monetised value of reducing annual exposure to $PM_{2.5}$ by 1 µg m^{-3} is estimated to be approximately £62.8 (range £16.9 to £178) per person. Thus, reducing the mean exposure of the whole UK population (around 66 million people) by 1 µg m^{-3} gives an annualised benefit of around £4.1 billion (£1.1billion to £11.8 billion).

The additional benefit of reducing NO_2 by 1 µg m^{-3} is estimated to be around £7.0 (range £0.5 to £27.6) per person, with larger uncertainties due to the difficulties of distinguishing the role of NO_x when mixed with other pollutants, notably $PM_{2.5}$. Here, NO_2 is only part of the total NO_x depending on local chemistry, and will depend on the total mix of pollutant sources, not just the road transport. To give an indicative estimate of the benefits of NO_x reduction, within this section without using the full UKIAM model, we have assumed that the NO_2 reduction is approximately 70% of the change in total NO_x, as a rough estimate for moderate to low annual average NO_x concentrations. This implies that reducing mean exposure of the UK population of 66 million by 1 µg m^{-3} of NO_x gives an annualised benefit of around £320 million (£23 million to £1,280 million).

To indicate the benefits of electrification of the fleet, these monetised values can be applied to the changes in exposure with electrification of the fleet relative to the 2030 baseline. To help in comparing different areas of the UK, we have calculated population weighted mean concentration, PWMC, by integrating the calculated concentrations weighted by the population over each area and then dividing by the total population of the area. Changes in PWMC for $PM_{2.5}$ reflect both changes in secondary inorganic aerosol, SIA, which will be affected by changes in NO_x; and in changes in primary $PM_{2.5}$, which are more important in populated urban regions. Based on applying the UKIAM model, Table 3.1 shows the change in $PM_{2.5}$ and NO_x concentrations relative to the adjusted 2030 baseline in which we have included the reduced NO_x emissions from new diesel cars. These changes reflect only changes in road transport emissions. Table 5.1 gives the breakdown between primary $PM_{2.5}$ and SIA as well as the total change in $PM_{2.5}$. The changes in primary $PM_{2.5}$ show that the small benefits of eliminating the exhaust emissions are counteracted by growth in the fleet giving additional non-exhaust emissions. It is also clear that the effect of reducing NO_x emissions is responsible for bigger changes in $PM_{2.5}$ by reducing SIA, than the changes in primary $PM_{2.5}$.

Table 5.1. Changes in population weighted mean concentration due to EV scenario.

	Year	National	Urban	Rural	London	England
$PPM_{2.5}$						
	2030	0.011	0.012	0.006	0.015	0.011
	2040	0.012	0.011	0.012	-0.047	0.011
	2050	0.009	0.008	0.013	-0.072	0.008
SIA						
	2030	0.032	0.034	0.025	0.052	0.036
	2040	0.098	0.104	0.079	0.148	0.109
	2050	0.109	0.115	0.088	0.163	0.121
$PM_{2.5}$						
	2030	0.043	0.046	0.032	0.067	0.047
	2040	0.110	0.115	0.091	0.102	0.121
	2050	0.118	0.123	0.100	0.090	0.129
NO_x						
	2030	0.786	0.898	0.399	1.653	0.865
	2040	2.311	2.619	1.244	4.197	2.532
	2050	2.514	2.846	1.365	4.499	2.756

The small increase in the contribution of $PPM_{2.5}$ in London is due to a small difference in the km driven in the DfT projections to 2050 as compared with the baseline in the NAEI. This is negligible compared with the uncertainty and the discussion above concerning the potential increase in km driven if costs per km driven are lower for EVs.

The changes in overall $PM_{2.5}$ in 2030 are modest, especially compared with a major overall reduction in national mean exposure relative to 2018 of around 2 µg m^{-3} for the base case without electrification. For comparison purposes the estimated national monetised benefit from electrification in 2030 due to overall reduction in $PM_{2.5}$ is around £180 (£50 to £500) million. The reduction increases by 2040, implying an annualised benefit of around £450 (£120 to £1300) million and £480 (£130 to £1400) million in 2050. The ranges given do not allow for the uncertainties in non-exhaust emissions which have been kept constant when changing from ICE vehicles to EVs in this analysis. The slightly different pattern in London reflects the higher importance of the primary $PM_{2.5}$ relative to SIA.

For NO_x, the changes in 2030 are again modest, with most of the improvement in NO_x emissions from road transport already achieved by cleaner diesel cars with post RDE testing. In 2030, the implied annualised national benefit is of the order of £250 (£20 to £1000) million due to reducing NO_2 with the removal of NO_x from EV emissions. As electrification penetrates the fleet by 2050 this rises to around £800 (£60 to £3200) million. This benefit from reducing

NO_2 is potentially more than from the reduction of $PM_{2.5}$, although with a wider range of uncertainty in ascribing monetary costs to NO_2 in a mix of pollutants.

These monetary benefits may seem large, but they are modest compared with potential changes in other sectors unless complemented by substantial reductions in vehicle use; and much larger reductions in $PM_{2.5}$ are needed in order to remove exceedance of 10 µg m^{-3}. Overall, it is the reduction in NO_x emissions that accounts for both the improvement in $PM_{2.5}$ exposure through reducing SIA as well as NO_2.

Indirect effects of electrification of road transport on other sources

In addition to the direct effects of electrification of road transport on air quality and health, there are also effects on other sources and sectors, and major benefits for CO_2 emissions. The decrease in petrol and diesel consumption by vehicles based on modelling studies is illustrated in Figure 5.4 below. A reduction in emissions will also be seen from its production by refineries. However, there is a corresponding increase in demand for electricity production, the carbon intensity of which will depend on the evolving UK energy mix. It is interesting to note that, with the assumptions made in this modelling, electricity peaks in 2047 as vehicle efficiencies improve faster than vehicle kilometres increase. The small residual petrol consumption in 2050 is largely from the motorcycle fleet, which in the DfT scenarios is only partially electrified.

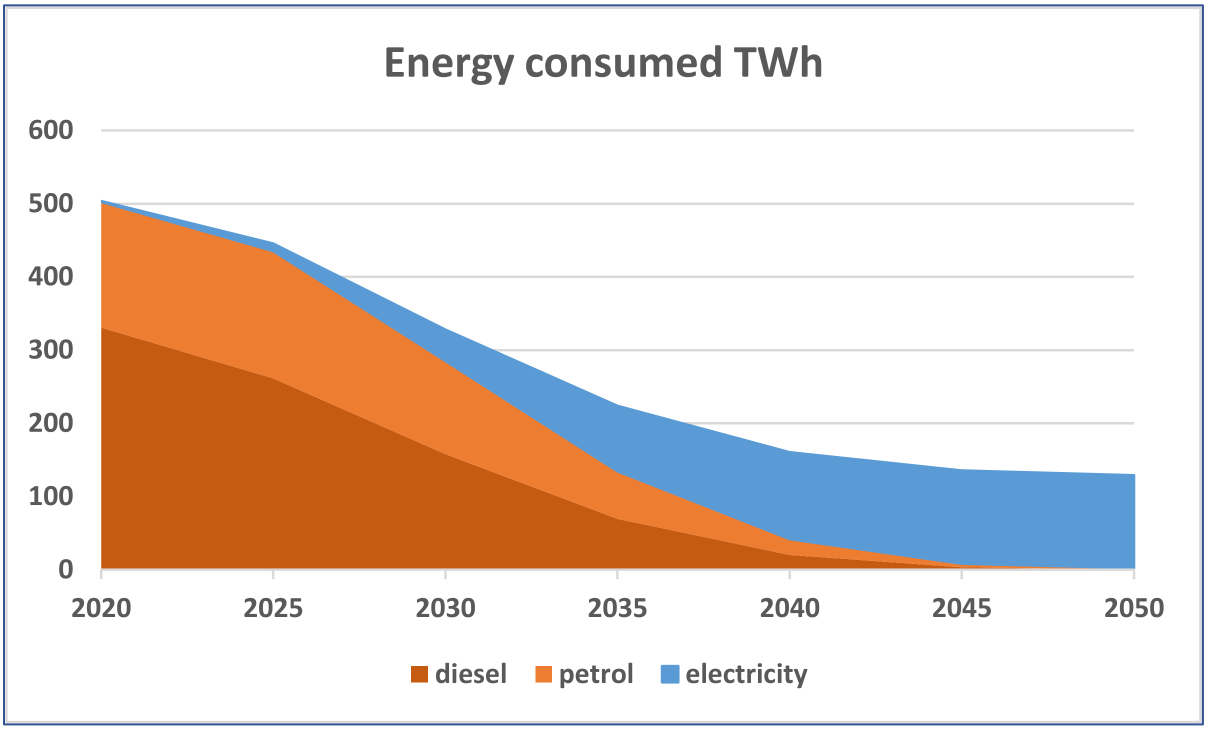
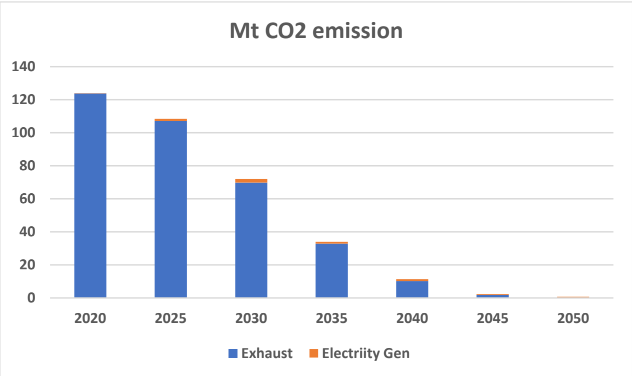


Figure 5.4. Illustration of change in energy consumption by vehicles with electrification.

With regards to electricity generation, the associated emissions of CO_2 depend on energy projections and the future energy mix, and how the growing need for electricity production is matched by the increasing capacity of renewables and nuclear to avoid a need for fossil fuels. This also avoids generation of air quality pollutants from fossil fuels, as discussed further in the later section of this report on energy generation and industrial combustion. As an indication of the overall potential reduction in CO_2, Figure 5.5 gives modelled estimates using data from a net zero pathway by the UK's Climate Change Committee, CCC (CCC 2020).



	Mt CO2 emissions		
	Exhaust	Electriity Gen	Total
2020	123.7	0.2	123.9
2025	107	1.4	108.4
2030	69.9	2.2	72.1
2035	32.9	1.2	34.1
2040	10.3	1.1	11.4
2045	2	0.5	2.5
2050	0.5	0.3	0.8

Figure 5.5. Illustration of potential CO2 reduction.

As indicated above, the emissions of NO_x and primary $PM_{2.5}$ from electricity generation will depend on the energy generation mix. But to put this in perspective, if the electricity demand in 2030 is around 45 TWh as indicated in Figure 5.4, and as a worst case this was provided entirely by conventional natural gas CCGT plants, then this would result in about 9kt of NO_x emission using emission factors for current power stations; and .045 kt of primary $PM_{2.5}$, which is a negligible amount. These NO_x emissions would have a smaller impact on local population exposure to NO_2 than equivalent exhaust emissions, due to their geographical locations and release from elevated stacks. If, as expected, much of the electricity generation is from renewables rather than gas, the contribution to air quality from electricity for battery charging is expected to be small in 2030. Beyond 2030, with electricity demand rising to around 125 TWh in our example, it is too speculative to give any quantitative assessment of air pollutant emissions due to uncertainties in, for example, the proportion of generation by natural gas plus CCS as opposed to nuclear and renewables. This is considered further in the section on energy and industry.

Summary and discussion

The large reduction in CO_2 emissions is the greatest benefit from electrification of road transport in the UK, and energy projections imply that any additional emissions of air quality pollutants from electricity generation should be minimal. There are also expected to be substantial reductions in NO_x emissions from road transport in the future, leading to lower secondary inorganic aerosol and reductions in NO_2. However, the contribution from electrification is moderated by the fact that NO_x emissions will already be considerably reduced by 2030 due to improvements in ICE vehicle emissions, and in particular from new diesel vehicles after the introduction of RDE testing. Since exhaust emissions are small compared with non-exhaust emissions the removal of exhaust emissions due to electrification has little overall effect. With regard to the non-exhaust emissions, these are very uncertain and may be better or worse for electric vehicles depending on possible savings from regenerative braking and larger emissions from tyres and road abrasion due to batteries adding to vehicle weight. Established measures to reduce non-exhaust emissions are limited, though better wheel alignment to reduce tyre wear and road abrasion may help as well as saving fuel. In the future there may be technology which can mitigate non-exhaust emissions, but this is still in development.

Some wider considerations have also been raised, including the growth of the transport sector especially if electric vehicles are cheaper to run. Following electrification, to reduce the remaining contribution of traffic to air pollution further will require reductions in km driven, especially in cities. Measures such as road charging may be important here, as well as investment in infrastructure for active travel and public transport. There are also questions about what will happen to the ICE vehicles displaced, where ideally the oldest and most polluting vehicles should be scrapped. Other side effects include the reduction in demand for petrol and diesel and refinery capacity.

Overall health benefits from future changes in air quality resulting from electrification of road transport in the UK are expected to be modest, unless they are accompanied by substantial reduction in vehicle use.

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Addendum: Road Transport Scenarios and fleet modelling

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Summary

This technical annex describes the methods and models used to provide road transport scenarios to the UKIAM framework.

For road transport, a scenario in UKIAM requires data giving the composition of vehicles in the fleet and the corresponding driven vehicle kilometres of the fleet. The composition of the fleet and the driven vehicle kilometres were produced separately for each scenario. This annex details how the fleet composition was derived for each road transport scenario, and how this data is used in UKIAM.

A Fleet Turnover Model was used to produce scenarios for UKIAM, based on new vehicle sales data provided by the Department for Transport. This model produces fleet composition data for the UK in future years for a given set of inputs describing a scenario. For a reference scenario, fleet composition data was taken from the NAEI 2018.

A. Scenarios

A scenario in UKIAM requires data giving both the fleet composition and the corresponding vehicle kilometres driven (abbreviated to vkm). The fleet composition (or fleet mix) gives the fractional proportion of vkm each vehicle type (e.g. cars, LGVs, buses) and then by the fuel/drivetrain (e.g. diesel, HEV, PHEV), and finally by the vehicle Euro Standard (e.g. Euro 5, Euro 6). This fleet mix is used with other data, such as vehicle average speeds and vehicle kilometres driven, in UKIAM via a bottom-up tier 3 methodology to calculate the emissions from road transport in the UK.

A.1. NAEI 2018 Scenario

The NAEI 2018 projections are based on similar fleet composition data from DfT, which was reformatted for use in UKIAM. This data covers the years 2018-2035. This is used for the baseline scenario with minimal uptake of EVs, but assuming no trend in purchasing new petrol cars rather than new diesel cars. This is relevant to the assessment of lower emissions from new diesel cars subject to post RDE testing.

A.2. Department for Transport Scenarios

Two scenarios were provided by the DfT containing the annual vehicle sales for the UK road transport fleet from 2020 to 2050. These sales were used to simulate how the fleet will evolve over time using the Fleet Turnover Model. These scenarios were modelled from 2025 to 2050.

The first, scenario 1, represents a scenario where internal combustion engine vehicles (ICEVs) are banned from sale in the years given in Table 1. In this scenario Plug-in Hybrid EVs (PHEVs) are banned at the same date as ICEVs. The second scenario, scenario 2, bans ICEVs before PHEVs. This second scenario matches the current government target dates for passenger cars and is used as the reference EV scenario in the main report. To illustrate the uptake rates of BEVs, Table 2 gives the years where BEV sales reach 50%.

Addendum Table 1. ICEV sales end date (implied by DfT sales).

Scenario	Cars		LGVs		HGVs	Bus	Motorcycles
	ICEV	PHEV	ICEV	PHEV	All*	All	All
Scenario 1	2035	2035	2035	2035	2045	2040	2050+
Scenario 2	2030	2035	2030	2035	2040	2035	2050+

* HGV sales end date varies by the size and type, and so only the latest date is given. No end date implied for Motorcycles, 2050+ implies a date beyond 2050

Addendum Table 2. Year when BEV sales reach 50%.

Scenario	Cars	LGVs	HGVs	Bus	Motorcycles
Scenario 1	2031	2032	2034	2029	2050+
Scenario 2	2028	2030	2032	2024	2050+

B. Fleet Turnover Model

B.3. <u>Overview</u>

The Fleet Turnover Model (FTM) employs a stock-flow cohort model structure. This structure is well established in the academic literature and is the same methodology as that used to produce the road transport emissions in the NAEI projections.

The FTM starts with the existing vehicle fleet and evolves the fleet on a yearly timescale by adding and removing vehicles. Vehicles exit the fleet over time, using the known survival rate of the vehicles. New vehicles are added to the fleet, which is defined by a scenario of future new vehicle sales.

The stock of vehicles in the fleet is then used to determine the mix of driven vkm by the fleet. In the UK, newer vehicles are driven more than older vehicles. This relationship is captured in a mileage-age curve. Using the mileage-age curve, the mix of driven vkm is derived from the stock of vehicles.

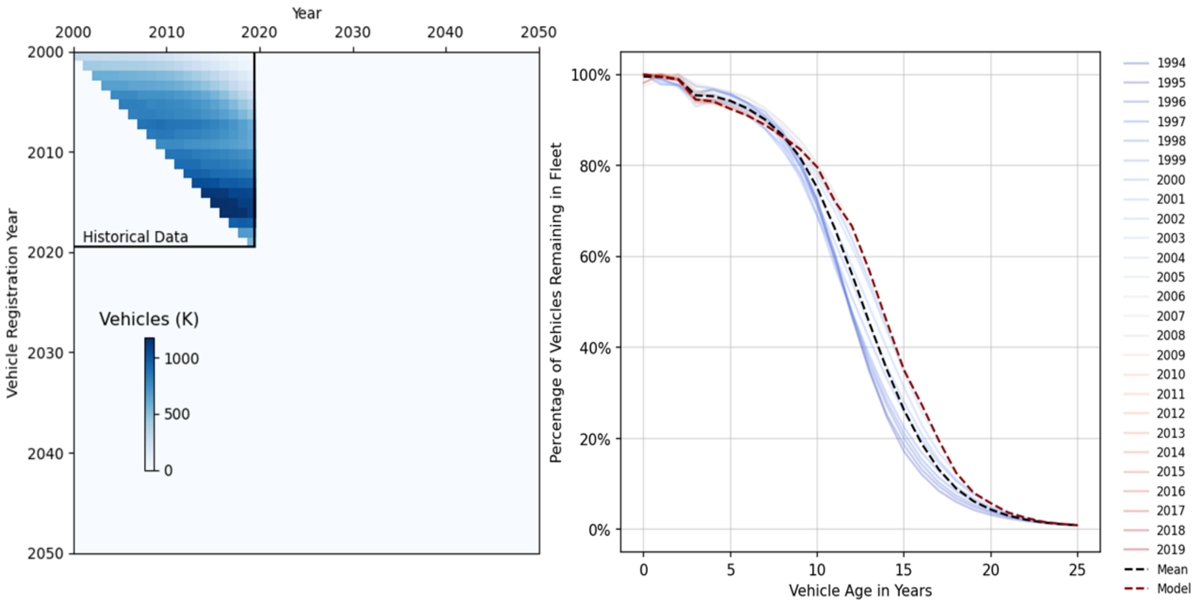
The FTM models each vehicle type (car, LGV, bus, etc) separately, and then aggregates them to produce the overall fleet mix. This annex uses cars as the example vehicle type to illustrate the FTM and methods.

B.4. Starting fleet

The starting fleet for each vehicle type was taken from the DfT's online vehicle licensing data tables[1]. The specific data table used to populate the starting fleet was the number of vehicles by year of registration (e.g. VEH0211 for cars). This data table shows how many vehicles remain in the fleet at a given year from each registration year, which was used to derive empirical survival curves.

B.5. Vehicle survival curves

From the starting fleet, empirical survival curves were derived. These survival curves show the net rate at which vehicles exit the fleet, through pathways such as scrappage and exportation. For each vehicle type, the same survival curve was used from 2020 to 2050, implying that future vehicles (including electric vehicles) survive as long as present-day vehicles. The starting fleet and corresponding survival curves for diesel cars are given in the figure 1 below. We found with this data that newer vehicles are surviving longer. Therefore, the FTM uses the survival rate for the newest vehicles where the data is available. This survival curve is labelled as 'Model' and is given in dashed red in figure 1.



Addendum Figure 1. Left, the starting fleet for diesel cars shown as a heatmap, where colour shows the number of vehicles in the fleet at each year by the year of the vehicle's registration. Right, the corresponding survival curve for diesel cars, where each registration year from 1994 to 2019 is given in a separate colour. Dashed black shows the mean of all registration years. Dashed red shows the survival curve used in the FTM, where the value from the latest registration year available was used.

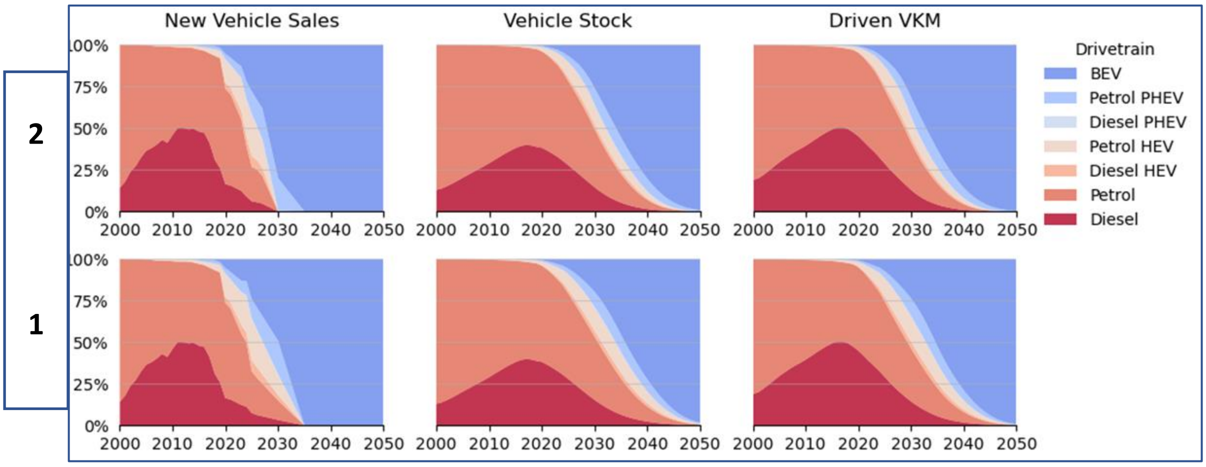
[1] Vehicle licensing data tables: https://www.gov.uk/government/collections/vehicles-statistics

Ricardo supplied the survival curves for cars and LGVs used in developing the NAEI projections, which have been used instead of the corresponding empirically derived survival curves. The remaining vehicle types, for which Ricardo data was not available, use the empirically derived survival curves from the DfT licensing data tables.

B.6. New vehicle sales

New vehicles were added to the fleet using the two DfT sales scenarios. These scenarios contained the number of vehicle sales per year from 2020 to 2050.

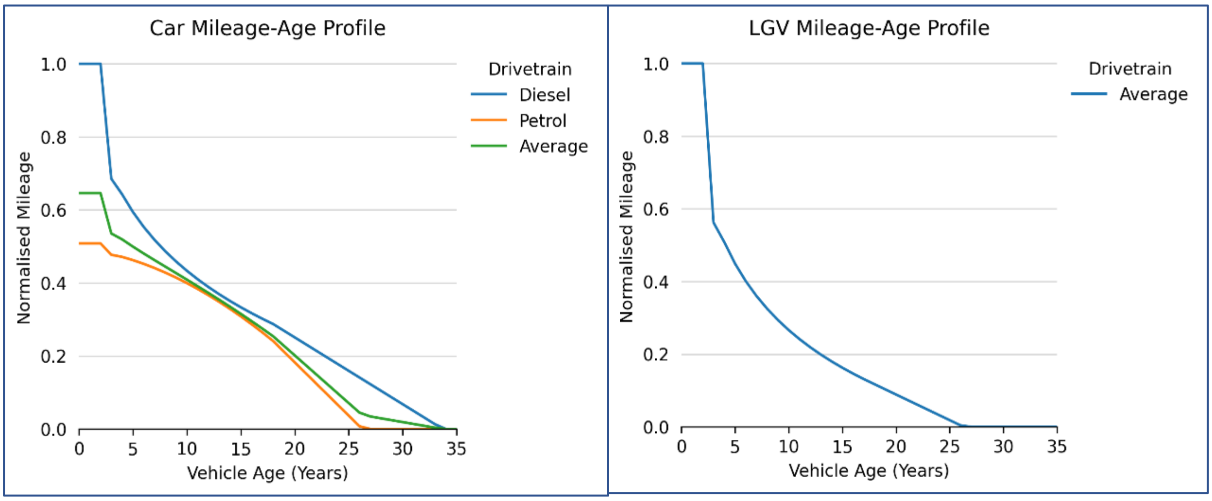
In the DfT scenarios, new car sales of conventional Internal Combustion Engine Vehicles (ICEVs) and Hybrid Electric Vehicles (HEVs) were given in the same category. However, as HEVs produce air pollutant emissions at a lower rate than ICEVs, the DfT TDP sales data was amended to disaggregate HEVs and ICEVs. This was done using SMMT data, using historical sales data from the previous 3 years and with their short-term forecast covering the next 3 years the sales during this period were amended. The observed trend from these years were extrapolated until HEVs reached 50% of sales of ICEVs, at which point an equal ratio of HEV to ICEV was maintained.



Addendum Figure 2. Top row shows results for cars for the scenario 2. Lower row gives the results for the scenario 1. Left column, the composition of new vehicle sales from the DFT scenarios. Central column, the mix of vehicle stock. Right column, the vkm mix for cars. Colour shows the drivetrain of the vehicle.

B.7. Vehicle mileage-age curves

In the UK, newer vehicles are driven more than older vehicles. The rate that vehicles drop in mileage over time as the vehicle ages is defined with a mileage-age curve. The mileage-age curve gives the percentage decrease in mileage year over year. The NAEI provided mileage-age curves for cars and LGVs, which were applied to the stock of vehicles to produce the relative mix of driven kilometres by the fleet.



Euro Standards

Addendum Figure 3. Left, mileage-age curve for cars. Right, LGV mileage-age curve. Both curves use data from Dun et al. (2014). For cars, 'Average' shows the fleet weighted mean of petrol and diesel curves and is used for all other drivetrains. For LGVs, data was only available for the 'Average' and was used for all drivetrains.

Vehicles are allocated to a Euro standard based on the registration year. This is an approximation, since the period from the date of the first registration of a vehicle with a new Euro Standard to the date where the Euro Standard is mandatory for all vehicles spans multiple years.

C. BRUTAL

The road transport sub-model of UKIAM, BRUTAL, uses a bottom-up approach to model the UK's road transport fleet at a 1km x 1km grid resolution (Oxley et al., 2009). The model uses the fleet composition data, as described previously, with other input data such as the driven vehicle kilometres, COPERT emission factors, and average vehicle speeds, to calculate the emissions from road transport within each grid cell. This emission data is then used in UKIAM, along with emissions from other sectors, to calculate the resulting concentrations and population exposure to the air pollutants.

<u>References</u>

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5.2 The domestic sector

The domestic sector makes a major direct contribution to primary $PM_{2.5}$ emissions due to fuel used for heating (see Figure 2.2). These emissions are concentrated in more densely populated areas, enhancing their impact on human exposure and health. In addition, the sector is a significant source of NO_x and also contributes to CO_2 emissions. Table 5.2 indicates the contributions from different fuels to air pollutant emissions in 2018 and in the projected baseline scenario to 2030, clearly showing the importance of wood-burning. In this section, we consider the resulting contributions to $PM_{2.5}$ exposure and explore the effect of potential abatement measures, including synergies with climate measures to reduce CO_2.
In addition to uncertainties in emissions there are also additional sources not included in the NAEI, in particular cooking. Below, we also consider an upper estimate of the additional contribution this might make, although there are large uncertainties.

Emissions from the domestic sector

The table below shows clear reductions between 2018 and projected emissions in 2030, for which we shall consider further abatement options. There is a clear reduction in coal use as the dominant source of SO_2 and reduction of emissions from wood burning through emphasis on burning suitable wood that has been cured and dried. Damp and green wood gives much higher PM emission. It should be noted that there are still very large uncertainties in $PM_{2.5}$ emissions from wood burning, as emphasized in an AQEG report (AQEG 2017) and in a previous contract report (ApSimon et al., 2020). These reflect not only uncertainties in the quantities of wood burned and the type of wood, but also on how it is burned in open grates or stoves with different efficiencies and modes of operation. In addition, 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 (EMEP 2020). Comparison with independent assessment by TNO suggest that NAEI2018 emission estimates (which are much higher than for example LAEI estimates - see ApSimon et al., 2020), cover the condensable material. It is also noted that wood-burning is a significant source of VOCs. Despite the large emissions of $PM_{2.5}$ from wood-burning, the amount of energy generated is modest compared with the widespread reliance on the domestic use of gas. Here improvements in NO_x emissions reflect updating to boilers with improved efficiency.

Table 5.2. Pollutant emissions (kt).

	2018			B2030 adj		
	$PM_{2.5}$	NO_x	SO_2	$PM_{2.5}$	NO_x	SO_2
Coal	3.98	3.53	30.2	1.02	1.06	9.20
Gas	1.22	20.24	0.30	0.90	16.02	0.28
Oil	0.16	4.30	0.64	0.11	2.57	0.55
Wood	41.43	6.26	0.96	26.36	6.87	1.00
SUM	46.79	34.32	32.15	28.39	26.52	11.03

NB There are additional emissions in SNAP2 from commercial premises and offices. These are not included in the emissions above and are smaller than the domestic emissions. In some cases, commercial sites such as office blocks might be of use as possible sites for CHP, but there is not sufficient information to model this.

Source apportionment and further abatement potential

Before considering additional abatement measures, it is useful to consider how the different fuels contribute to $PM_{2.5}$ concentrations in the 2030 baseline scenario above. This is summarised in Table 5.3 and reflects the spatial distribution of emissions, where coal and oil are mainly used in less populated rural areas. The numbers are the contribution of the baseline emissions in 2030 from each fuel source in Table 5.2 to the population weighted mean concentrations in the respective areas of the UK. This includes exposure to both primary $PM_{2.5}$ and the difference in secondary inorganic aerosol, SIA, from reducing the source nationally. Despite the small proportion of heating from the use of wood, relative to that from gas, the emissions from wood-burning are by far the largest contribution to $PM_{2.5}$ population exposure.

Table 5.3. Source apportionment of contributions to $PM_{2.5}$ for B2030adj.

Unit= µg m^{-3}	National	Urban	Rural	London	England
Coal	0.044	0.046	0.039	0.038	0.047
Gas	0.089	0.103	0.040	0.206	0.097
Oil	0.006	0.005	0.008	0.006	0.006
Wood	0.610	0.696	0.314	0.926	0.654
SUM	0.749	0.850	0.402	1.176	0.804

Turning to abatement measures, first there is the potential to reduce emissions by improved efficiency, especially by improved insulation of houses and improved new builds, and behavioural change. Sources such as the CCC (CCC, 2020) have suggested that this could reduce heating demand by 12% to 22% by 2050, with over half of this achieved by 2030. Concerns after COVID-19 regarding ventilation may dilute this improvement. As a conservative estimate, a 5% reduction uniformly across the sources above by 2030 would reduce exposure proportionately, giving a modest reduction in national exposure of 0.037 µg m^{-3}. The contributions from coal and oil are small, so climate measures to eliminate the remaining use of these and replace with electricity or heat-pumps also has a relatively small effect on population weighted mean concentration of 0.05 µg m^{-3}.

For wood burning as the most important source, in addition to the improved efficiency measure above, there are potential reductions both from reducing use of wood, especially in open grates, and from technological improvements to meet eco-stove standards including retrofitting. Defra have commissioned new research on this topic, both to improve estimates of emissions and the potential for improvement. Meanwhile, as an indicative illustration we have considered a potential 50% reduction in emissions from wood burning by 2030 on top of the 5% efficiency measures above. This results in a reduction of primary $PM_{2.5}$ emissions to 12.5 kt and NO_x to 3.26 kt. The resulting improvement in population exposure is 0.32 µg m^{-3} nationally and nearly 0.5 µg m^{-3} in London. The uncertainties need to be considered, with emissions from wood-burning a particularly uncertain source (as discussed in section 8.1), but this is a substantial improvement compared with other measures. The effectiveness will be enhanced if focused on populated urban areas, such as in clean air zones, and where exceedance of the WHO guideline is greatest.

Combustion of gas as the major fuel for domestic heating gives primary $PM_{2.5}$ emissions an order of magnitude smaller than those from wood. However, it is also a source of NO_x emissions, despite boiler improvements. Future plans to reduce CO_2 emissions are a combination of replacing natural gas with green hydrogen, initially with a mix of the two; and secondly by installing heat pumps, which require up-front investment. For the first option, the burning of hydrogen is still a combustion process generating NO_x; whereas heat pumps require a small amount of electricity to operate and would not generate air pollutants if covered by renewable capacity. Assuming such measures will take time to implement, we have assumed for illustration a 30% reduction in domestic use of gas by 2030 with a corresponding reduction in both $PM_{2.5}$ emissions and NO_x, again on top of the 5% efficiency measures. The resulting reduction in population exposure is 0.03 µg m^{-3} nationally and 0.07 µg m^{-3} in London. This is an order of magnitude less than the effect of reducing wood-burning emissions above.

The effect of the measures above, as a combined scenario for abatement of the domestic sector in 2030, is summarised in Table 5.4 below. In addition to reductions in $PM_{2.5}$, gives a breakdown between primary and secondary contributions, and reductions in NO_x with respect to benefits in reducing NO_2 exposure. The overall combined reduction in $PM_{2.5}$ PWMC is 0.4 µg m^{-3} nationally and 0.6 µg m^{-3} in London, where concentrations are highest. This is a substantial improvement by 2030, as discussed below with respect to monetised health benefits, with potential for further improvements by 2040 and 2050.

Table 5.4. Reduction in population weighted mean concentration for combined scenario relative to the adjusted 2030 baseline (B2030adj). The combined scenario assumes a 5% reduction in all domestic emissions due to efficiency measures, along with further 30% and 550% reductions in gas and wood burning, respectively.

Reduction in $PPM_{2.5}$ (µg m^{-3})	**National**	**Urban**	**Rural**	**London**	**England**
Coal	0.013	0.014	0.010	0.007	0.013
Gas	0.020	0.025	0.006	0.054	0.022
Oil	0.002	0.001	0.004	0.001	0.001
Wood	0.307	0.351	0.154	0.466	0.328
SUM	**0.342**	**0.390**	**0.174**	**0.528**	**0.364**
Reduction in SIA (µg m^{-3})	**National**	**Urban**	**Rural**	**London**	**England**
Coal	0.031	0.032	0.029	0.032	0.034
Gas	0.009	0.010	0.007	0.015	0.010
Oil	0.005	0.004	0.005	0.005	0.005
Wood	0.014	0.015	0.011	0.020	0.015
SUM	**0.059**	**0.061**	**0.052**	**0.072**	**0.064**
Reduction in $PM_{2.5}$ (µg m^{-3})	**National**	**Urban**	**Rural**	**London**	**England**
Coal	0.044	0.046	0.039	0.038	0.047
Gas	0.030	0.034	0.013	0.069	0.033
Oil	0.006	0.005	0.008	0.006	0.006
Wood	0.320	0.365	0.165	0.486	0.343
SUM	**0.401**	**0.451**	**0.226**	**0.600**	**0.429**
Reduction in NO_x (µg m^{-3})	**National**	**Urban**	**Rural**	**London**	**England**
Coal	0.013	0.014	0.011	0.007	0.013
Gas	0.364	0.439	0.106	0.959	0.399
Oil	0.037	0.023	0.086	0.031	0.024
Wood	0.080	0.091	0.040	0.121	0.085
SUM	**0.495**	**0.568**	**0.243**	**1.118**	**0.522**

<u>Missing sources including cooking</u>

Apart from the uncertainties above, especially in emissions from wood-burning, there may also be additional sources not included in the NAEI. In particular, emissions from cooking are a likely source. This has been considered in an earlier SNAPS contract report (Oxley et al., 2020), where a review of evidence, including measurements, indicated a range between 2 kt and 7.5 kt for annual primary emissions of $PM_{2.5}$ from cooking in the UK; and suggested using an average value of 4.6 kt as a sensitivity study for the potential additional contribution to $PM_{2.5}$ concentrations. This would add another 0.275 µg m^{-3} to national population weighted mean concentrations, cancelling out a large part of the reduction in exposure from the combined scenario above and illustrating the potential importance of missing sources. Table 5.5 gives the corresponding spatial breakdown. Bearing in mind the increase in pre-prepared meals and takeaway/delivery services, as well as use of microwave cookers, this may be on the pessimistic side. But there is also the use of barbeques and outside cooking which was not included. Future emissions will be affected by factors like the proportion of meat eaten and frying of foods in fat.

Cooking emissions will also affect indoor air pollution, where extraction units sited over stoves can be effective. With regard to emissions to ambient air, the efficiency with which emissions can be captured and filtered from both domestic cooking and commercial food outlets is key information with respect to potential emission abatement. Although there are large uncertainties, cooking is likely to be a significant source warranting further study.

Table 5.5. Case study on potential additional contribution to $PM_{2.5}$ from cooking.

Unit= $\mu g\ m^{-3}$	National	Urban	Rural	London	England
Cooking	0.275	0.328	0.093	0.748	0.301

<u>Monetised benefits of abatement in the domestic sector</u>

We have not considered the abatement costs or the need for behavioural change involved in the abatement measures consider above. However, in this section we can address the potential monetised benefits reflecting reduced health effects from exposure of the population to lower concentrations of $PM_{2.5}$ and NO_2. From the introductory section of this report, based on the recently revised assessment of damage costs in appendix B, the monetised benefit per person per reduction of 1 $\mu g\ m^{-3}$ in annual concentration of $PM_{2.5}$ is estimated at £62.7 (range £16.9 to £178.2 indicating the uncertainties). Assuming a UK population of 67 million, the reduction of 0.4 $\mu g\ m^{-3}$ in population weighted mean concentration from the combined scenario for abatement of domestic emissions in 2030 discussed above, corresponds to an annualised benefit for the UK population of £1.7 billion (range £0.45 billion to £4.8 billion) in 2020 prices. This is a substantial sum to justify the effort and costs involved.

In addition, there is a small improvement in NO_x of approximately 0.5 $\mu g\ m^{-3}$, mainly due to the assumed reduction from gas use if replaced by heat pumps (but less if gas is replaced by green hydrogen). The corresponding reduction in $NO_{2,}$ (which is non-linear) would be around 70% of the reduction in NO_x at low to moderate concentrations. Using corresponding damage costs for $NO_{2,}$ of £7.02 (range £0.53 to £27) per person per $\mu g\ m^{-3}$, results in an additional annualised monetised benefit from the 0.5 $\mu g\ m^{-3}$ reduction in mean exposure of the UK population to NO_x of £165 million (range £12million to £630 million). This is a much smaller sum than the direct benefit of reducing $PM_{2.5}$, but is relevant to the NO_x emissions and relative benefits from replacing gas use by heat pumps instead of by using hydrogen.

<u>Summary</u>

In this section, we have considered the contribution of emissions from the use of different fuels in the domestic sector, and shown that significant reductions in $PM_{2.5}$ exposure are possible with associated large monetised benefits. Such measures will be particularly important in London, where large numbers of people are exposed to higher concentrations. We have also illustrated that cooking is a potentially important source missing from the NAEI.

We have not considered the contribution from commercial buildings and offices, which also contribute to SNAP2 emissions. Some of these buildings may be useful for CHP plants, but more information would be needed to represent potential emission reductions.

We have focused particularly on emission reductions by 2030. There are large uncertainties in projected emissions and trends beyond 2030; but there is also potential for further reduction particularly for wood burning as a large source of primary $PM_{2.5}$, as well as increased efficiency, reduced heat demand and extended installation of heat pumps.

Addendum

During the course of this work there has been a substantial reduction in the estimated amounts of wood-burned, with data in DUKES 2021 suggesting that this is a factor of two thirds lower than the 2018 NAEI value. However further research for Defra is ongoing on emission factors depending on the proportions of dry and wet wood burned and the mode of combustion in open grates and stoves. Therefore, revised overall NAEI estimates of emissions may not be reduced as much as this. To allow for such potential overestimation, in the scenario analysis undertaken in this report we propose sensitivity studies reducing $PM_{2.5}$ emissions from wood-burning by up to two thirds. It is noted that such a reduction would roughly counteract missing emissions from cooking with respect to population weighted mean concentrations. This illustrates that, although comparison with measurements of $PM_{2.5}$ in section 2 shows little obvious bias, this does not necessarily apply to the contributions from component sources.

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5.3 The agricultural sector

The agricultural sector is a major source of greenhouse gas emissions and has been identified by the Climate Change Committee, CCC, (CCC, 2020) as a sector which requires significant government investment in order to adapt to meet the challenge of reaching net zero. The agricultural sector is also important as the source of most of the NH_3 emissions in the UK. NH_3 is a precursor for the formation of SIA particles and can also have a significant impact on biodiversity; both through deposition onto nitrogen-sensitive habitats and in the exposure of lichens and bryophytes to excess concentrations of NH_3 in the air. These factors must be kept in consideration while planning the adjustment of the agriculture sector to meet climate targets.

NH_3 from agriculture is generated from fertiliser use and livestock wastes. Table 5.6 gives a summary of NH_3 emissions from agricultural sources for both the 2018 and 2030 baselines, with very little change in this period. These baseline scenarios are a slightly earlier version of the B2018adj and B2030adj scenarios considered in Section 6; while the NH_3 emissions are the same between these versions, there are small differences in the non-agriculture NO_x emissions. At a national scale, emissions from cattle (113 kt) and fertiliser (48 kt) are the major sources within the UK, however these vary significantly between regions and counties. Fertiliser NH_3 emissions are sensitive to the type of fertiliser used, where use of urea gives higher emissions.

Table 5.6. Emissions of NH_3 in the B2018 and B2030 scenarios.

NH_3 (kT)	**B2018**	**B2030**
Agriculture	**231.7**	**229.7**
Beef	*49.2*	*47.7*
Dairy	*65.1*	*65.6*
Pigs	*18.1*	*19.2*
Layers	*8.1*	*7.3*
Other Poultry	*26.5*	*23.9*
Sheep	*11.7*	*11.4*
Other Livestock	*6.1*	*6.1*
Fertiliser	*46.9*	*48.4*
Anaerobic Digestion	**15.0**	**14.9**
Other	**27.6**	**29.5**
SUM	**274.3**	**274.1**

Large uncertainties are associated with these NH_3 emissions. NH_3 is a widespread dispersed source and the degree of NH_3 volatilization is dependent on multiple factors such as temperature, water content and pH of the soil when animal wastes are spread on the ground. Some of this NH_3 is diffused upwards and forms secondary inorganic aerosol, contributing to the total PM concentrations in the air. This secondary PM can travel long distances before eventually being deposited on the ground or sea. This deposition contributes to the eutrophication of soils which is harmful to nitrogen-sensitive species and can lead to a loss of biodiversity. A proportion of the NH_3 remains in gaseous form and is redeposited locally. High concentrations of NH_3 can occur near major point sources, such as large poultry farms, leading to vegetation damage, with lichens and bryophytes particularly sensitive.

The agricultural sector also contributes to NO_x emissions from machinery, reported as non-road mobile machinery, NRMM. The agriculture NRMM NO_x emission for B2030 is 11 kt. NO_x, in the form of NO, is also emitted from the soil, due to the nitrification and denitrification processes which occur. The magnitude of these emissions is highly uncertain; however agricultural activities such as fertiliser application increases the otherwise naturally occurring soil emissions. For B2030 the agriculture NO_x emissions from fertiliser and manure spreading are taken to be 27 kt, however this figure is also highly uncertain. Despite this, the total contribution of agriculture to the total UK NO_x emissions is relatively small and therefore has only a modest effect on N deposition and ecosystems. Similarly, the contribution to SIA is small, as is the localised change in NO_x, which is confined to rural, less populated areas. Agriculture also generates small amounts of primary $PM_{2.5}$; but again, as rural sources, dilution takes place before reaching more populated urban areas.

NO_x and primary $PM_{2.5}$ emissions from agriculture are therefore less important than NH_3 emissions and are not considered further in this section of the report.

Abatement measures

As illustrated in Figure 5.6, NH_3 emissions from livestock manure occur at each stage after excretion; from housing, then storage, and finally application to soils as a fertiliser. The efficacy of an abatement measure at one of these stages is dependent on the nitrogen loss at each other stage. For example, if a measure is applied to reduce emissions from storage, this can increase emissions from spreading, depending on measures applied at this subsequent stage. It is therefore important to consider the interactions between these stages and apply measures at each stage accordingly. Effective mitigation at each stage increases the final

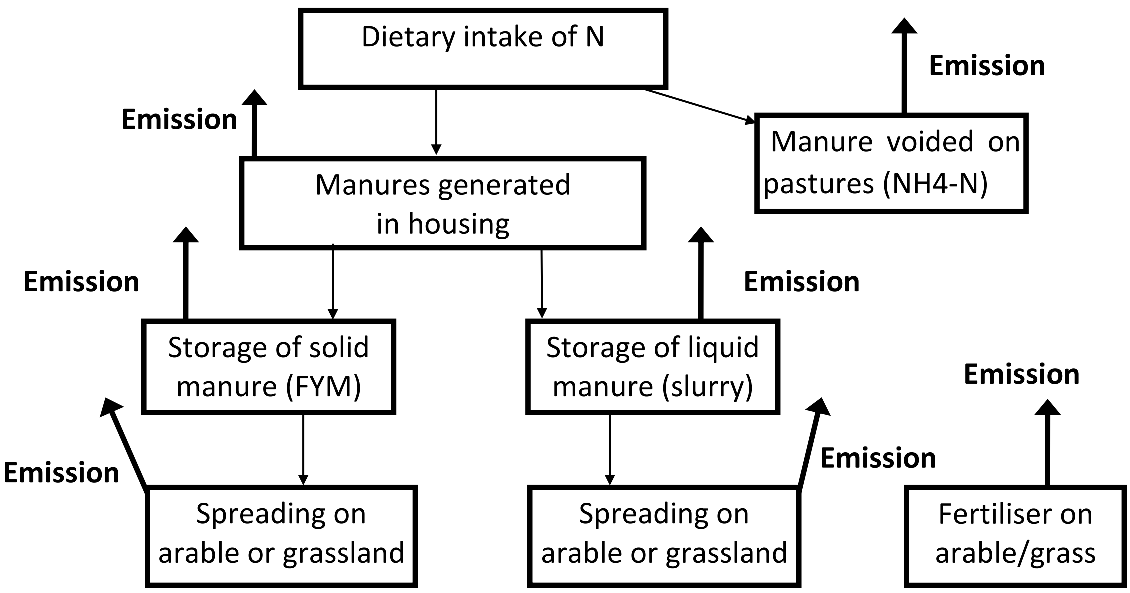

Figure 5.6. NH3 emissions from agriculture.

nitrogen content of the manure applied to the soil, increasing N use efficiency and reducing the need for additional N input from other fertilisers, although this may not be recognised in determining fertiliser needs.

Effective measures for the abatement of agricultural ammonia emissions have been widely studied in work by the UNECE (UNECE, 2015) as well as in the UK (Defra, 2018a). Recommended measures include improved nitrogen management, livestock feeding strategies and improved housing systems, low emission manure storage and low emission spreading. Due to the fugitive nature of NH_3 emissions, these measures tend to have lower efficiencies than measures for sources of NO_x, emissions of which tend to be point sources. This again emphasises the importance of applying measures at each available stage in order to maximise emission reductions.

As agriculture is also a major source of greenhouse gas emissions, mainly methane and nitrous oxide, there is an increasing focus on dietary change, away from meat and dairy consumption, as a necessary measure to reach climate targets. Further, climate measures such as afforestation and increased bioenergy crop production are contributing to the increasing demand for land. Currently 85% of UK land used to produce food is used for livestock grazing or to produce crops to feed animals (National Food Strategy, 2021). Reducing the production of livestock products is necessary both to reduce GHG emissions and to free up land for other climate causes. Dietary change measures could also lead to significant reductions in NH_3 emissions from livestock and dairy products. However, the UK is both an importer and exporter of meat and dairy products, therefore the relationship between consumption and production within the UK is complex and difficult to predict.

<u>Scenarios</u>
A range of scenarios have been considered with varying levels of ambition. Two scenarios, Central and Higher, are based on previous work where technological measures have been applied with varying uptake rates. These represent the emission reductions feasible through technological measures only, with total NH_3 emission reductions of 53 kt and 60 kt reflecting varying degrees of ambition. An additional two scenarios were run to explore the potential impact of dietary change on SIA formation and N deposition. These dietary change measures were added to the Higher scenario, therefore representing very high ambition scenarios. The first, Higher + Meat, assumes an additional 20% reduction in emissions from meat production, as suggested as part of the CCC's balanced net zero pathway (CCC, 2020), leading to an additional 19 kt reduction in NH_3. The second, Higher + Beef, assumes an additional 15 kt reduction in NH_3 from reduced beef consumption only.

To cover a wider range of scenarios, we also consider a lower ambition scenario, referred to as Lower, taken from initial modelling undertaken to inform Defra, with a total of 27.7 kt reduction in NH_3 emissions. All scenarios considered here, other than the Lower scenario, would meet the UK's NECD target of 16% reduction in NH_3 emissions, relative to 2005 levels, by 2030.

Table 5.7. Reduction in NH3 emissions relative to B2030.

Unit = kt NH_3	Lower	Central	Higher	Higher + Meat	Higher + Beef
Beef	2.5	5.7	5.7	14.1	20.2
Dairy	8.1	17.0	19.9	19.9	19.9
Pigs	1.5	2.0	2.0	5.4	2.0
Layers	0.2	1.0	1.6	1.6	1.6
Other Poultry	0.2	6.0	9.6	12.5	9.6
Sheep	0.0	0.0	0.0	2.3	0.0
Other Livestock	0.0	0.0	0.0	1.2	0.0
Fertiliser	15.1	22.0	22.0	22.0	22.0
SUM	**27.7**	**53.6**	**60.8**	**79.0**	**75.3**

Effects on $PM_{2.5}$ concentrations

Table 5.8 shows the reduction in the contribution of agriculture to the total PWMC relative to B2030 for each scenario. The greatest reduction for each scenario is seen in rural areas, reflecting the widespread nature of NH_3 emissions, away from urban areas. The Higher + Meat scenario achieves the greatest reduction in PWMC, as the scenario with the greatest reduction in NH_3 emissions, with a reduction of 0.095 µg m^{-3} nationally. London, where exposures are at their highest, sees the lowest benefit from these reductions in NH_3 emissions.

Despite an ambitious reduction of 79 kt NH_3 for the Higher + Meat scenario, a fairly modest reduction in population weighted concentration is achieved. Due to the non-linearity which is not captured by the UKIAM model, we expect that the sensitivity of SIA concentrations to emission reductions is somewhat underestimated, and we expect this to be particularly true for NH_3 for which the non-linear correction is greater than for NO_3 and SO_4. Therefore, the values given in Table 5.8 are likely to be conservative. However, it should also be noted that the sensitivity of SIA concentrations to NH_3 emissions is likely to reduce in future as SO_2 and NO_x emissions continue to reduce and NH_3 may no longer be the limiting factor for the formation of SIA. This was found to be the case in the modelling of Vieno et al. (2016) for which the sensitivity of SIA concentrations to a 30% reduction in NH_3 emissions reduced significantly between 2010 and 2030 baseline scenarios. Despite this, modelling studies have suggested that reductions in NH_3 have the greatest effect on area weighted $PM_{2.5}$ concentrations, e.g. Vieno et al. (2016) and Gu et al. (2021) (for population weighted concentrations, the sensitivity to primary $PM_{2.5}$ is greater). In the case of Gu et al. (2021), global NH_3 emissions are reduced, rather than only UK emissions. As a large proportion of SIA concentrations in the UK originate from imported emissions, the degree of the reduction in SIA concentrations in the UK will be highly dependent on emission reductions across Europe, in addition to UK emission reductions.

Table 5.8. Reduction in agriculture PWMC (ug m^{-3}) relative to B2030.

Unit = µg m^{-3}	National	Urban	Rural	London	England
Lower	0.040	0.038	0.047	0.024	0.045
Central	0.068	0.065	0.079	0.041	0.075
Higher	0.075	0.071	0.087	0.045	0.083
Higher + Meat	0.095	0.091	0.110	0.056	0.105
Higher + Beef	0.087	0.083	0.101	0.051	0.096

Monetised benefits of abatement in the agriculture sector

Taking the monetised benefit given in the introduction of this report of £62.7 (range £16.9 to £178.2 indicating the uncertainties) per person per reduction of 1 µg m^{-3} $PM_{2.5}$, we can estimate the annual benefit of the above concentration reductions. Assuming a UK population of 67 million, the reduction of 0.068 µg m^{-3} in national population weighted mean concentration for the Central scenario for 2030 corresponds to a benefit of £286 million (£77 million to £812 million). For the highest ambition scenario, Higher + Meat, for 2030 the monetised benefit corresponds to £0.4 billion (£0.1 billion to £1.13 billion).

The mitigation of NH_3 emissions also has a positive impact on biodiversity. While we do not attempt to estimate the monetised benefit of the reduction of N deposition on sensitive habitats in this report (for which the monetised benefits are not as well-developed as for health impacts and as such the uncertainties are considerably greater), we do estimate the degree of improvement expected for each scenario in terms of exceedances of critical loads (CLs).

Effects on ecosystems

While the impact of the considered NH_3 emission reductions on SIA concentrations are modest, they do result in significant benefits to N-sensitive habitats. Figure 5.7 shows the change in % area of sensitive habitats assigned to different critical load (CL) exceedance categories relative to B2030. These exceedance categories were developed to provide a stable indicator of progress in reducing CL exceedances within the UK (Woodward et al. 2022). Details on the derivation of the exceedance categories can be found in the addendum to this chapter. Categories P0 and P1 (shown in dark and light green) indicate very low and low likelihood of exceedance, while categories P4 and P5 (shown in orange and red) indicate high and very high likelihood of exceedance. Categories P2 and P3 (shaded) indicate marginal cases.

Each of the NH_3 abatement scenarios achieve significant improvements in the UK-wide outlook of N exceedance, with a maximum increase of 8% of habitat area in the “unlikely to be exceeded” categories for the Higher + Meat scenario relative to B2030 (Figure 5.8), along with a similar reduction in the area of habitats in the “likely to be exceeded” categories. This is a 3% gain above the Higher scenario, for which only technological measures are considered, indicating that dietary change away from livestock products will likely have a positive impact on biodiversity. For England only, the Higher + Meat scenario leads to a 13% increase in habitat area unlikely to be in exceedance relative to the 2030 baseline.

For comparison we have also included an EV2040 scenario, for which the impact on ecosystems of the NO_x reductions due to the electrification of the traffic fleet by 2040 is modelled. This results in a 67 kt reduction in NO_x emissions. Despite this significant reduction in NO_x, only a modest improvement in CL exceedances is achieved as compared to that achieved by mitigating NH_3 emissions. NO_x tends to be transported long distances before being deposited, with a significant proportion of the oxidised nitrogen deposited in the UK imported from international shipping and other countries. In contrast, a large proportion of NH_3 emissions is deposited locally, leading to a greater proportion of UK NH_3 emissions being deposited on UK land.

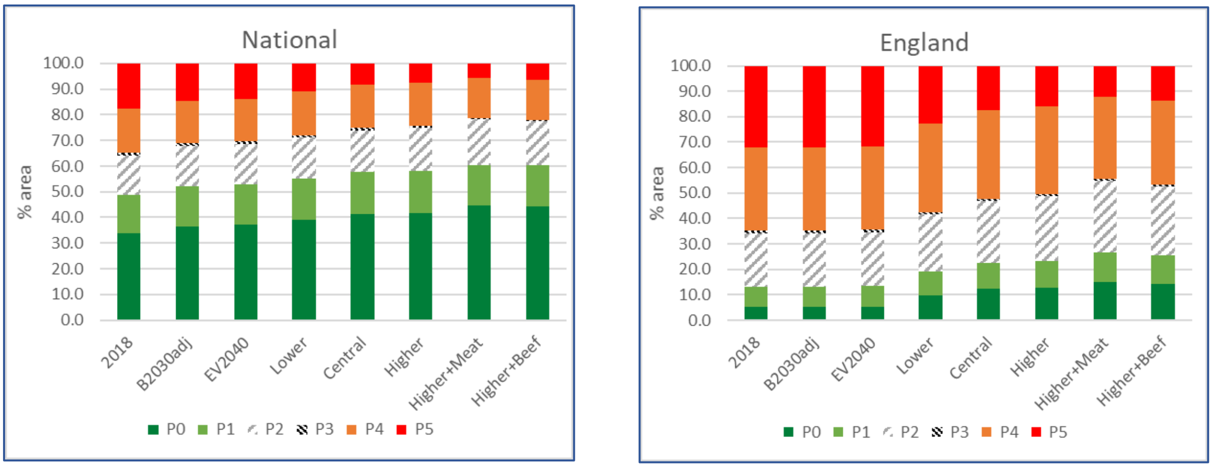

Figure 5.7: Percentage area of all N-sensitive habitats assigned to each exceedance score for (a) UK and (b) England.

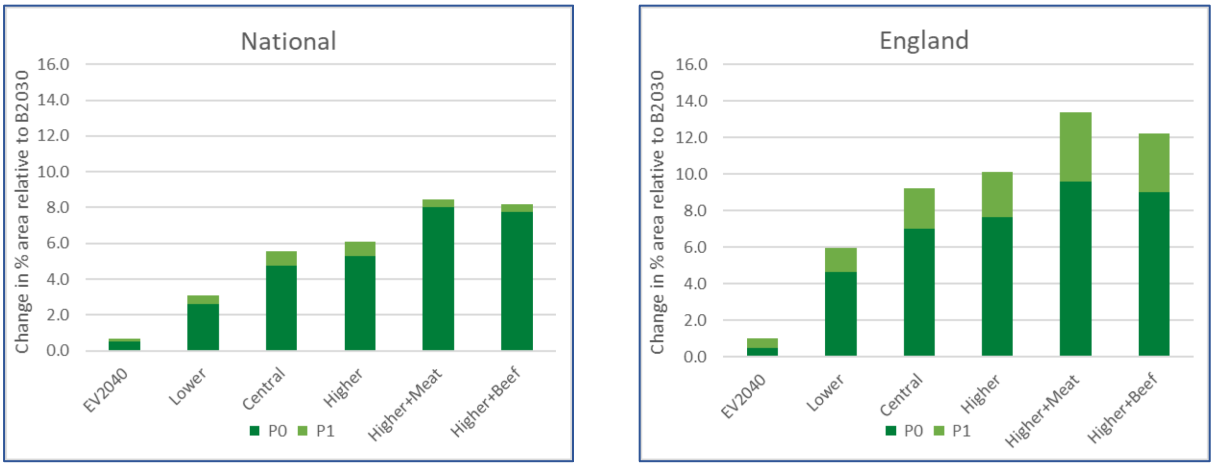

Figure 5.8: Change in percentage area of all N-sensitive habitats assigned to each exceedance score for (a) UK and (b) England relative to B2030.

While the reductions in exceedances achieved by the NH_3 abatement scenarios considered here are significant, such national emission reductions alone will not be sufficient to protect habitats to the degree outlined in the government's 25 Year Environment Plan (DEFRA, 2018b) which includes a target to restore 75% of the area of protected sites to favourable condition. As a high proportion of NH_3 is deposited locally, local measures such as the enforcement of Emission Reduction Zones in areas immediately surrounding sensitive sites has been shown to be a cost-effective way of reducing exceedances at these sites (see the Nitrogen Futures Report (Dragosits et al., 2020)). These are likely to be necessary to complement national-level emission reductions.

Summary

A range of scenarios have been considered for the abatement of NH_3 emissions from agriculture, including both technological measures and dietary change. Fairly modest reductions in population exposure to $PM_{2.5}$ were achieved even by the most ambitious scenarios considered; however, we expect that these reductions are somewhat underestimated due to limitations of the model. NH_3 abatement is also both effective and necessary in order to protect N-sensitive habitats in the UK from the impacts of eutrophication and to prevent further loss of biodiversity. Dietary change away from meat and dairy is likely to be an effective way of reducing N deposition within the UK and therefore reduce the impact on N-sensitive habitats.

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Addendum – Exceedance score

The critical load (CL) exceedance score was developed in order to account for some of the uncertainties in the modelling of nutrient nitrogen exceedance for sensitive habitats, and to provide a more stable indicator for improvement in CL exceedances. The method is outlined in detail in Woodward et al. (2022), however here we provide a short overview.

The method is based on that outlined in the JNCC's Nitrogen Decision Framework (Jones et al. 2016) for national-scale evaluation ("Factor 1" score). We use the minimum and maximum deposition values for a given habitat in each grid square to provide an indicator of the uncertainty, as illustrated in Addendum Figure 4. The two deposition estimates consist of the UKIAM estimate, and the UKIAM-Scaled estimate. The UKIAM-Scaled estimate is generated by scaling the UKIAM deposition in each grid square by a ratio of the UKIAM and CBED values for the 2016 base year. CBED is a semi-empirical model used for official reporting of CL exceedances. This analogous to using the 2016 CBED deposition estimates to estimate the deposition in future years, while still accounting for reductions in emissions.

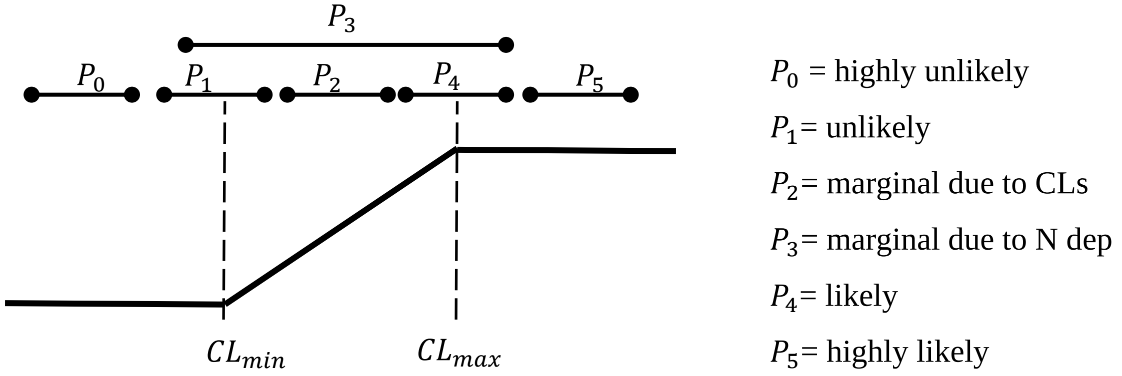
Six scores, P0, P1, P4 and P5, are defined ranging from highly unlikely to be in exceedance to highly likely to be in exceedance, and P2 and P3 which are defined as marginal due to CL estimates and deposition estimates, respectively. The difference between the deposition estimates provided by the two models varies in magnitude across the UK, providing an indicator of the varying degrees of uncertainty in these estimates. The largest differences are seen in areas of higher altitude and higher precipitation where complex wet deposition processes occur, such as occult and seeder-feeder deposition, and where the uncertainty is at its greatest. The exceedance score provides a more stable measure of progress than the exceedance of a single limit value which can be subject to step changes in response to very small reductions in deposition.

For each habitat within each grid square

$$N_{min}^{i} = \min\left(N_{UKIAM}^{i}, N_{UKIAM-Scaled}^{i}\right)$$

$$N_{max}^{i} = \max\left(N_{UKIAM}^{i}, N_{UKIAM-Scaled}^{i}\right)$$

Moorland or woodland deposition values are used depending on the habitat.



Addendum Figure 4. Definition of exceedance scores.

5.4 Energy and industrial combustion

Emissions of air quality pollutants

This section covers emissions from energy generation and from industrial combustion. Figure 5.9 shows the emissions from energy generation sources in SNAP1 for 2018; and for the baseline 2030 business as usual projections including changes already committed towards improvement of air quality emissions, and on which further abatement measures and changes reflecting climate policy can be superimposed. Most of these sources are in SNAP1, but also included is anaerobic digestion as an additional source of energy from biological wastes and of importance as a source of ammonia adding to agricultural emissions (see section 5.3 on agriculture and NH_3). Combustion of MSW is included in "small power other" sources and is another area of potential growth.

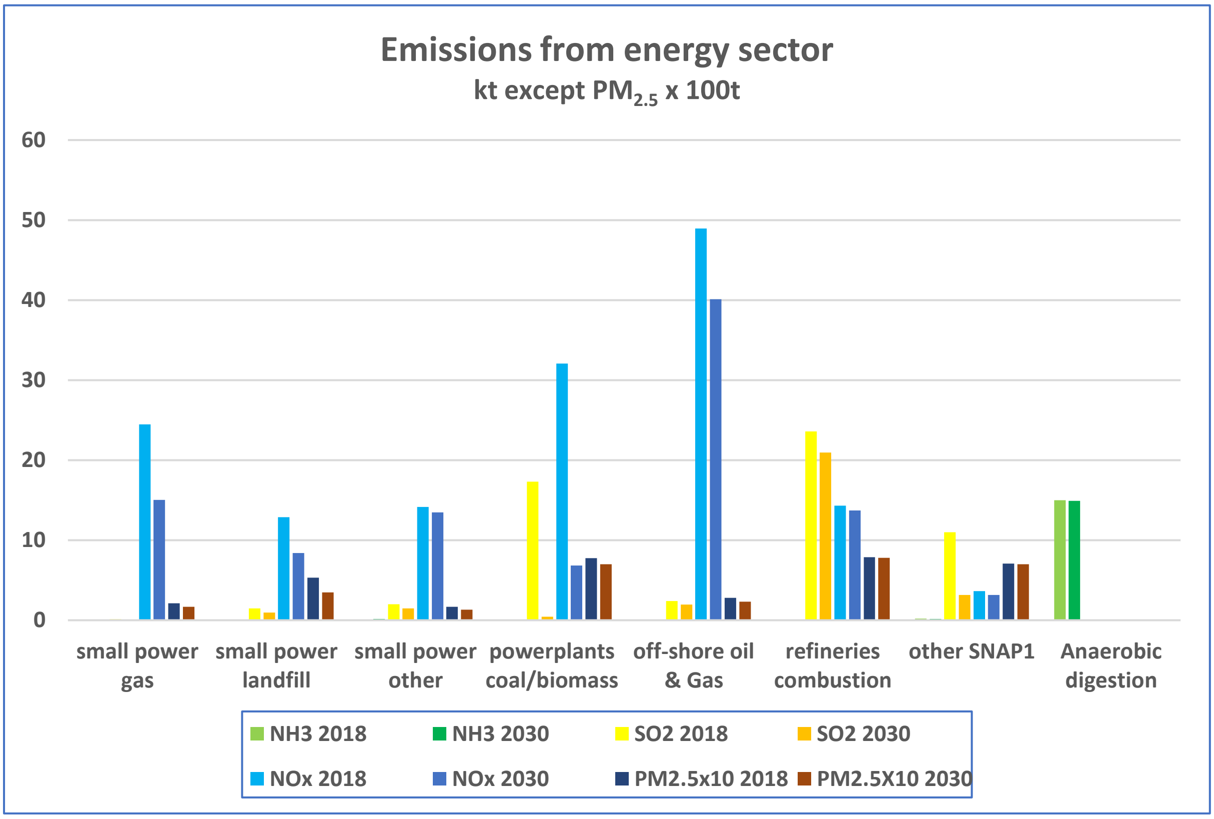


Figure 5.9. Emissions from the power sector in 2018 and the baseline 2030 scenario (units are in kt except for primary $PM_{2.5}$ where emissions have been multiplied by 10 to give units of 100 tons).

It can be seen that there are large reductions in some of the emissions, reflecting the major changes taking place in the energy sector, with increasing capacity from renewables and reduced reliance on gas-fired power plants. The large source of SO_2 from major power plants has been almost eradicated with the end of coal use, accompanied by a reduction in NO_x. Drax has undergone a conversion of 80% of its capacity to biomass and wood pellets, ending the use of coal. The major remaining source of SO_2 is refineries, where the 2030 projection does not allow for reduced needs for petrol and diesel with electrification of the fleet (see section 5.1 on road transport).

Emissions of NO_x are also significantly reduced in the 2030 baseline, with some possible further reductions in offshore oil and gas emissions depending on future demand. It is noted that these off-shore emissions are very small compared with those of international shipping emissions, currently generating 660 kt of NO_x in the seas surrounding the UK (see report on shipping - ApSimon et al., 2019).

With regard to primary $PM_{2.5}$ sources, emissions are smaller but can have concentrated local effects depending on the source characteristics. Emissions from power plants are tightly controlled; and overall total emissions of primary $PM_{2.5}$ from SNAP 1 sources are much smaller than the primary $PM_{2.5}$ emissions from industrial combustion in SNAP3, as discussed below.

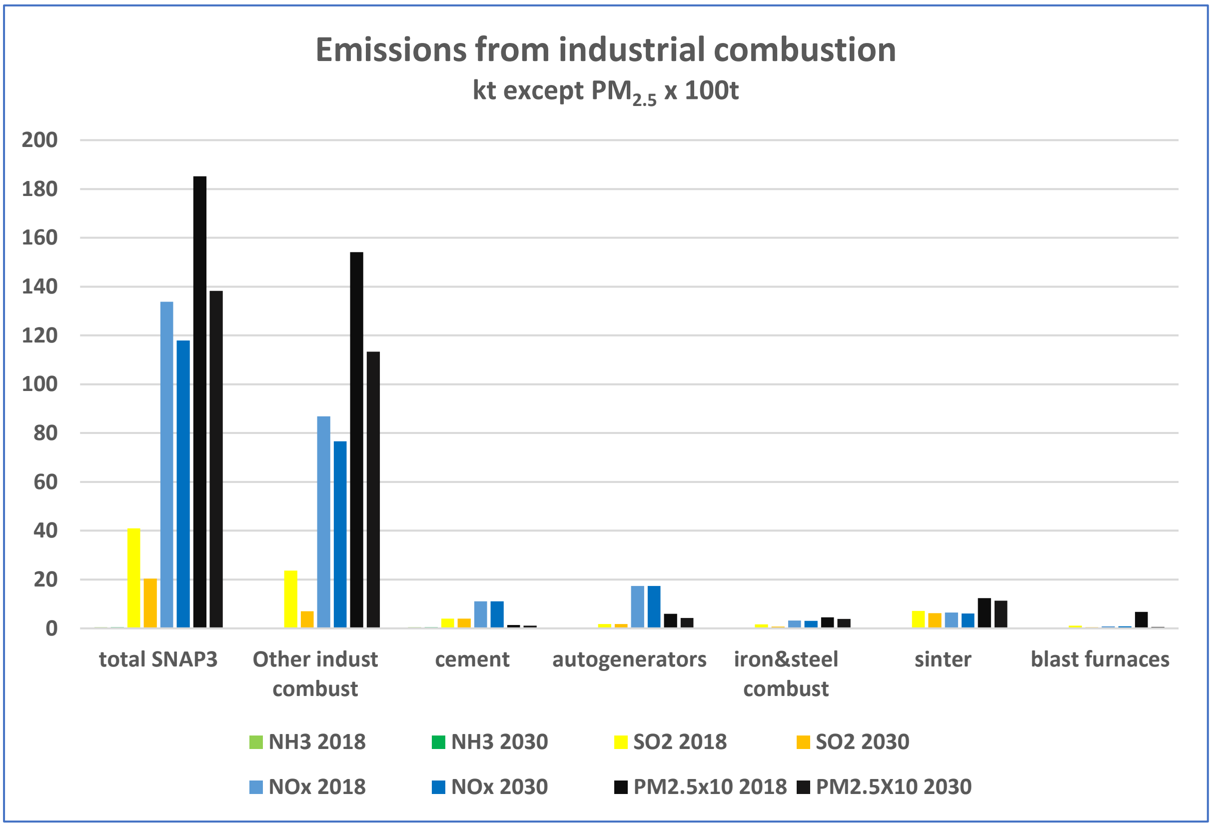


Figure 5.10. Emissions from industrial combustion sources in 2018 and the baseline 2030 scenario (units are in kt except for primary $PM_{2.5}$ emissions which are times 10 to give units of 100 tons).

Figure 5.10 shows the largest contributions to emissions from industrial combustion sources, together with total emissions from SNAP3. It is clear that "other industrial combustion", covering a range of smaller industries, dominates this category accounting for a large proportion of the total emissions. The larger industrial sources such as steel, auto-generator plants and the cement industry, which is a large source of CO_2, are already more tightly controlled. Turning to "other industrial sources", there is some reduction in emissions by 2030, reflecting the Medium Combustion Plant Directive, MCPD. Of particular importance is the major contribution to primary $PM_{2.5}$ emissions still accounting for 11 kt in 2030, which is a significant percentage of total UK $PM_{2.5}$ emissions.

Impact factors

The magnitude of the emission of a pollutant from a source is not the only factor determining its impact. The release characteristics and atmospheric dispersion patterns also play a role, and the surrounding distribution of population. Thus, a power plant with a tall stack and additional plume rise will not give rise to high ground level concentrations locally, whereas an industrial plant with a low-level release can disperse in a populated local area. Emissions of SO_2 and NO_x give rise to secondary inorganic particulate matter, SIA, through chemical transformation as they travel longer distances downwind.

This is reflected in the Table 5.9 of impact factors for $PM_{2.5}$ exposure below. An impact factor is the effect of a change of 1 kt of emission of a pollutant from a source on population exposure, expressed below as the change in population weighted mean concentration across the UK. Thus, the effect of changing emissions from a source can be approximated by adding the change in emission of each pollutant times the impact factor for that pollutant. Relating health impacts to exposure (see section 8.2) can then give a monetised value of impact on health to compare with any abatement costs.

Table 5.9. Impact factors.

Impact factors PM2.5 ng/m3/kt			
source	**NOx**	**SO2**	**PPM2.5**
gas landfill	**1.87**	**5.36**	**6.01**
gas CCGT	**1.24**	**2.56**	**5.74**
large power plants (Drax)	**0.76**	**3.59**	**0.79**
off-shore oil & gas	**0.16**	**0.98**	**0.14**
refineries	**0.97**	**1.11**	**5.65**
other industrial combustion	**1.05**	**3.30**	**8.36**

NB. power station impact factors are based on Drax, and there will be some variation with location and size of plant. But comparison with other power station sites show a similar picture.

It can be seen that there is a much bigger variation between sources in impact factors for primary $PM_{2.5}$ than for SO_2 and NO_x contributing to secondary $PM_{2.5}$. Thus, the impact of a 1 kt change in primary $PM_{2.5}$ emission from a major power plant like Drax, with release from a tall stack, is around ten times smaller than a corresponding 1 kt change in emission from "other industrial combustion". With regard to NO_x, the impact factors vary less between sources because it is the long-range formation of SIA that is relevant here. They are generally of the order of 1, although the impact factor is an order of magnitude smaller for more remote sources like off-shore oil and gas. However, there is also the contribution of NO_x to NO_2 concentrations which is a local effect and will vary in a comparable way to the primary $PM_{2.5}$.

The benefits for overall population exposure of additional air quality abatement measures for a source, taken for example from the Mult-Pollutant Measures Database, MPMD, can be assessed approximately by combining the changes in emissions with the impact factors as explained above. The full UKIAM model is necessary to map this exposure across the population and assess reductions in population weighted mean exceedance, as is currently being undertaken for overall future scenarios compiled by Defra. However, future emissions and exposure will also depend on climate measures and changes in energy generation.

Effects of changes in energy generation and net zero scenarios

There are large uncertainties in future energy scenarios and the achievement of net zero. However, the target of carbon neutral electricity generation by 2035 will drive the increase in renewables, including the use of biomass - although this may reduce subsequently as other energy sources increase. In this context as shown above, the conversion of Drax to biomass has eliminated SO_2 emissions from coal burning. Control of primary $PM_{2.5}$ emissions and release from the tall stack with additional plume rise gives a very small contribution to $PM_{2.5}$ exposure. The biggest effect will be the emission of NO_x, which, as shown in Figure 9, is an order of magnitude higher than for $PM_{2.5}$ but has a similar impact factor per kt of emissions due to secondary particulate formation.

Beyond 2035, scenarios differ in their relative emphasis on carbon capture and storage applied to gas use, and on expansion of nuclear energy, with the latter contributing little directly to air pollutant emissions. The amount of continued gas use is thus likely to be the critical factor for future NO_x emission from electricity generation, and air quality. Emission factors for gas plants fitted with CCS are uncertain; but are likely to be a bit larger than for conventional CCGT due to extra energy requirements for the CCS and lower overall efficiency. Some concerns about emissions of NH_3 now seem to have been resolved with alternative reagents. The potential contribution of anaerobic digestion to NH_3 emissions is of far greater importance.

In addition to electricity generation, other SNAP1 sources giving high air pollutant emissions are off-shore oil and gas, and refineries. Off-shore oil and gas give high NO_x emissions, but their effect on $PM_{2.5}$ exposure is limited by their location and the lower impact factor. This source is also likely to reduce over time, as UK resources of gas decrease. Refineries, which are a major remaining source of SO_2, as well as a source of NO_x and $PM_{2.5}$, are also expected to reduce as the need for production of fuel for ICE vehicles declines (see section 5.1 on electrification of road transport).

Concerning industrial emissions, the increased use of biomass needs more careful consideration than in a large power station such as Drax; both with respect to the mode of combustion and control of $PM_{2.5}$ emissions. This is also because the impact factors are an order of magnitude higher on average, though this will vary considerably from site to site with respect to dispersion characteristics and proximity to populated areas. As an example, an increase of say 5 kt of $PM_{2.5}$ combined with an impact factor of 8 from Table 5.9, gives an increase in the national averaged PWMC of 0.04 µg m^{-3}. This may seem small, but there will be localised spatial peaks that may be orders of magnitude higher, giving rise to high concentrations in local areas unless carefully regulated. The current problems of domestic wood-burning illustrate the potential effects of low-level chimney releases in urban areas. However, there will also be some conversion of industries to use of electricity, and opportunities for efficiency savings including from combined heat and power. There are also auto-generators and some individual industries generating significant air pollutant emissions such as iron and steel. The cement industry is also requiring control, as a large source of CO_2.

Summary and conclusions

Overall emissions of air quality pollutants from the energy sector are expected to decrease, but will depend on such factors as the continued use of gas plants fitted with CCS. A decrease is also likely up to 2050 for off-shore oil and gas, and refineries. With regard to industrial emissions one aspect that needs consideration is the potential effects of increased biomass use, especially in relation to smaller plants in urban areas.

Another factor which has not been considered above is the longer-term use of hydrogen and ammonia as fuels, where air quality emissions will depend on the mode of use (combustion versus fuel cell). However, this is unlikely to play a significant role until 2035 and beyond.

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6. Scenarios

In this section, we describe the application of UKIAM to a range of scenarios (see the list provided at the start of the document) up to 2050 towards the setting of future targets for $PM_{2.5}$. These scenarios consider a wide range of measures with different levels of ambition and influence of climate measures. They are based on emissions data produced using the Scenario Modelling Tool, SMT, to superimpose abatement measures on baseline NAEI projections, complemented by more detailed modelling of the road transport sector and electrification. The aim is to compare what the different scenarios achieve by 2030, 2040 and 2050 in reducing population exposure as a result of national application of the measures involved, and to investigate the higher end of the exposure distribution and the most exposed populations.

Description of scenarios

The first three scenarios investigated span different levels of ambition for air pollution abatement measures, applied to baseline NAEI 2018 emission projections with some adjustments to reflect recent developments and updates. These are the “medium”, “high” and “speculative scenarios” as described in more detail below; and include recent DfT projections for electrification of road transport, not included in the NAEI baseline. For 2030 these have been compared with an “NECR+EV” scenario, combining a scenario aimed at achieving the National Emission Ceiling Regulations, NECR, in 2030 coupled with electrification of road transport.

To investigate the effect of climate measures, a further net zero scenario has been included based on BEIS projections for achieving net zero by 2050, reflecting future changes in energy generation and fuel use to reduce greenhouse gas emissions. There are inevitably uncertainties in such projections, and this is just one of many potential future energy scenarios with associated dependence of air quality pollutant emissions (see section 5.4).

<u>SMT data & use of MPMD</u>
Abatement measures have been developed following consultations in the form of sectoral workshops with stakeholders and extensive review by Wood Plc, with potential emission reductions from different sources quantified in their Multi Pollutant Measures Database, MPMD. The measures can relate to new technology, or to changes in behaviour. These have been superimposed on baseline emissions to give revised emissions using the Scenario Modelling Tool,SMT. The SMT was developed by Ricardo EE (Energy & Environment) to enable the impact of different abatement measures on future emissions to be assessed. The tool works by applying specified measures to a baseline, modifying the emissions factor and/or activity level to produce a change in emissions. In application to the scenarios modelled here, it was assumed that measures applied nationally, whereas for the Environment Act we are concerned with England only. For this reason, UKIAM provides a breakdown of source apportionment for population exposure if required, distinguishing the contributions from the different devolved administrations.

The SMT baseline adopts the NAEI 2018 projections, with some baseline adjustments to reflect more recent information as described below. A limitation currently is that the NAEI 2018 projections only go up to 2030. Beyond 2030, only the road transport and energy projections vary in the SMT, as longer-term projections were not available for other sectors; other sectors remain at 2030 values up to 2050.

A further limitation is that the SMT is based on the NAEI and uses NFR codes. This means that if a source is not included in the NAEI, it will not be included in the SMT. One such source not included in the NAEI is emissions from cooking; the impact of cooking can act to counteract some of the benefits which may be achievable from other sources. This is illustrated in section 7 for London, and taken up in the discussion of uncertainties in relation to the setting of targets.

One area where more detail was needed for modelling with UKIAM is the road transport sector, where we need a detailed breakdown of the fleet by age and Euro standard for each vehicle type. Further, some of the abatement measures vary spatially, but information on this is scant. For example, some of the measures affecting car use, or last mile deliveries, apply in urban areas or specific areas such as the London ULEZ. Hence, we have separated the road transport measures out and modelled these specifically using the BRUTAL sub-model for road transport in UKIAM. This includes electrification of the fleet, as discussed in section 5.1.

There are generally around 50-75 measures per scenario, with different implementation start dates, maximum uptake and profile of uptake over time. These measures modify the baseline emissions (NAEI 2018) by changing the emission factor (EF) and/or activity levels.

The SMT then outputs emissions (both air pollutants and greenhouse gas emissions) for all baseline dates, including baseline adjustments and abatement measures. These emissions are then allocated to the appropriate UKIAM sources (which distinguish around 95 sources as subdivisions of SNAP sectors in each region- see section 2) based upon NFR classifications, and additional criteria where there is no clean mapping between NFR codes and SNAP sectors. The combination of the baseline emissions and emission reductions are then used as the basis of the (sub-)SNAP sector emissions required by UKIAM for each scenario and date. There were some notable exceptions where inconsistencies were detected in the SMT outputs and were adjusted in discussion with Defra.

The SMT only covers UK emissions. Imported contributions from other countries have been based on the With Additional Measures, WAM scenario of IIASA. Emissions from shipping have been modelled based upon the Ricardo AIS tracking data for the domestic and international fleets around the coast of the UK and in the North and Irish Seas. These imported contributions are described in section 2.

<u>The baseline scenario</u>
The baseline scenario includes some adjustments to the original NAEI 2018 projections, reflecting various updates and revisions for the following:

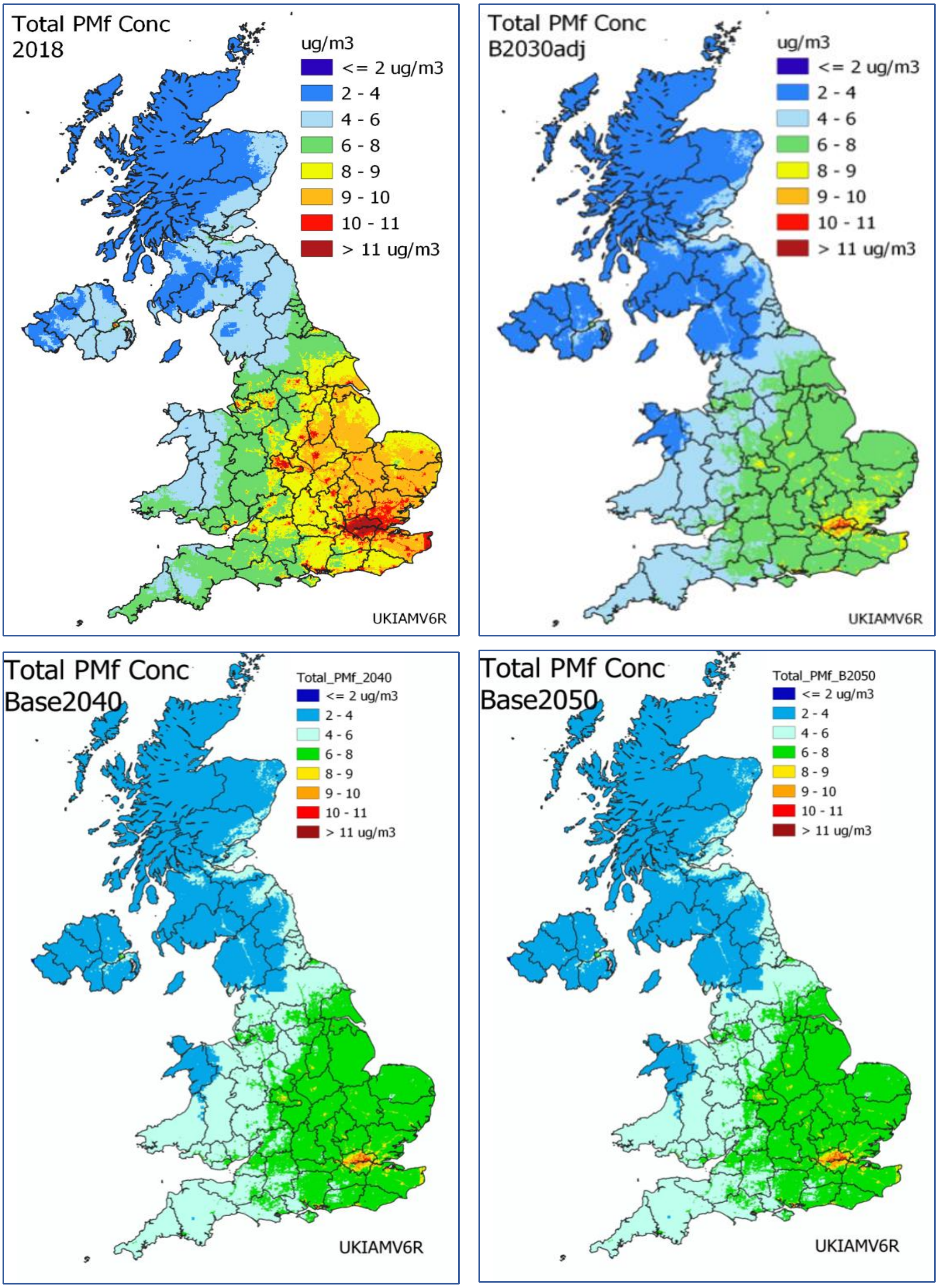
- The emission factors for new diesel cars were updated to reflect Euro 6 RWE standards
- The impact of the new regulations on the sale of small quantities of wet wood and house coal
- The wood burning emissions are adjusted to reflect updated evidence (but note further recent changes discussed in section 8)
- The impact of the recent changes to the regulations on red diesel
- The impact of the Medium Combustion Plan Directive and High NO_x generators
- The power stations natural gas production was adjusted to align with updated BEIS projections
- The revision of the Directive on emissions from NRMM gas oil
- Adjustment to reflect BAT conclusions for Waste Incinerations

The resulting emissions broken down by SNAP sector are given in Table 6.1 for different years up to 2050. Relative to 2018, there are large emissions reductions by 2030 in the baseline projections, but subsequently there are smaller further reductions to 2040, and thereafter emissions remain almost constant. This is reflected in the corresponding maps of concentrations in Figure 6.1.

Table 6.1. Emissions by sector for the baseline scenario (kt).

SNAP	2018				2025				2030				2040				2050			
	NH_3	SO_2	NOx	$PM_{2.5}$	NH_3	SO_2	NOx	$PM_{2.5}$	NH_3	SO_2	NOx	$PM_{2.5}$	NH_3	SO_2	NOx	$PM_{2.5}$	NH_3	SO_2	NOx	$PM_{2.5}$
1	0.3	57.9	150.5	3.5	0.3	30.7	114.4	3.5	0.3	29.0	100.7	2.8	0.3	28.7	96.4	2.7	0.3	28.7	96.4	2.7
2	2.5	33.1	46.1	47.0	2.9	14.0	37.6	28.5	2.9	11.3	37.9	28.6	2.5	4.8	38.8	28.7	2.1	2.9	38.8	28.7
3	0.4	40.9	133.7	18.5	0.4	26.8	122.0	14.9	0.4	20.3	118.0	13.8	0.4	20.0	116.1	13.6	0.4	20.0	116.1	13.6
4	2.6	8.8	10.8	7.5	2.5	9.7	8.3	6.7	2.5	9.3	7.7	6.6	2.5	9.2	7.7	6.6	2.5	9.2	7.7	6.6
5	0.0	0.6	2.0	0.5	0.0	0.4	1.5	0.4	0.0	0.2	0.8	0.2	0.0	0.2	0.7	0.2	0.0	0.2	0.7	0.2
6	1.2	0.0	0.0	1.2	1.3	0.0	0.0	1.1	1.3	0.0	0.0	1.1	1.3	0.0	0.0	1.1	1.3	0.0	0.0	1.1
7	4.4	1.3	254.9	15.8	4.8	1.3	110.6	12.5	4.9	1.3	62.5	10.3	4.7	1.1	64.8	12.6	4.3	1.1	71.1	13.8
8	0.0	2.7	82.6	6.2	0.0	2.7	67.1	3.5	0.0	2.7	62.8	3.3	0.0	2.7	62.9	3.4	0.0	2.7	62.9	3.4
9	22.3	0.6	1.3	1.7	22.5	0.6	1.3	1.7	22.5	0.6	1.3	1.7	23.5	0.6	1.3	1.7	23.5	0.6	1.3	1.7
10	231.7	0.0	26.9	2.8	230.9	0.0	27.2	2.8	229.7	0.0	27.1	2.8	229.7	0.0	27.1	2.8	229.7	0.0	27.1	2.8
11	9.0	0.0	0.2	3.3	9.2	0.0	0.2	3.2	9.4	0.0	0.2	3.1	9.4	0.0	0.1	3.1	9.4	0.0	0.1	3.1
TOTAL	**274.3**	**145.9**	**709.0**	**108.0**	**274.9**	**86.2**	**490.1**	**78.8**	**274.1**	**74.8**	**419.0**	**74.4**	**274.3**	**67.2**	**415.9**	**76.3**	**273.5**	**65.3**	**422.2**	**77.5**

Figure 6.1. Maps of $PM_{2.5}$ concentration for the baseline in 2018, 2030, 2040 and 2050.



The Medium, High and Speculative air pollution abatement scenarios

As indicated above, three distinct air pollution abatement scenarios have been created for the target modelling. These are referred to as *Medium*, *High* and *Speculative*. These scenarios provide different levels of ambition/optimism by the inclusion of different measures, varying the measure implementation date, and specifying maximum uptake and uptake rates.

All scenarios include substantial action to reduce $PM_{2.5}$. However, the *Medium* tends to include measures based on existing technology and limited behavioural change, with longer implementation times and lower uptake. *High* includes additional measures based on proven technology and moderate behavioural change, with conservative implementation rates and uptakes. Finally, *Speculative* includes measures based on emerging technologies and significant behavioural change, with optimistic uptake rates and rapid implementation of measures. A full description of measures is available in the sector report produced by Wood Plc. These measures are not government policy, and are only indicative measures for the purpose of understanding the achievable targets under different circumstances.

The Medium scenario

The Medium scenario is the least ambitious and is based on measures and activity levels identified during the sectoral workshops organised by Wood Plc. These scenarios include the implementation of proven technologies and limited behavioural changes, with increasing levels of implementation and uptake in 2030, 2040 and 2050 relative to 2018, including:

- Increasing the use of eco-design stoves and reducing the use of open fires by 50% by 2050
- Up to 10% reduction in urban traffic
- Uptake of electric/hydrogen non-road mobile machinery (NRMM) reaching 50% uptake by 2050
- Reduced industrial combustion and increased use of filtration technologies to reduce PM emissions

The High Scenario

The High scenario is more ambitious and is again based on measures and activity levels identified during the sectoral workshops organised by Wood Plc. These scenarios include uptake of technologies considered likely to be implementable in the future by stakeholders during the workshops, and an increased rate of behavioural change together with more rapid uptake of measures over time. These measures include:

- The banning of domestic indoor wood burning in smoke control areas which are also likely to include other solid fuels
- Restrictions on domestic outdoor burning
- A 22% reduction in urban car traffic by 2040
- Uptake of electric/hydrogen non-road mobile machinery (NRMM) reaching 95% uptake by 2050

The Speculative Scenario

The Speculative scenario is the most ambitious and is again based mainly on measures and activity levels identified during the sectoral workshops organised by Wood Plc. These scenarios include all feasible measures including emerging technologies and assumptions of significant behaviour change. These measures include:

- Up to a 100% ban on domestic indoor wood burning nationally
- Up to a 40% reduction in urban car traffic by 2040. New technologies designed to capture particulates from tyre wear which may still be in the research stage
- Uptake of electric/hydrogen non-road mobile machinery (NRMM) reaching 95% uptake by 2040
- An assumption that the NO_x emission control area (NECA) is expanded to include shipping in the Irish sea, implementable by the International Maritime Organisation (IMO). This does not come in until 2050 and could lead to a reduction of NO_x of up to 256 kt in the non-ECA sea areas round the UK including the Irish Sea

The NECR scenario for 2030

As well as the above scenarios, an additional scenario has been analysed aimed at attaining the UK's emissions ceilings in 2030, as specified in the National Emission Ceiling Regulations, set in the context of reducing transboundary air pollution in Europe. Reciprocal commitments in other countries are reflected in the reduction of imported contributions to $PM_{2.5}$. This scenario did not allow for electrification of the fleet, and this has been added to make this scenario more comparable with the above scenarios, called the NECR+EV scenario. This additional benefit of adding electrification of the fleet is investigated in section 5.1. The NECR+EV scenario has only been modelled for the year 2030.

The Net Zero scenario

This scenario is based on projections of future energy generation, derived by the TIMES energy model for BEIS, reflecting climate measures aimed at reaching net zero greenhouse gas emissions. This is similar to the core scenario developed by the Climate Change Committee, CCC (CCC 2020). This scenario also reflects the commitment to achieve net zero emissions from electricity production by 2035, the year in which new ICE 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 domestic wood-burning, which therefore remain set as the emissions in the baseline.

It should be noted that there were some anomalous data in this scenario for certain sources, giving unexpected air quality emissions, which have been adjusted in discussion with Defra to avoid distorted contributions from some sources. It is hoped to investigate these aspects in more detail in future and the results presented here are regarded as preliminary, but the adjustments made are not thought to change the overall picture significantly. We have also included the same projections for road transport and electrification of the fleet based on DfT data as in the previous scenarios, instead of the BEIS projections based on earlier DfT projections.

Table 6.2 summarises the air pollutant emissions for the scenarios above. A more detailed breakdown of emissions by SNAP sector is given in the appendix of ancillary data. It is clear that the emissions reduce in each scenario over time, and that the reductions are greatest for the speculative scenario.

Table 6.2. Scenario Emissions.

scenario	2018				2030				2040				2050			
	NH3	SO2	NOx	PM2.5	NH3	SO2	NOx	PM2.5	NH3	SO2	NOx	PM2.5	NH3	SO2	NOx	PM2.5
Baseline	274	146	709	108.0	274	75	419	74.4	274	67	416	76.3	274	65	422	77.5
Medium					257	74	403	65.5	254	66	340	58.4	251	53	278	54.3
High					244	73	397	55.1	238	65	324	43.6	236	53	263	42.1
Speculative					241	72	363	40.5	230	54	290	36.2	229	52	262	34.1
NECR+EV					223	70	380	51.4								
NZ					279	48	512	85.6	278	44	323	64.4	278	30	249	56.1

6.1 Scenario results

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 6.2a, b and c show maps for the medium, high and speculative scenarios respectively in 2025, 2030, 2040 and 2050. These clearly show the improvement over time for each scenario; and the reduction not only in areas of red calculated as above 10 µg m^{-3}, but also in the orange area between 9 and 10 µg m^{-3} and eventually in the yellow area between 8 and 9 µg m^{-3}, respectively. In this context, allowing for model uncertainties, those areas in orange are clearly at risk of exceeding 10 µg m^{-3}; and in more adverse meteorological years areas in yellow may also be at risk. 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. Emissions for the NECR+EV scenario are similar to those for the high scenario in 2030. The map is not reproduced here, as it is so similar to the corresponding map in Figure 6.2b for 2030.

Table 6.3. Population weighted mean concentrations, PWMC: and population weighted mean exceedance, PWME, above 5ug .m-3 $_5$ (ug m^{-3}).

			PWMC					PWME>5		
Scenario	**National**	**Urban**	**Rural**	**London**	**England**	**National**	**Urban**	**Rural**	**London**	**England**
Baseline 2018	**9.16**	**9.54**	**7.84**	**12.34**	**9.70**	**4.22**	**4.57**	**2.86**	**7.33**	**4.76**
2030										
Baseline	**7.11**	**7.36**	**6.24**	**9.61**	**7.48**	**2.09**	**2.31**	**1.28**	**4.42**	**2.41**
Medium	**6.86**	**7.09**	**6.09**	**9.19**	**7.22**	**1.88**	**2.07**	**1.16**	**4.05**	**2.17**
High	**6.62**	**6.81**	**5.95**	**8.82**	**6.95**	**1.65**	**1.80**	**1.04**	**3.68**	**1.91**
Speculative	**6.16**	**6.30**	**5.67**	**8.16**	**6.46**	**1.25**	**1.35**	**0.85**	**3.04**	**1.46**
NECR+EV	**6.44**	**6.62**	**5.80**	**8.66**	**6.76**	**1.50**	**1.65**	**0.94**	**3.54**	**1.75**
NZ	**7.06**	**7.30**	**6.23**	**9.46**	**7.44**	**2.06**	**2.27**	**1.27**	**4.31**	**2.38**
2040										
Baseline	6.93	7.18	6.05	9.40	7.29	**1.86**	**2.07**	**1.07**	**4.12**	**2.14**
Medium	**6.41**	**6.60**	**5.73**	**8.60**	**6.72**	**1.41**	**1.57**	**0.83**	**3.40**	**1.64**
High	**6.03**	**6.18**	**5.52**	**8.03**	**6.32**	**1.08**	**1.18**	**0.68**	**2.84**	**1.26**
Speculative	**5.64**	**5.76**	**5.24**	**7.47**	**5.90**	**0.78**	**0.85**	**0.51**	**2.83**	**0.92**
NZ	**6.35**	**6.54**	**5.69**	**8.48**	**6.66**	**1.37**	**1.52**	**0.80**	**3.29**	**1.59**
2050										
Baseline	6.94	7.20	6.04	9.43	7.30	**1.85**	**2.07**	**1.07**	**4.13**	**2.14**
Medium	**6.12**	**6.28**	**5.55**	**8.12**	**6.41**	**1.16**	**1.28**	**0.69**	**2.92**	**1.35**
High	**5.80**	**5.92**	**5.37**	**7.63**	**6.06**	**0.87**	**0.97**	**0.57**	**2.43**	**1.04**
Speculative	**5.45**	**5.54**	**5.14**	**7.08**	**5.69**	**0.62**	**0.67**	**0.42**	**1.84**	**0.73**
NZ	**6.08**	**6.25**	**5.55**	**8.12**	**6.41**	**1.13**	**1.23**	**0.66**	**2.89**	**1.32**

To assess the improvement in exposure, population weighted mean concentrations have been calculated, averaged over the whole UK population, broken down into urban and rural populations, and then also for England and London. These PWMC values are given in Table 6.3. Also shown for interest are the population weighted mean exceedance of the revised WHO guideline of 5 µg m^{-3}. This shows the significant exceedance of this revised guideline even for rural areas and the most ambitious speculative scenario, illustrating the problems of ever reaching it because the irreducible contribution from natural and non-UK sources is already close to 5ug.m^{-3} over large areas of the UK . Exceedance of higher thresholds and the original WHO guideline of 10 µg m^{-3} is considered in section 8 in relation to setting targets, when account also needs to be taken of uncertainties.

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 NECR+EV scenario is only for 2030 and lies within the middle of the range. The net zero scenario gives reductions similar to the less ambitious 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.

The maps of concentration in Figure 6.2a to 6.2e at the end of this section give a corresponding picture of improvement, with successive reductions in the red, orange and yellow areas of the map for the medium, high and speculative scenario. These areas become increasingly concentrated in the London area; and are investigated in more detail in section 7.

Figure 6.2a. Maps for the medium scenario.

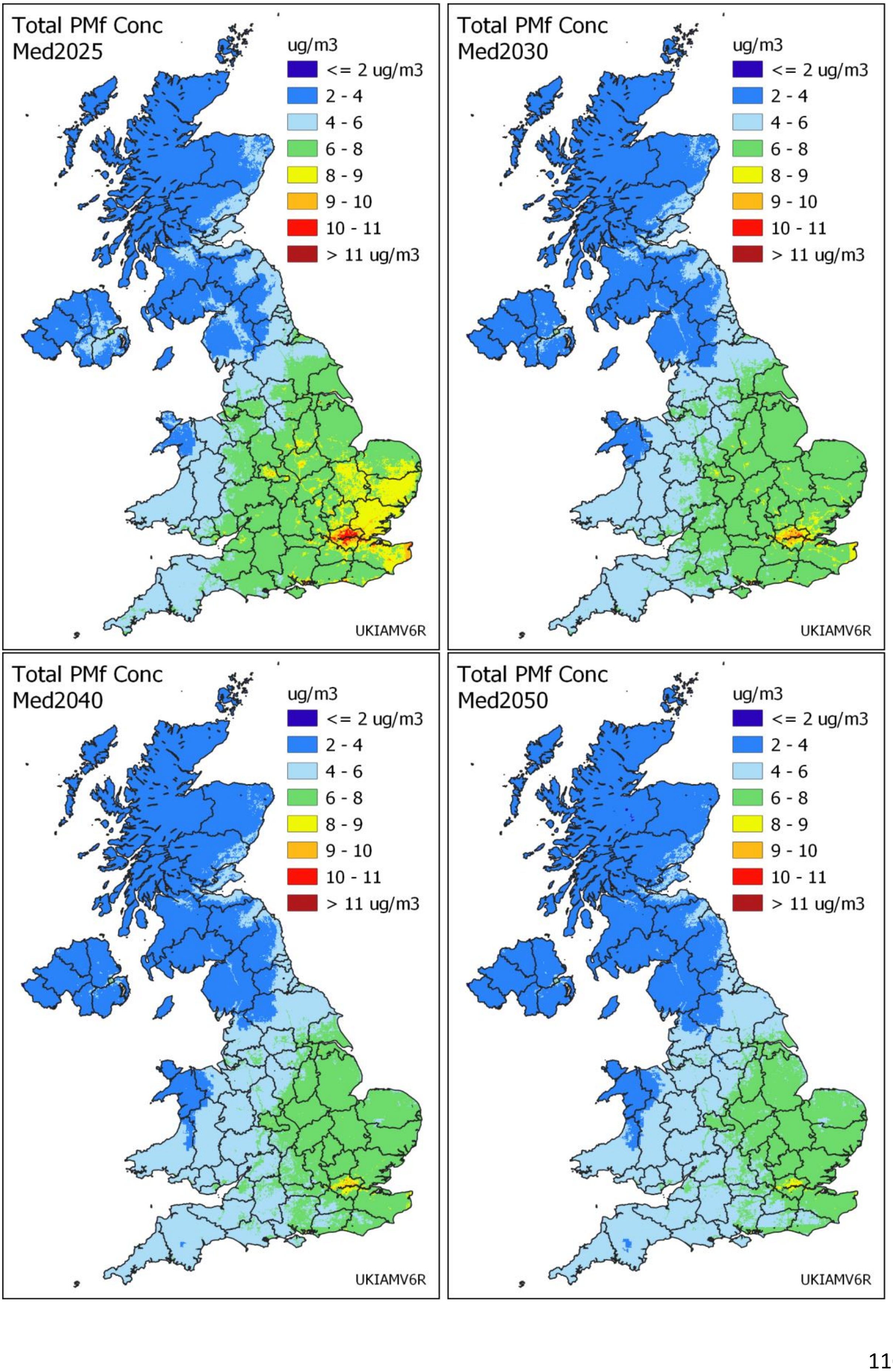


Figure 6.2b Maps for the High scenario

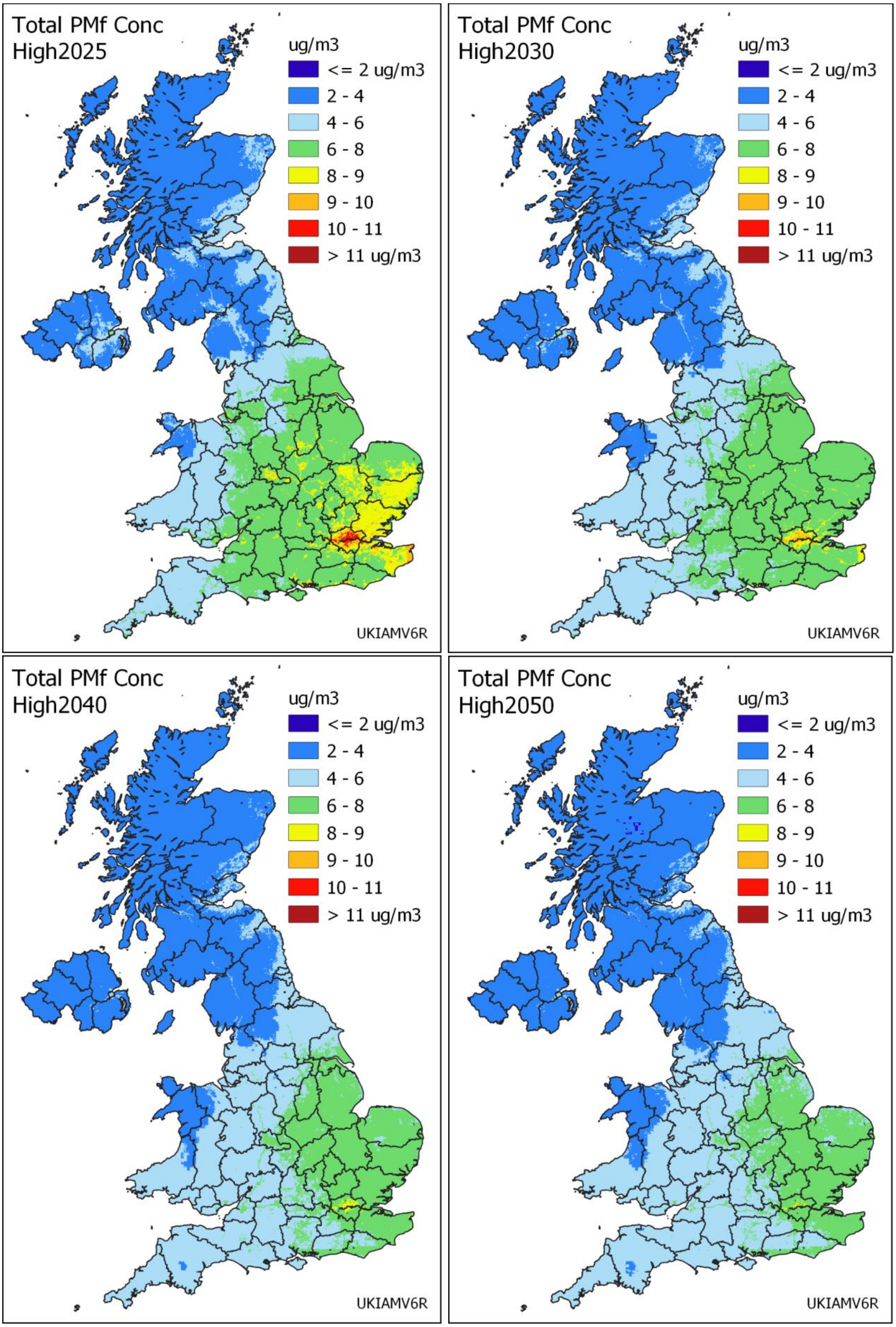


Figure 6.2 c Maps for the Speculative scenario

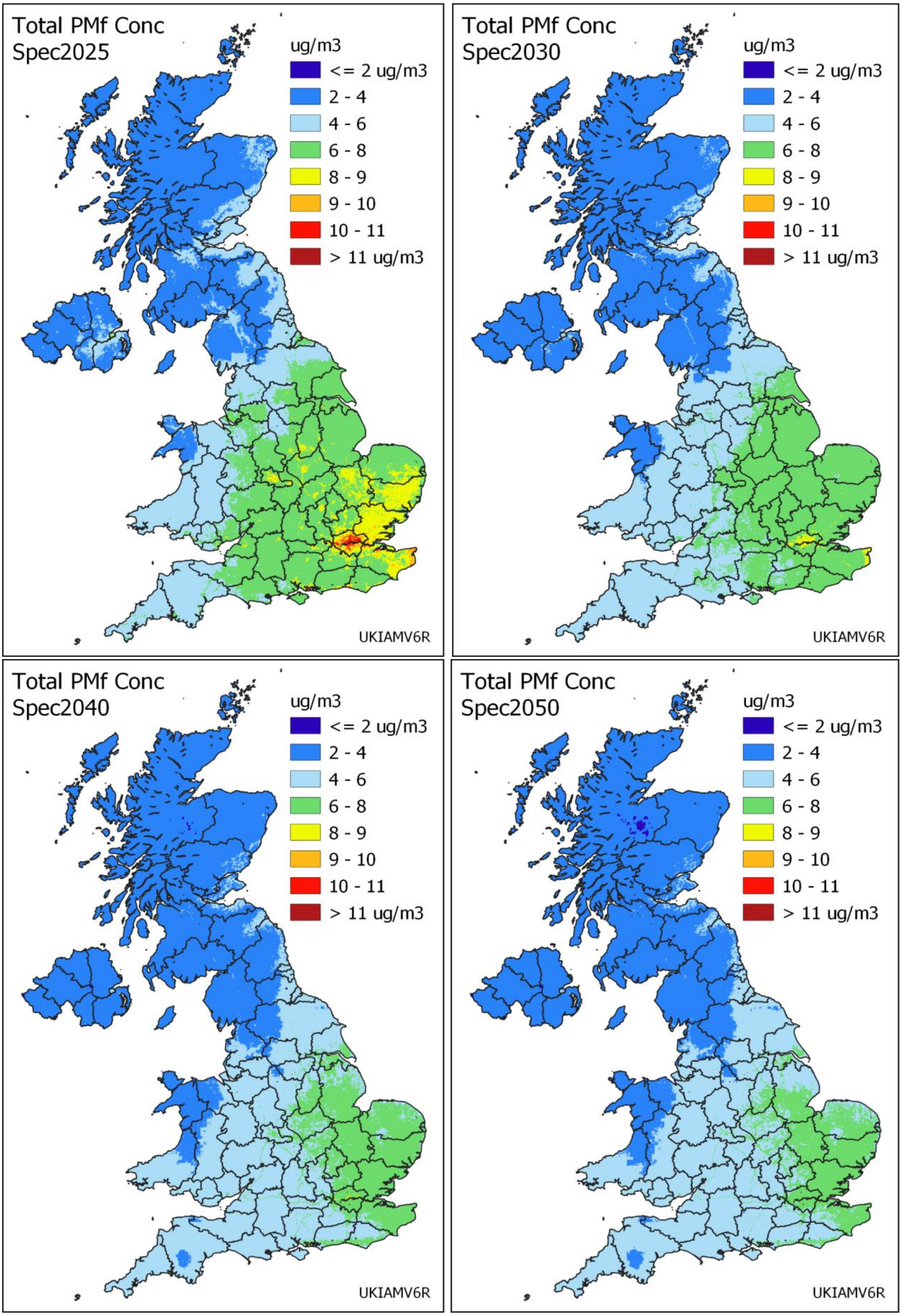


Figure 6.2 d Map of $PM_{2.5}$ concentrations for NECR+EV scenarios

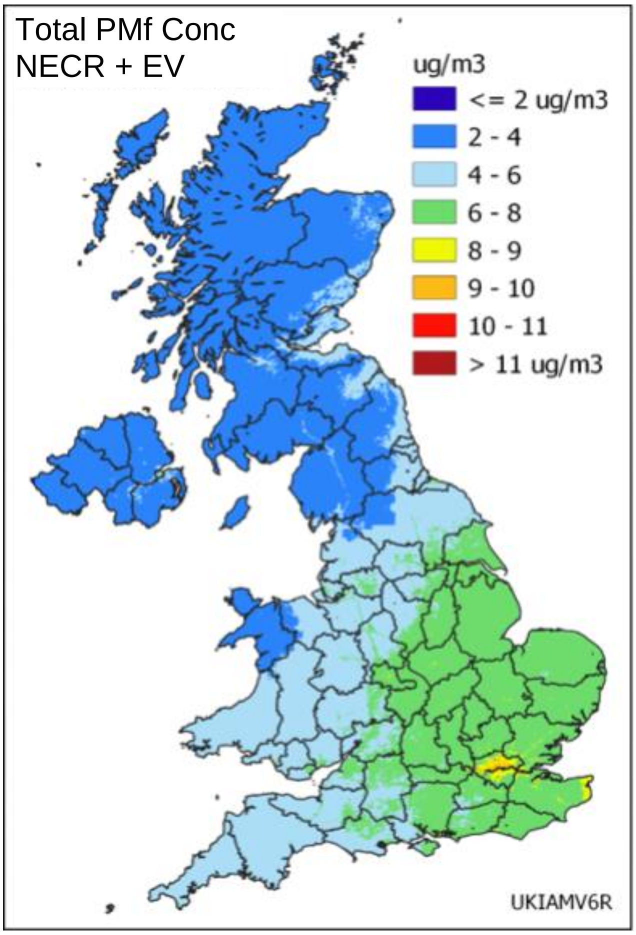
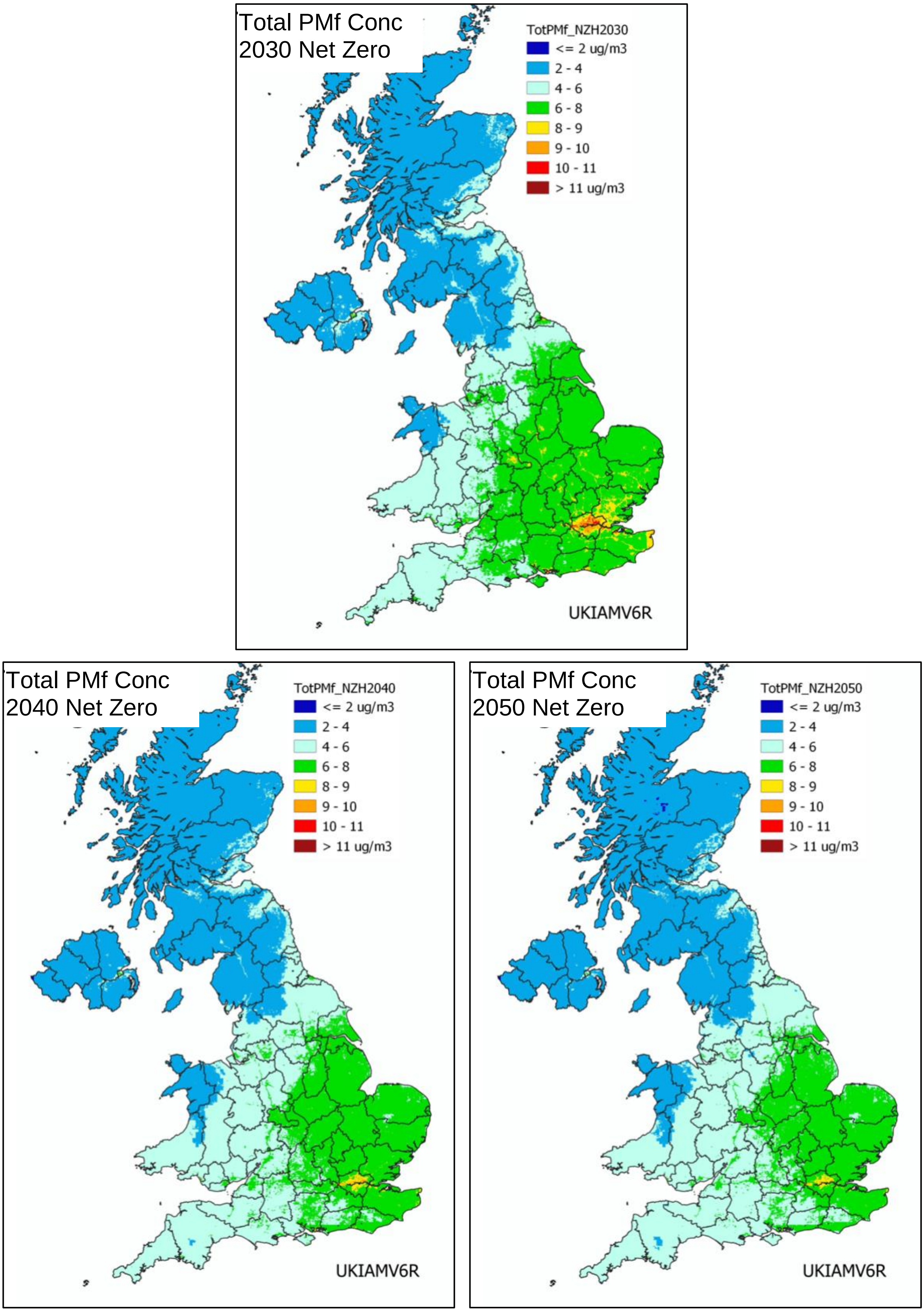


Figure 6.2e Maps of $PM_{2.5}$ concentrations for the Net Zero scenario



6.2 Summary and additional considerations

In this section, we have considered a range of scenarios with different levels of ambitions for abatement, and also net zero scenarios reflecting the effect of climate measures to explore the synergies with improving air pollution. The baseline scenario already shows a marked improvement of over 2 $\mu g\ m^{-3}$ by 2030, relative to 2018, in the PWMC for England. Further abatement generates up to another reduction of 1 $\mu g\ m^{-3}$ in the speculative scenario, and a further 0.8 $ug.m^{-3}$ by 2050, though with large uncertainties over the extended time scale.

It is also clear that London is a special case, with higher concentrations and exposure than elsewhere. This is critical when setting limits for the highest concentrations/exposure and is addressed in more detail in the next section, section 7.

With respect to additional considerations, there are also co-benefits of the scenarios in reducing NO_2. This has been assessed approximately in UKIAM, although the model has not been developed and tested with respect to NO_2 concentrations to the same extent, and in common with other models tends to underestimate (by around 20 %). The calculated reduction in exposure to NO_2 is taken into account when considering the overall health benefits in section 8.2. This is generally a relatively modest addition, with large uncertainties attached to the health effects of combined exposure to $PM_{2.5}$ and NO_2. More details of the reduction in NO_x are provided in the appendix of additional data.

An additional consideration for abatement of $PM_{2.5}$ is the extent to which this is also reducing black carbon, which contributes to short-term forcing with respect to global warming . Black carbon will be associated with combustion sources, and not with primary $PM_{2.5}$ generated by grinding and friction or SIA formed from SO_2, NO_x and NH_3 precursors. This is discussed in section 8 with respect to the relative toxicity of different $PM_{2.5}$ components.

In comparing the abatement scenarios, it is clear that some sources are particularly important, in particular road traffic. Another source is wood-burning in the domestic sector, where there are very large uncertainties in emissions and current revisions are underway to the NAEI. Sensitivity studies to the assumed emissions are therefore included when using these results towards target setting in section 8.

References:

CCC (2020) *The Sixth Carbon Budget – The UK's path to Net Zero*. Climate Change Committee. Available from: www.theccc.org.uk/publications/sixth-carbon-budget/. [Accessed 14 February 2022].

7. Reducing $PM_{2.5}$ concentrations in London

Analysis of potential abatement scenarios with UKIAM in section 6 has illustrated the much higher $PM_{2.5}$ concentrations across London, compared with the rest of the UK. In particular, the results show the difficulties of eliminating exceedance of the original WHO guideline of 10 µg m^{-3} by 2030. We now explore how superimposing stronger measures in London, on top of national measures, might get closer to achieving this guideline. These can be either London-wide or targeted on areas of higher concentrations within London – for example the enlarged London ULEZ. In earlier chapters, we have discussed the most important sources, and this is revisited here for London, including the uncertainties in wood burning and possible missing sources like cooking.

At a national level, UKIAM has been applied to study a range of scenarios including medium ambition, high ambition, and a speculative scenario with more extreme measures. Each scenario gives modelled concentrations for 2030, 2040 and 2050 as described in section 6. In this section, we start with a more detailed look at these scenarios for London in 2030, and then in 2040. In addition, we have modelled an NECR scenario aimed at achieving the UK's national emission ceilings for 2030 coupled with electrification of the fleet. This "NECR+EV" scenario gives intermediate results for improvement, similar to the High scenario.

Figure 7.1 shows maps of concentration across London for 2018; and for 2030 the medium, high and speculative scenarios plus the NECR+EV scenario. Under the baseline scenario there is clearly a huge improvement between 2018, when most of London is red and clearly above 10 µg m^{-3}, and 2030. Further abatement in the medium, high and NECR+EV scenarios leads to successively smaller areas in red down to a few grid-cells. The Net Zero scenario gives the least improvement for London, which might be expected since there are no additional air quality abatement measures – e.g. addressing domestic wood burning or traffic.

Bearing in mind model uncertainties, the areas in orange, between 9 and 10 µg 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. As a practical, less cautious indicator for achievement of the goal of bringing concentrations below 10 µg m^{-3}, we focus on removing the orange map areas. This is almost the case for the speculative scenario in 2030.

7.1 <u>London scenarios for 2030 and 2040</u>

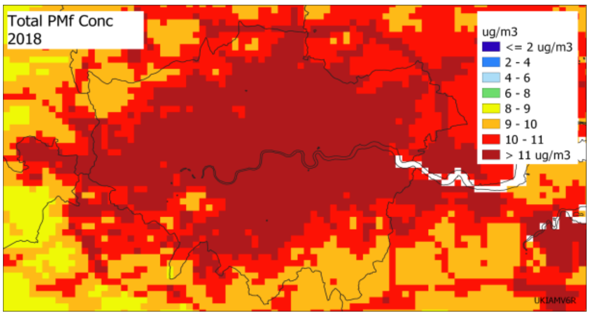
However, the speculative scenario is an extremely ambitious scenario, with optimistic assumptions about behavioural change and international imported contributions outside UK control. So, the question arises as to whether effective improvements in London could still be achieved by superimposing stronger measures in London on top of one of the other scenarios. As a first attempt, we tried coupling the national medium scenario with stronger measures in London from the high scenario (M2030LH); and then added even stronger measures in London from the speculative scenario (M2030LS). We then added a further reduction in cars to give an overall 60% reduction within the extended ULEZ region where most of the remaining orange cells in the map were located (M2030LSC). This was repeated with the High 2030 scenario as the starting point nationally, superimposing the measures for London from the speculative scenario (H2030LS). Since this still left some areas of inner London as orange, we finally explored whether spatially targeted measures reducing car use within the ULEZ area in London could solve this problem. This scenario (H2030LSC) is consistent with plans to reduce the large proportion of short trips by car in London, with greater use of public transport- or walking and cycling: and finally removes nearly all the orange squares from the map.

The maps for the H2030LS and H2030LSC scenarios are included in Figure 7.1 to illustrate this, and the table below shows the successive improvements in the population weighted mean concentrations, PWMC values in London, for all these hybrid scenarios in 2030. The national medium scenario coupled with the speculative scenario measures for London (M2030LS) gives a bigger improvement in London than the national high scenario. And the final H2030LSC scenario achieves almost the same as the national speculative scenario, eliminating nearly all the orange grid cells across London, and giving a similar improvement in population weighted mean concentration across London (8.296 µg m^{-3} instead of 8.164 µg m^{-3} for the speculative scenario).

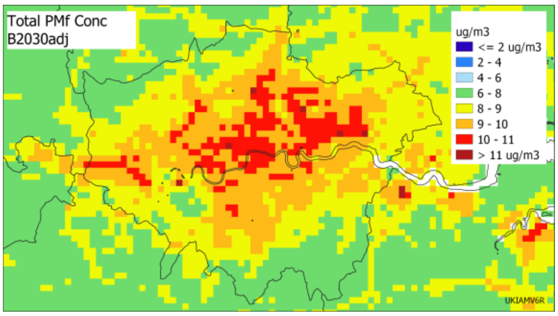
Moving on, this was repeated for 2040. The corresponding maps show a clear improvement in the national high 2040 scenario resulting in slightly more improvement in London than the extra measures in 2030 in the H2030LSC scenario. However, adding extra measures in London, culminating in the high scenario nationally coupled with the speculative scenario in London in 2040 (the H2040LS scenario), and then further reduction of car kilometres to give a total 60% reduction within the extended ULEZ area in the H2040LSC scenario, shows that these scenarios further reduce concentrations in London, eliminating any remaining areas in orange above 9ug.m^{-3} completely in the H2040LSC scenario. This is promising with respect to setting limit values in the next section.

Figure 7.1. Concentration maps for London.

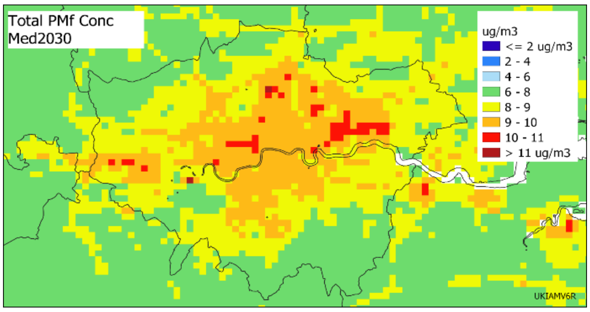
2018 PWMC=12.3397



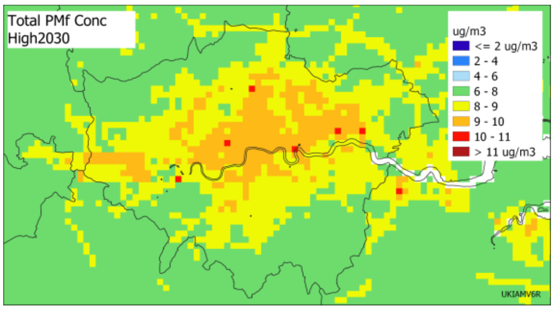
2030Badj PWMC= 9.606



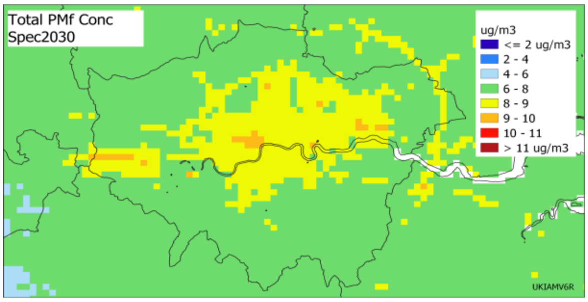
Medium 2030 PWMC=9.192



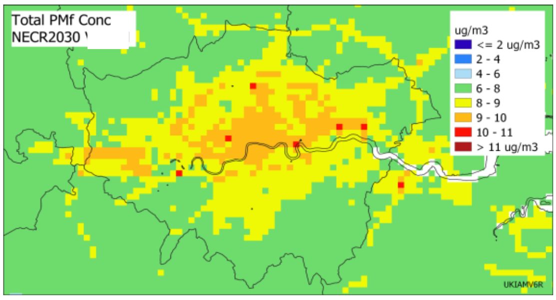
High 2030 PWMC= 8.82



Speculative 2030 PWMC = 8.165



NECR+EV 2030 PWMC= 8.657



Net Zero 2030 PWMC=9.461

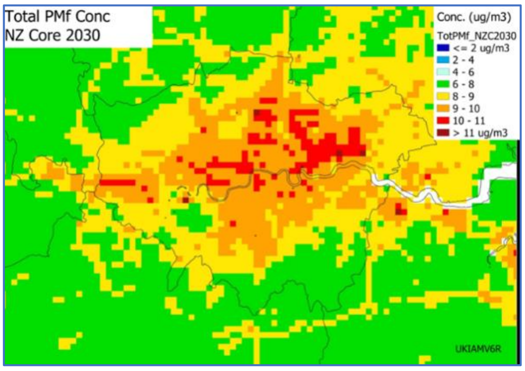
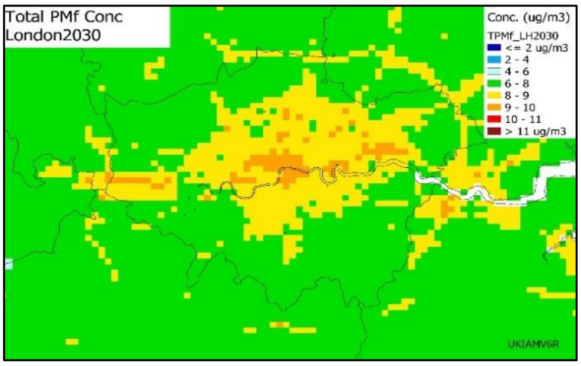
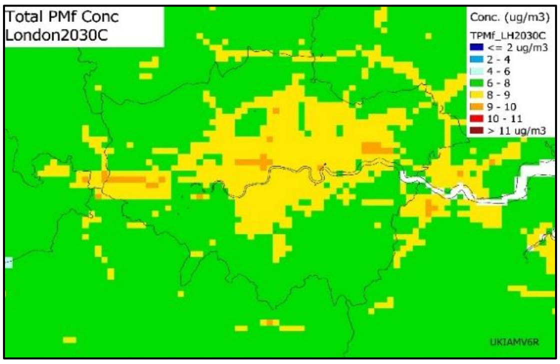


Figure 7.1 continued.

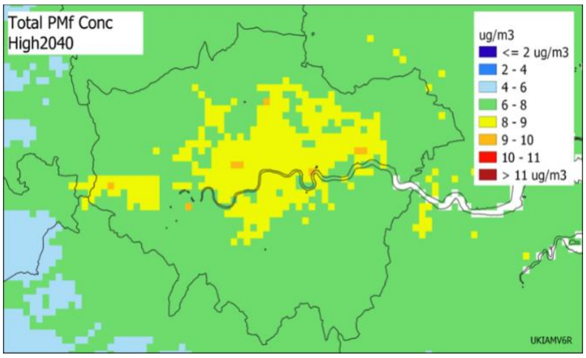
H2030LS PWMC=8.382



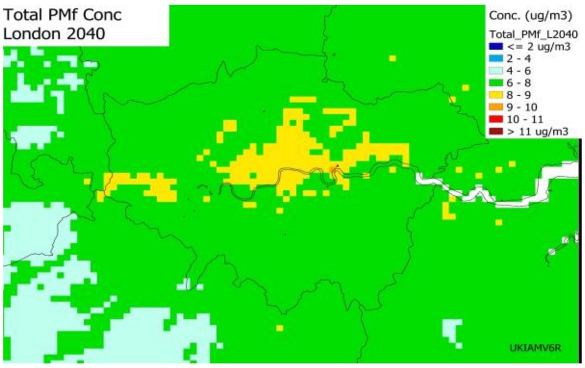
H2030LSC; PWMC=8.296



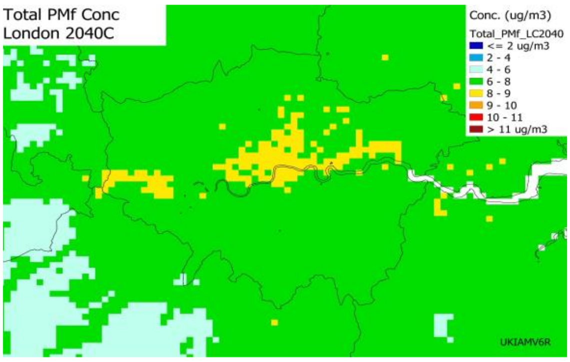
2040 high 2040 PWMC=8.034



H2040LS PWMC=7.772



H2040LSC; PWMC=7.718



PWMC values for hybrid scenarios with stronger measures in London (ug.m^{-3})

2030	PWMC	2040	PWMC
M2030LH	8.906	M2040LH	8.163
M2030 LS	8.467	M2040 LS	7.900
M2030LSC	8.380	M2040 LSC	7.847
H2030LS	8.382	H2040LS	7.772
H2030LSC	8.296	H2040LSC	7.719

To look into this in more depth for 2030, we first look at how the emissions in London in these more targeted emission reduction scenarios, compared with the baseline. This is shown broken down by SNAP sector in Table 7.1, followed by the reductions relative to the 2030 baseline in the second part of the table for the H2030LS and H2030LSC scenarios.

Table 7.1. Emissions and emission reductions for the B2030, HIGH2030, H2030LS and H2030LSC scenarios.

Total London emissions by SNAP (kt/yr)

	B2030		HIGH2030		H2030LS		H2030LSC	
SNAP	NO_x	$PM_{2.5}$	NO_x	$PM_{2.5}$	NO_x	$PM_{2.5}$	NO_x	$PM_{2.5}$
1	3.076	0.030	3.117	0.030	3.202	0.031	3.202	0.031
2	3.634	1.592	3.307	0.999	2.281	0.334	2.281	0.334
3	2.231	0.166	2.225	0.088	2.073	0.088	2.073	0.088
4	0.744	0.088	0.743	0.081	0.694	0.085	0.694	0.085
5	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
6	0.000	0.011	0.000	0.011	0.000	0.011	0.000	0.011
7	3.505	0.851	1.875	0.716	1.719	0.568	1.526	0.492
8	6.259	0.107	5.977	0.102	5.282	0.051	5.282	0.051
9	0.199	0.141	0.198	0.133	0.198	0.128	0.198	0.128
10	0.009	0.001	0.010	0.001	0.010	0.001	0.010	0.001
11	0.013	0.279	0.013	0.279	0.013	0.279	0.013	0.279
TOTAL	**19.669**	**3.266**	**17.466**	**2.440**	**15.471**	**1.575**	**15.278**	**1.499**

Change in emissions by SNAP sector relative to B2030

	B2030		HIGH2030		H2030LS		H2030LSC	
SNAP	NO_x	$PM_{2.5}$	NO_x	$PM_{2.5}$	NO_x	$PM_{2.5}$	NO_x	$PM_{2.5}$
1	0	0	-0.041	0.000	-0.126	-0.001	-0.126	-0.001
2	0	0	0.327	0.593	1.352	1.257	1.352	1.257
3	0	0	0.005	0.079	0.157	0.079	0.157	0.079
4	0	0	0	0.007	0.051	0.004	0.051	0.004
5	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0
7	0	0	1.630	0.135	1.786	0.283	1.979	0.359
8	0	0	0.281	0.006	0.977	0.056	0.977	0.056
9	0	0	0	0	0.001	0.013	0.001	0.013
10	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0
TOTAL	**0.000**	**0.000**	**2.203**	**0.826**	**4.199**	**1.691**	**4.392**	**1.767**

The largest emission reductions come from SNAP2, the domestic sector, where domestic gas and wood-burning are important sources; from SNAP7, road transport; and also from non-road mobile machinery, NRMM in SNAP8. The emissions of these sources for the different scenarios are given in Table 7.2. Figure 7.2 shows the contributions of these individual sources to $PM_{2.5}$ across London for the baseline B2030 scenario, noting that road transport with the highest concentrations is on a different scale.

Table 7.2. London emissions of key individual sources in 2030.

Source Name	London $PM_{2.5}$ emissions (t/yr) - selected sources B2030	H2030	H2030LS	H2030LSC
02_Domestic_Combustion_Gas	115.833	104.249	106.078	106.078
02_Domestic_Combustion_Wood	1462.853	883.622	220.255	220.255
NRMM (incl. Agri & Resid)	48.768	45.508	6.065	6.065
Road Transport (all vehicle types)	851.153	716.328	567.855	491.816

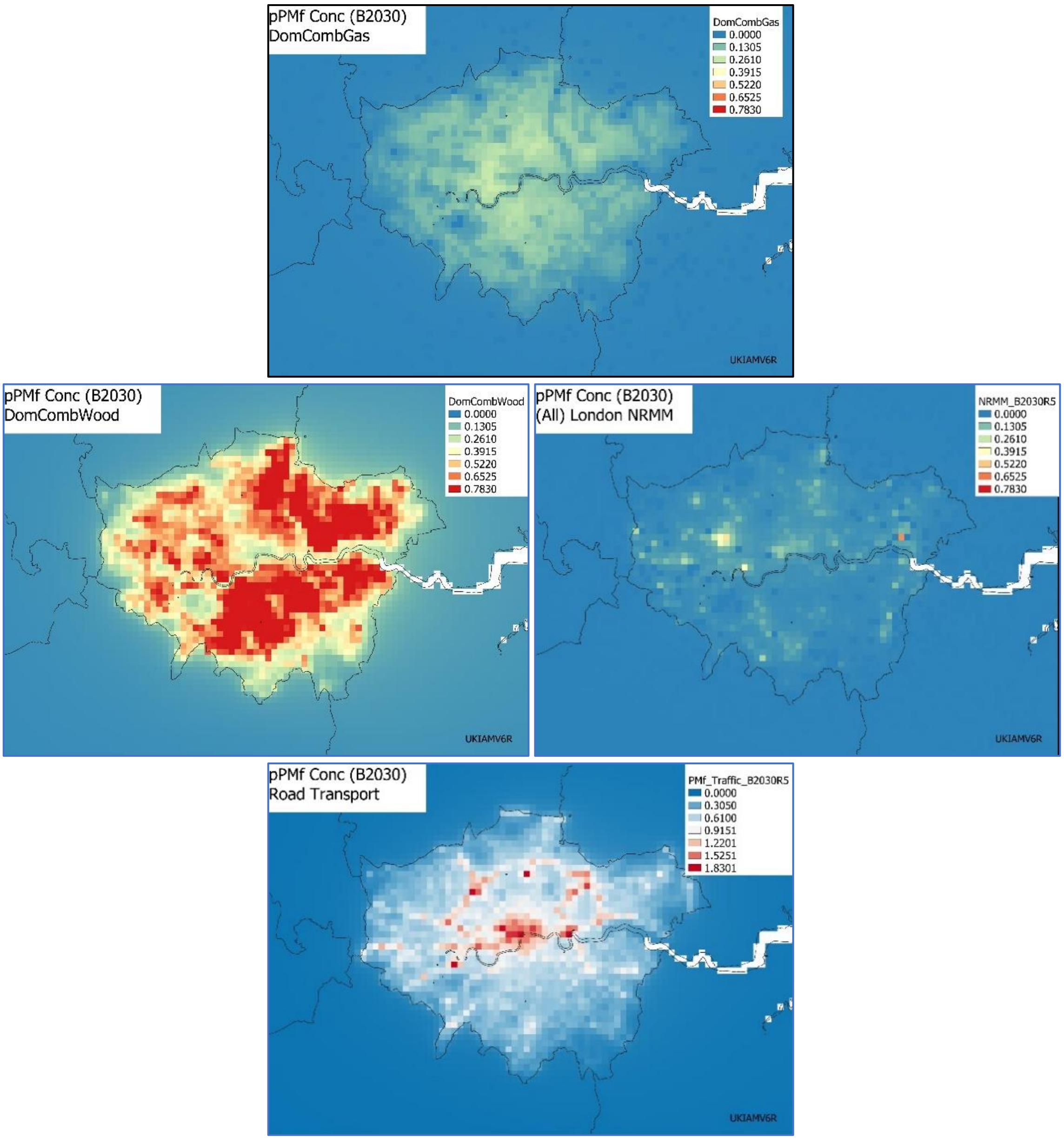


Figure 7.2. Footprints of key sources for the B2030 scenario.

It is clear that wood-burning, with high emissions of primary $PM_{2.5}$, has a much bigger effect than natural gas, despite the small proportion of energy generated. Consequently, wood burning has been targeted in the abatement scenarios, with much larger reductions in the London scenarios than in the national high scenario. The NRMM is almost removed in the London scenarios, though this has a limited effect on concentrations, and is mainly due to industrial and construction machinery. The successive emission reductions from traffic make an important difference, especially the traffic reduction measures which reduce the non-exhaust emissions. These are important for the improvement from the L2030 to the L2030C scenario in the extended ULEZ area of inner London, although traffic remains the largest contribution. The effect of abatement of the different sources is evident from Table 7. 3, showing the contribution of each of these source categories to population weighted mean concentrations in London for the different scenarios.

Table 7.3. Source contributions to PWMC in London (µg m-3).

		London PWM Concentration ($PM_{2.5}$) *from <u>London Sources</u>* - µg m^{-3}			
Source	**SID**	**B2030**	**H2030**	**H2030LS**	**H2030LSC**
02_Domestic_Combustion_Gas	**8**	0.148298	0.133467	0.135809	0.135809
02_Domestic_Combustion_Wood	**10**	0.711139	0.429557	0.107073	0.107073
NRMM (incl. Agri & Resid)	**59-61**	0.042912	0.040217	0.005149	0.005149
Road Transport (all vehicle types)	**46-50**	0.705433	0.503147	0.461045	0.377351

7.2 Uncertainties and other sources

It is clear from the above that there are large advantages in applying more stringent measures in London, as compared with universal application to the whole country, and suggests that further analysis is needed of hybrid scenarios extending beyond 2030. But there are also large uncertainties, which become particularly important for the densely populated London area.

In relation to wood burning, we have noted in the domestic sector analysis in section 5.2 that there are large uncertainties in emissions from wood burning and that recent updates in DUKES energy statistics have suggested amounts of wood burnt used may be a factor of two thirds less than has been assumed in the NAEI 2018 estimates. Work is continuing to refine emission factors allowing for a proportion of wet wood. This implies that the contribution from wood burning could be as little as a third of the PWMC values above, which would be more in line with the London Atmospheric Emissions Inventory, LAEI estimates (ApSimon et al., 2019). This is addressed as a sensitivity study in section 8. We are also aware of other substantial differences between the LAEI and the NAEI including spatial mapping (e.g. for NRMM) as well as magnitude of emissions.

However, of greater concern are sources omitted in the NAEI which might counteract the overestimate of wood burning emissions in the baseline NAEI data, but whose control is not addressed in the abatement scenarios above. A specific source is the contribution from cooking, where in previous work we suggested an upper estimate of the potential contribution from commercial and domestic cooking. This is especially important in areas of London with restaurants and commercial food outlets. The effect of adding this to the H2030LSC scenario is shown in Figure 7.3, and clearly shows how omission of such a source could completely counteract efforts to control other sources.

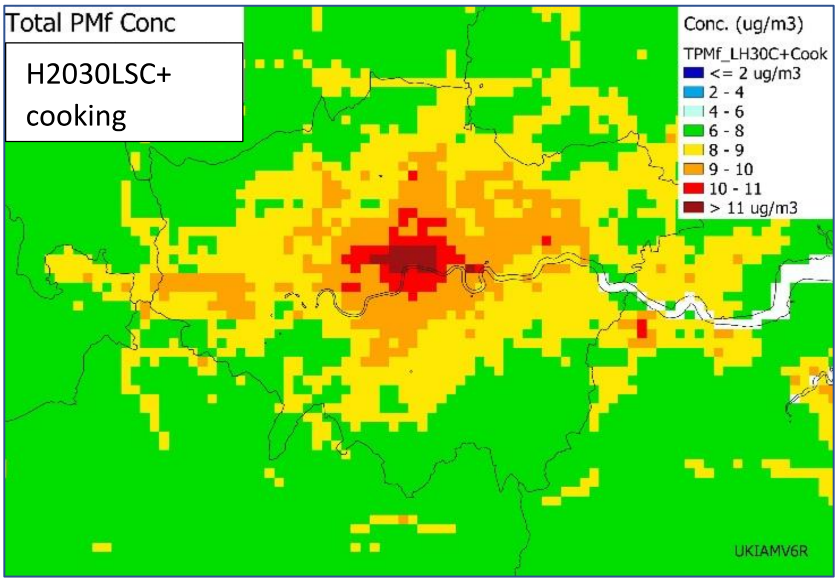


Figure 7.3. Possible effect of missing source such as cooking to the H2030LSC scenario.

With the major reduction of key sources in the H2030LSC scenario there are still several smaller, but uncertain, sources contributing to $PM_{2.5}$ concentrations. This is illustrated below in Figure 7.4, for the combined effect of fireworks (national $PM_{2.5}$ emissions 172 tons), cigarette smoking (57 tons) and accidental fires (52 tons). These are all very small but concentrated sources in London, contributing a very uncertain 0.4 µg m^{-3} to the population weighted mean concentration.

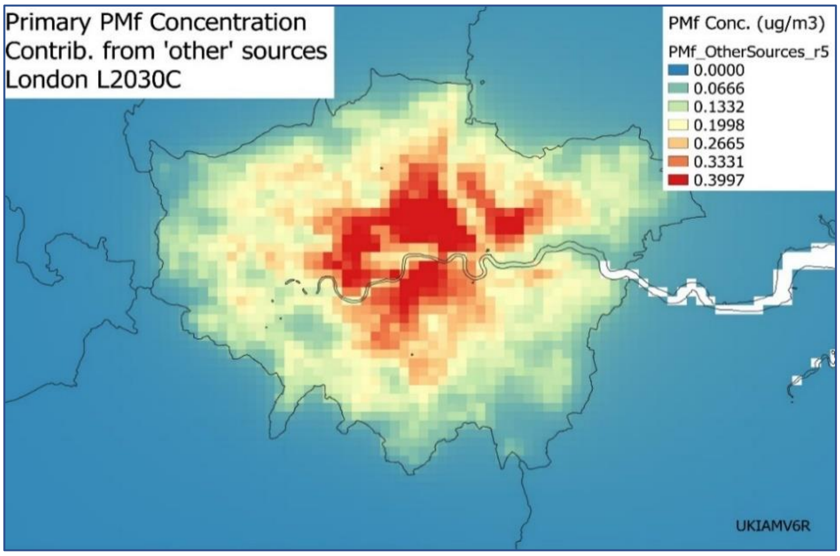


Figure 7.4. Contribution from fireworks, smoking and accidental fires.

7.3 Summary

In this section, we have focused on London as the area with the highest concentrations, and the extent to which the various national scenarios in section 6 improve population exposure here. These imply that the speculative scenario nearly achieves the original WHO guideline of 10 μg m^{-3} in 2030, but it would be very difficult to implement. However, the imposition of stronger measures just in London, superimposed on the high scenario, helps convergence towards the same result. Other scenarios for 2030 and 2040 superimposing stricter measures in London also show corresponding benefits for overall improvement. It is therefore useful to add such hybrid scenarios both for 2030 and 2040 towards the consideration of target setting in section 8, together with sensitivity studies to assumed emissions from wood-burning and consideration of uncertainties.

Reference:

ApSimon, H., Oxley T, Woodward, H., Mehlig, D. (2020) *Uncertainties in modelling the contribution from primary particulate sources to PM2.5 concentrations*. SNAPCS contract report. Available from: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/930109/annex1-pm25-imperial-college-report.pdf [Accessed 25 February 2022].

Analysis of abatement options to reduce $PM_{2.5}$ concentrations

Part 3: Towards setting targets

8. Application to setting targets

Defra is committed to developing two air quality targets as required in the Environment Act. it is proposed that the first is a reduction in population exposure and associated health impacts which are represented in this report by population weighted mean concentrations. The second, which is specified in the Act, is concerned with limiting outdoor concentrations for those living in the worst areas with the highest concentrations. These targets need to be achievable and robust with respect to assumptions made. In this section we assemble the results of our analysis for population weighted mean concentrations with respect to the first target. This is followed by estimates of population weighted mean exceedance of threshold values in the range 8 to 12 ug.m^{-3} with respect to setting limit values, where it is important to recognise that UKIAM calculates average concentrations over 1x1 km^2 grid-squares within which there can be hot-spots of higher concentration. It is also important to consider uncertainties in setting any safety margin for model underestimation, including allowance for more recent information- for example on wood-burning.

This is followed by assessment of the health impacts and overall economic benefits of the different abatement scenarios, and the needs for further consideration of cost- benefit aspects in section 8.2. Other social aspects are also relevant to target setting. In this context we have looked at the relationship between deprived areas and higher concentrations using the spatially mapped deprivation index. The change in this relationship for different scenarios as improvements are made with successively stronger abatement, is described in section 8.3. Finally, in section 8.4 additional environmental benefits are considered for natural ecosystems, an aspect not directly included in the monetised values in section 8.2.

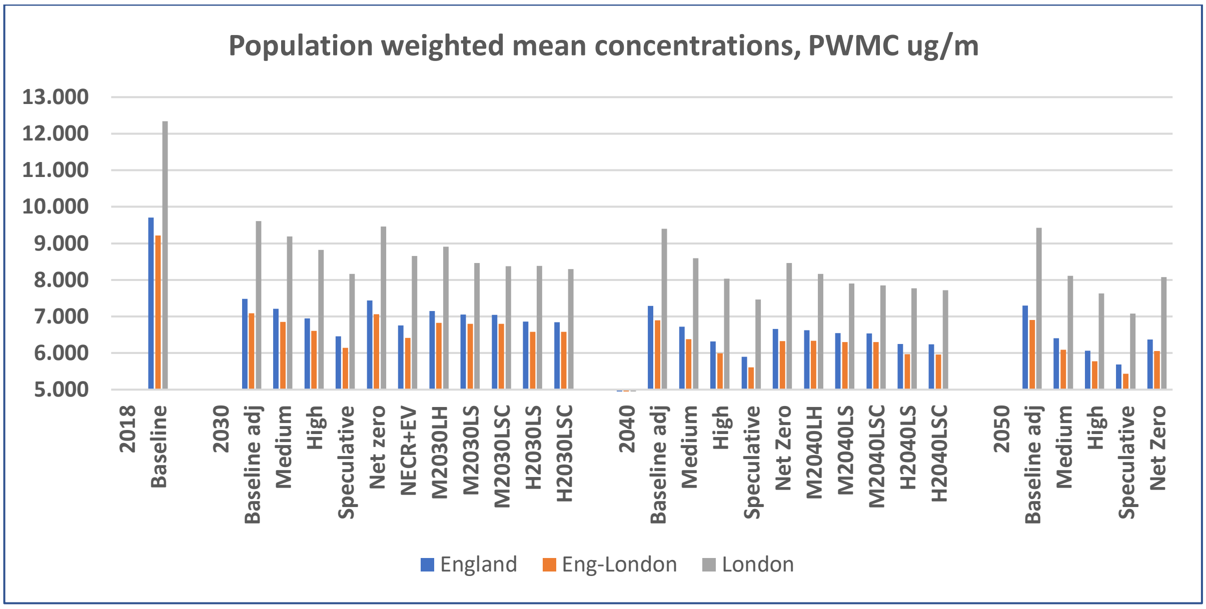
8.1 Scenario results and target setting

Setting targets for improvement in PWMC

The first requirement is to set a population exposure reduction target. Legal compliance will be assessed based on the percentage reduction in average urban background measurements compared to the base year (2018) , but the reduction of population weighted mean concentrations in England is a good indicator of this. In this context it has been shown how concentrations and exposure are generally higher in London than in the rest of England. Accordingly Figure 8.1 and the table below indicate the calculated PWMC values for each scenario for England, and then divided into England-London and London. Relative to 2018 the reductions in PWMC from the different scenarios in 2030 range up to 3ug.m^{-3} in England outside London and up to 4 ug.m^{-3} in London for the speculative scenario, with the hybrid London scenario H2030LSC achieving a similar improvement for London. Looking ahead to 2040 there are larger reductions of up to 3.6 ug.m^{-3} in England outside London and 4.9 ug.m^{-}

³ in London: and in 2050 improvements up to 4.8 ug.m^{-3} in England outside London and 5.3 ug.m^{-3} in London, although with increasing uncertainty in projections this far ahead. The net zero scenario is generally similar to the medium scenario in reducing concentrations if a little slower in bringing improvements; but has no additional air pollution abatement measures, and hence is not considered further in this section. It would be useful in future work to combine air pollution measures with the net zero scenario. We have also extended the modelling of the hybrid scenarios for London beyond 2030 since the results for 2030 imply that such an approach of combining stricter measures in London with the lower ambition of the high scenario for the rest of England can be an effective strategy.

Figure 8.1. Calculated population weighted mean concentrations.



	England	Eng-London	London
2018			
Baseline	9.704	9.219	12.340
2030			
Baseline adj	7.482	7.091	9.606
Medium	7.216	6.852	9.192
High	6.949	6.604	8.821
Speculative	6.460	6.147	8.164
Net zero	7.436	7.063	9.461
NECR+EV	6.760	6.411	8.657
M2030LH	7.148	6.824	8.906
M2030LS	7.057	6.797	8.467
M2030LSC	7.042	6.796	8.380
H2030LS	6.859	6.579	8.382
H2030LSC	6.845	6.577	8.296

2040	England	Eng-London	London
Baseline adj	7.288	6.899	9.402
Medium	6.721	6.375	8.598
High	6.315	5.999	8.034
Speculative	5.898	5.609	7.468
Net Zero	6.658	6.326	8.462
M2040LH	6.621	6.337	8.163
M2040LS	6.549	6.300	7.900
M2040LSC	6.541	6.301	7.847
H2040LS	6.245	5.964	7.772
H2040LSC	6.236	5.963	7.719
2050			
Baseline adj	7.299	6.908	9.426
Medium	6.407	6.093	8.116
High	6.063	5.775	7.629
Speculative	5.690	5.434	7.076
Net Zero	6.368	6.053	8.080

An alternative way of looking at the improvements is to consider % reductions in exposure relative to 2018 instead of absolute changes in concentration. The advantage of this is that this gives more comparable improvements in London and outside London. This is shown in

Table 8.1 with the percentage reductions relative to the 2018 baseline shown in bold figures. It can be seen that the % reductions are very similar for London and the rest of England except for the hybrid scenarios with stronger measures in London, where the % reduction in London can be a bit larger as expected

However, a major concern in this work has been the large, but uncertain, contribution from the domestic sector; and in particular from wood- burning. There are large uncertainties in the estimates of wood-burning emissions, and the NAEI2018 emissions appeared very large compared with other estimates. Defra has since commissioned work to improve estimates of wood-burning emissions. The work on emission factors is ongoing. but recently there was a revision in the amount of wood burned published in the DUKES2021 digest of UK energy statistics based on updated activity estimates. This is equivalent to a very large two-thirds reduction in the amount of wood burned. This may not be equivalent to a two-thirds reduction in emissions when more reliable data is available on the relative amounts of wet and dry wood, and the modes of combustion and stove operation. However, as a sensitivity study we have investigated how reducing wood emissions downwards by two thirds, with corresponding scaling of the emissions abated and reduction of the improvement, would affect the percentage reductions in the table above. This assumes the same total unabated concentrations, which would be consistent with suggestions earlier in this report that there are missing sources in the NAEI such as cooking which remain unabated; and could replace any overestimate of wood-burning emissions, while still retaining agreement between modelled concentrations and measurements as presented in section 2 of this report. Since such emissions could probably also be abated this sensitivity study is likely to be on the pessimistic side and underestimate potential improvements.

The % reductions for this sensitivity study with lower wood-burning emissions are shown in italics in Table 8.1 beside the calculated values in bold for the scenarios modelled in this report derived from NAEI2018 emissions. This gives PWMC reductions 3% to 6% smaller in 2030 than those from the original scenario modelling, and should be taken into account together/ with other uncertainties discussed below. More recent hybrid scenarios modelled for 2040 with stronger measures in London are also included in this table.

Table 8.1. Percentage reductions in PWMC relative to 2018 for the different scenarios.

2030	England	*less wood*	Eng-Lon	*less wood*	London	*less wood*
baseline	**22.9%**	*20.4%*	**23.1%**	*20.7%*	**22.2%**	*19.4%*
medium2030	**25.6%**	*22.6%*	**25.7%**	*22.8%*	**25.5%**	*22.2%*
high 2030	**28.4%**	*24.2%*	**28.4%**	*24.3%*	**28.5%**	*23.9%*
spec 2030	**33.4%**	*27.3%*	**33.3%**	*27.4%*	**33.8%**	*27.0%*
M2030LH	**26.3%**	*23.1%*	**26.0%**	*23.0%*	**27.8%**	*23.4%*
M2030LS	**27.3%**	*23.7%*	**26.3%**	*23.3%*	**31.4%**	*25.3%*
M2030 LSC	**27.4%**	*23.8%*	**26.3%**	*23.3%*	**32.1%**	*26.0%*
H2030LS	**29.3%**	*24.8%*	**28.6%**	*24.6%*	**32.1%**	*25.7%*
H2030LSC	**29.5%**	*24.9%*	**28.7%**	*24.6%*	**32.8%**	*26.4%*
2040						
baseline	**24.9%**	*22.5%*	**25.2%**	*22.9%*	**23.8%**	*21.1%*
medium 2040	**30.7%**	*27.1%*	**30.8%**	*27.4%*	**30.3%**	*26.3%*
high 2040	**34.9%**	*29.5%*	**34.9%**	*29.7%*	**34.9%**	*28.8%*
spec 2040	**39.2%**	*33.0%*	**39.2%**	*33.1%*	**39.5%**	*32.5%*
M2040LH	**31.8%**	*27.8%*	**31.3%**	*27.7%*	**33.8%**	*28.2%*
M2040LS	**32.5%**	*28.4%*	**31.7%**	*28.1%*	**36.0%**	*29.6%*
M2040LSC	**32.6%**	*28.5%*	**31.7%**	*28.1%*	**36.4%**	*30.1%*
H2040LS	**35.6%**	*30.1%*	**35.3%**	*30.0%*	**37.0%**	*30.3%*
H2040LSC	**35.7%**	*30.2%*	**35.3%**	*30.0%*	**37.4%**	*30.7%*
2050						
baseline	**24.8%**	*22.4%*	**25.1%**	*22.7%*	**23.6%**	*20.9%*
medium 2050	**34.0%**	*29.9%*	**33.9%**	*29.9%*	**34.2%**	*29.6%*
high 2050	**37.5%**	*32.1%*	**37.4%**	*32.1%*	**38.2%**	*32.1%*
spec 2050	**41.4%**	*35.2%*	**41.1%**	*35.1%*	**42.7%**	*35.8%*

Taking the estimates in bold from the original calculations and ignoring the more pessimistic sensitivity study, for 2030 the reductions from the medium to speculative scenarios lie between 25% and 33% with the high scenario in the middle achieving a 28% reduction, increasing to 33% for the London area when stronger measures are superimposed there. Even for the sensitivity study figures in italics which are likely to be on the pessimistic side, an average reduction of 24% is achieved both across London and England-London by 2030 in the high scenario. This increases to 26% for the higher exposure in London with additional measures there. Overall, this suggests that **a reduction of 24 to 25% in population exposure could be achievable by 2030** even for these more pessimistic assumptions.

For the original calculations higher % reductions of between 30% and 40% are shown for 2040, increasing again to between 34% and 42% in 2050, though predictions that far ahead are very uncertain. For 2040 the high scenario shows estimated improvements of around 35% relative to 2018 for both London and the rest of England. Even for the more pessimistic assumptions in the sensitivity study **a 30% reduction in population exposure is achieved in 2040** with the high scenario plus additional measures in London.

Setting limit values

To support the setting of limit values for the maximum levels of exposure we have used UKIAM to estimate population weighted mean exceedance of different threshold levels from 8 to 12 $ug.m^{-3}$ for each scenario. These results are given in Table 8.2 for the baseline in 2018, and then for the different years 2030, 2040 and 2050 showing the progressive improvements over time. In addition to the baseline and the medium, high and speculative scenarios for 2030 there are also the hybrid scenarios with stronger action in London than elsewhere, together with the NECR+EV scenario. We have not included the Net Zero scenario since this reflects only revised energy projections and climate action to attain net zero greenhouse gas emissions by 2050, and excludes any additional air pollution abatement measures.

Recognising the higher levels of concentration in London separate tables have been derived for England outside London, and in London, as well as for the whole of England. To aid setting of a limit value a "traffic light" colour coding has been added, indicating the magnitude of exceedance. Thus large values of PWME above 500 $ng.m^{-3}$ (0.5 $ug.m^{-3}$) are in red; intermediate levels of exceedance between 500 and 100 $ng.m^{-3}$ are in yellow; and small levels of exceedance between 100 and 5 $ng.m^{-3}$ are in white. Zero or negligible levels of exceedance below 5$ng.m^{-3}$ are labelled in green. These small residual contributions are explained by a few grid squares in the NAEI mapping where emissions from small disperse sources are aggregated in single grid squares. This has been addressed for some sources, such as emissions from spoil tips at steel plants which were allocated to single grid-squares giving high artificial peaks in the modelling for those grid squares, but not for every such minor source.

In previous work it has been suggested that modelling uncertainty of the order of 1 $ug.m^{-3}$ should be allowed for when assessing concentrations, or up to 2$ug.m^{-3}$ for years with adverse meteorology. Excluding the latter means that a safety margin of 1$ug.m^{-3}$ should be allowed, equivalent for example to assuming that grid squares with concentrations between 9 and 10 $ug.m^{-3}$ could be contributing to exceedance of 10 $ug.m^{-3}$. This means referring to the PWME values above 9$ug.m^{-3}$ when considering 10$ug.m^{-3}$ as a limit value, and a corresponding margin when considering alternative limit values.

Applying the approach above to Table 8.2 a suggests that 10$ug.m^{-3}$ would be a possible limit value in 2030 outside London for the high scenario and the similar NECR+EV scenario, and also almost attainable for the medium scenarios too. However, the situation is very different in London, where it takes the speculative scenario to meet these conditions for a limit value of 10 $ug.m^{-3}$, or a delay until 2040. But by taking additional measures in London superimposed on the high ambition scenario in the H2030LSC scenario, the conditions above for applying a limit value of 10 $ug.m^{-3}$ in London as well as the rest of England might possibly be satisfied by 2030. This is assuming emissions data from the 2018 NAEI which are also subject to uncertainties.

An alternative approach to assuming a uniform safety margin is to explore the more pessimistic assumptions in the sensitivity study applied above to improvements in population exposure; and derived assuming that the important contribution from wood-burning is over-estimated in the NAEI with compensating emissions from missing sources such as cooking. This will give a spatially varying safety margin with higher deviations in populated urban areas including London. Exceedance values for this sensitivity study are shown in Table 8.2b in italics compared with the original values in bold for selected scenarios, illustrating that this can increase the estimated exceedance substantially. In this case there is considerable exceedance of 9ug.m^{-3} in London in 2030 and areas verging on 10ug.m^{-3}, even for the H2030LSC scenario adding extra measures in London to the high scenario. However, this exceedance is much reduced in 2040.

Bearing in mind that the assumptions in the sensitivity study are likely to be a bit pessimistic, our modelling results suggest that, for the high scenario with additional measures in London including behavioural change and traffic reduction, concentrations below a limit of 10 ug.m^{-3} could still almost be achieved in the H2040LSC scenario except close to roads and other localised hot-spots by 2040. This is with these adverse assumptions. Outside London, or with more favourable assumptions this could be achieved earlier by 2030.

Although the medium scenario coupled with stronger measures in London is also effective towards attainment of a limit value of 10ug.m^{-3}, it gives less improvement than the high in population exposure and associated health impacts reflected in the monetised benefits below.

Table 8.2. a) Population weighted mean exceedance PWME (ng.m-3);

								England				
	2018		Base 2030	Med 2030	High 2030	Spec 2030	NECR+EV	M2030LH	M2030LS	M2030LSC	H2030LS	H2030LSC
8	1902		305	213	133	43	108	166	103	90	75	62
9	1136		101	55	21	1	16	29	8	6	4	2
10	591		14	3	1	0	3	1	1	1	0	0
11	278		1	0	0	0	2	0	0	0	0	0
12	112		0	0	0	0	2	0	0	0	0	0
								England outside London				
	2018		Base 2030	Med 2030	High 2030	Spec 2030	NECR+EV	M2030LH	M2030LS	M2030LSC	H2030LS	H2030LSC
8	1455		97	53	21	2	14	48	42	42	18	18
9	732		13	7	2	0	4	6	5	5	2	1
10	269		3	1	0	0	3	1	1	1	0	0
11	73		1	0	0	0	2	0	0	0	0	0
12	18		0	0	0	0	2	0	0	0	0	0
								London				
	2018		Base 2030	Med 2030	High 2030	Spec 2030	NECR+EV	M2030LH	M2030LS	M2030LSC	H2030LS	H2030LSC
8	4334		1433	1078	739	263	620	809	435	350	381	299
9	3334		577	318	124	5	85	155	25	7	16	5
10	2338		77	14	2	0	2	3	0	0	0	0
11	1394		3	0	0	0	0	0	0	0	0	0
12	620		0	0	0	0	0	0	0	0	0	0

Table 8.2. a) Continued

					England									
	Base 2040	Med 2040	High 2040	Spec 2040	M2040LH	M2040LS	M2040LSC	H2040LS	H2040LSC		Base 2050	Med 2050	High 2050	Spec2050
8	225	91	28	2	43	22	17	11	7		226	35	6	0
9	67	9	1	0	2	1	1	0	0		68	1	0	0
10	6	1	0	0	1	1	1	0	0		6	0	0	0
11	1	0	0	0	0	0	0	0	0		1	0	0	0
12	1	0	0	0	0	0	0	0	0		1	0	0	0
					England outside London									
	Base 2040	Med 2040	High 2040	Spec 2040	M2040LH	M2040LS	M2040LSC	H2040LS	H2040LSC		Base 2050	Med 2050	High 2050	Spec2050
8	54	10	1	0	9	8	8	1	1		54	3	0	0
9	8	2	0	0	1	1	1	0	0		8	0	0	0
10	2	1	0	0	1	1	1	0	0		2	0	0	0
11	1	1	0	0	1	0	0	0	0		1	0	0	0
12	1	0	0	0	0	0	0	0	0		1	0	0	0
					London									
	Base 2040	Med 2040	High 2040	Spec 2040	M2040LH	M2040LS	M2040LSC	H2040LS	H2040LSC		Base 2050	Med 2050	High 2050	Spec2050
8	1155	529	174	13	231	103	69	67	41		1161	212	36	1
9	386	51	0	0	4	1	0	0	0		396	6	0	0
10	29	1	0	0	0	0	0	0	0		30	0	0	0
11	2	0	0	0	0	0	0	0	0		2	0	0	0
12	0	0	0	0	0	0	0	0	0		0	0	0	0

Table 8.2 b) Population weighted mean exceedance PWME (ng.m^{-3}) Sensitivity study

Numbers in bold are original estimates, and figures in italics are for sensitivity study

England											
ug/m3	**B2018**	**Med2030**	*less wood*	**M2030LH**	*less wood*	**M2030LSC**	*less wood*	**High 2030**	*less wood*	**H2030LSC**	*less wood*
8	**1902**	**213**	*336*	**166**	*305*	**90**	*250*	**133**	*273*	**62**	*220*
9	**1136**	**55**	*113*	**29**	*93*	**6**	*55*	**21**	*83*	**2**	*47*
10	**591**	**3**	*19*	**1**	*12*	**1**	*6*	**1**	*9*	**0**	*4*
11	**278**	**0**	*2*	**0**	*1*	**0**	*1*	**0**	*0*	**0**	*0*
12	**112**	**0**	*0*	**0**	*0*	**0**	*0*	**0**	*0*	**0**	*0*
		Med2040	*less wood*	**M2040LH**	*less wood*	**M2040LSC**	*less wood*	**High 2040**	*less wood*	**H2040LSC**	*less wood*
		91	184	**43**	*146*	***17***	*110*	**28**	*124*	**7**	*90*
		9	47	**2**	*27*	***1***	*13*	**1**	*20*	**0**	*8*
		1	5	**1**	*3*	***1***	*2*	**0**	*1*	**0**	*0*
		0	1	**0**	*1*	***0***	*1*	**0**	*0*	**0**	*0*
		0	0	**0**	*0*	***0***	*0*	**0**	*0*	**0**	*0*
England outside London											
		Med2030	*less wood*	**M2030LH**	*less wood*	**M2030LSC**	*less wood*	**High 2030**	*less wood*	**H2030LSC**	*less wood*
8	**1455**	**53**	*126*	**48**	*118*	**42**	*109*	**21**	*90*	**18**	*83*
9	**732**	**7**	*22*	**6**	*20*	**5**	*19*	**2**	*15*	**1**	*14*
10	**269**	**1**	*6*	**1**	*5*	**1**	*5*	**0**	*4*	**0**	*4*
11	**73**	**0**	*2*	**0**	*1*	**0**	*1*	**0**	*1*	**0**	*1*
12	**18**	**0**	*0*	**0**	*0*	**0**	*0*	**0**	*0*	**0**	*0*
		Med2040	*less wood*	**M2040LH**	*less wood*	**M240LSC**	*less wood*	**High 2040**	*less wood*	**H2040LSC**	*less wood*
8		**10**	43	**9**	*38*	***8***	*33*	**1**	*22*	**1**	*19*
9		**2**	9	**1**	*8*	***1***	*8*	**0**	*4*	**0**	*4*
10		**1**	3	**1**	*3*	***1***	*2*	**0**	*1*	**0**	*0*
11		**1**	1	**1**	*1*	***0***	*1*	**0**	*0*	**0**	*0*
12		**0**	0	**0**	*0*	***0***	*0*	**0**	*0*	**0**	*0*
London											
		M2030	*less wood*	**M2030LH**	*less wood*	**M2030LSC**	*less wood*	**High 2030**	*less wood*	**H2030LSC**	*less wood*
8	**4334**	**1078**	*1476*	**809**	*1320*	**350**	*1015*	**739**	*1271*	**299**	*968*
9	**3334**	**318**	*611*	**155**	*487*	**7**	*253*	**124**	*453*	**5**	*226*
10	**2338**	**14**	*89*	**3**	*47*	**0**	*8*	**2**	*40*	**0**	*6*
11	**1394**	**0**	*3*	**0**	*1*	**0**	*0*	**0**	*1*	**0**	*0*
12	**620**	**0**	*0*	**0**	*0*	**0**	*0*	**0**	*0*	**0**	*0*
		M2040	*less wood*	**M2040LH**	*less wood*	**M2040LSC**	*less wood*	**High 2040**	*less wood*	**H2040LSC**	*less wood*
8		**529**	948	**231**	*735*	**69**	528	**174**	*676*	**41**	*475*
9		**51**	253	**4**	*129*	**0**	44	**0**	*104*	**0**	*33*
10		**1**	15	**0**	*3*	**0**	0	**0**	*2*	**0**	*0*
11		**0**	1	**0**	*0*	**0**	0	**0**	*0*	**0**	*0*
12		**0**	0	**0**	*0*	**0**	0	**0**	*0*	**0**	*0*

Uncertainties when deriving targets

Throughout this report 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. Some of these result in an optimistic assessment and others pessimistic, while others are indeterminate and qualitative. But these all need to be considered when setting targets for improvement. In what follows it is useful to bear in mind that comparison with measurements suggests that the modelling bias is small; and also the suggestion made above to allow for model uncertainty of the order of 1ug.m^{-3} when assessing calculated concentrations, but when allowing for adverse meteorological years increasing this to around 2 ug.m^{-3}.

Uncertainties in modelling

Starting with atmospheric dispersion the UKIAM uses long-term annual average meteorology and has a very simplified treatment of the secondary inorganic aerosol, SIA, with linear scaling of source footprints in order to make it fast to run for the hundreds of scenarios modelled during the work described, and for source apportionment. In sections 3 and 4 comparison has been made with the more sophisticated model EMEP4UK with detailed meteorology and chemistry, and which has been shown to be consistent with trends in measurements over 10 years. This comparison indicates that UKIAM may underestimate improvements in secondary inorganic aerosol due to the simple adjusted linear approach, though the difference between the models is within 1 ug.m^{3} for the scenarios modelled; and is less than the effect of different years of meteorology which EMEP4UK illustrated could give concentrations up to 2 ug.m^{-3} higher in adverse years (such as 2003 with a large number of high air pollution episodes).

Although UKIAM models the response of primary $PM_{2.5}$ and SIA to changes in emissions, other components are kept fixed. Here again there are uncertainties in the contribution of natural dust and sea salt, and evolving scientific understanding of secondary organic aerosol, SOA, and the role of intermediate volatility organic compounds, IVOCs. Meanwhile the contribution of SOA is similar in UKIAM to EMEP4UK but stays constant over time; whereas EMEP4UK shows a very small reduction in response to reduction of anthropogenic emissions. Overall UKIAM gives a conservative estimate of reduction in $PM_{2.5}$ concentrations in response to emission abatement compared with EMEP4UK, but slightly higher primary $PM_{2.5}$ concentrations in urban areas with a higher grid resolution, as discussed in section 4.1 of this report.

It has been stressed when setting limit values that UKIAM estimates average concentrations across a 1x1km^2 grid, but that within such grid-squares there will be hot-spots and spatial variation close to local sources. To address this problem, we have examined the spatial variability exhibited by fine scale modelling of $PM_{2.5}$ with the ADMS model used for regulatory applications, using a grid with much higher resolution of 10x10m^2. This is described in section 4.2 of this report, and shows that close to the main arterial roads, modelled concentrations can be 3 to 4 times the average value over a 1x1km^2 area. However, for the vast majority of London in grid squares which do not contain these arterial roads, the normalised standard deviation of the 10x10m^2 values is typically within 10% of the mean. It was concluded that using a 1x1 km^2 grid is sufficient for assessing population exposure even in the more extreme conditions in London.

With regard to future compliance with limit values, if this is to be judged against evidence from monitoring data, the ADMS modelling in section 4.2 reiterates the difficulties of providing representative measurements, and understanding their dependence on nearby roads or other local sources generating hot-spots for which detailed and reliable emission data is lacking. This reinforces the conclusions from comparison of UKIAM with measurements from AURN sites which gave fair agreement between UKIAM and calculations of population exposure based on measurements in each agglomeration outside London, but where better measurement data was needed for London. The assessment of exceedance using measurements is extremely difficult and needs careful investigation, especially in view of the limited existing network and accuracy of $PM_{2.5}$ measurements. Meanwhile it has to be recognised that within 1x1 km^2 grid squares there are likely to be local hot-spots with higher concentrations than the spatially averaged concentrations calculated with UKIAM.

Uncertainties in imported contributions outside UK control

The long-range transport of fine particulate matter makes it a transboundary problem which has been addressed under the Air Convention of the UNECE, with the setting of emission ceilings for each country as set out in the Gothenburg protocols and adopted for the UK as the National Emission Ceiling Regulations, NECR. In this study we have used projected emissions for each country from IIASA based on application of the GAINS model to future scenarios for Europe. As a sensitivity study we have compared the effect of assuming the Mix55 scenario, giving more ambitious emission reductions than the WAM(with additional measures) scenario. These start from the same point in 2018 and show the maximum deviation in 2030 converging as emissions reduce across Europe to 2050 (see section 2). However, the effect on the UK is dominated by a few countries including France, Germany and the Low countries, and there is a minor difference between the scenarios in the contribution to the UK national PWMC of ~ 0.05 $ug.m^{-3}$.

Of more concern is the contribution from shipping in the seas round the UK, generating estimated annual emissions of 660 kt of NO_x encircling the UK, which is greater than the ceiling for NO_x emissions within the UK in 2030. The amount of shipping is increasing, though rates for different types of ship are very variable and our future extrapolation to 2050 is uncertain. Regulation of these shipping emissions lies outside the remit of the UNECE with the International Maritime Organisation, IMO; with emission control areas mandatory for SO_x (which is now tightly controlled) and future NO_x emissions. There is a NO_x control area, NECA, covering emission through the English Channel and into the North Sea, which brought in stricter emission limits for new ships from 2021, but this does not extend to the west of the UK into the Irish Sea. Further details of ECA and non-ECA regions are given in an earlier contract report for Defra on shipping (ApSimon et al 2019). In 2018 the contribution from shipping to population weighted mean concentration in the UK was estimated to be .56 $ug.m^{-3}$ decreasing to .43 ug. m^{-3} in 2050. Hence shipping is a substantial source. A modelling experiment extending the NECA to cover the whole sea area round the UK including the Irish Sea suggested a 37% decrease to .27 $ug.m^{-3}$ but any such extension would require action by the IMO, who have suggested but not agreed use of NH3 as a fuel as a measure to reduce CO_2 emissions from shipping. The effect of such a change on air pollutant emissions is uncertain, and further attention to shipping is recommended.

Uncertainties in UK emissions and the effects of abatement

A major uncertainty in assessing the future is the difficulty of predicting changes in energy, transport and agriculture. This has been addressed by considering a range of scenarios to 2050 with different levels of ambition, and also a net zero scenario incorporating climate measures. However, the potential range of scenarios is much wider, and does not yet include a combination of climate and air pollution measures which might achieve greater emission reductions.

The contribution of key sources in different sectors has been considered in section 5 of this report, where particular attention was given to the domestic sector and road transport which are responsible for the biggest reductions in $PM_{2.5}$ in the scenarios analysed above. With regard to road transport the big reduction in NO_x emissions gives substantial improvements in air quality, reducing both NO_2 and secondary $PM_{2.5}$. This is driven initially by improved emissions from new diesel vehicles post RDE testing, and reinforced by electrification of the fleet. 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, although there may be some reduction from regenerative braking. Apart from some potential measures such as better wheel alignment to reduce tyre wear, and without implementation of possible new technologies currently under development, further improvements ultimately depend on reducing kilometres driven especially in London and 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 like road charging, as well as local action in urban conurbations and by local authorities. Sensitivity studies have been undertaken to explore the difference when percentage reductions in kilometres driven are widely applied in all urban areas, or restricted to major agglomerations and populated areas of London. This will be relevant to urban planning but had little effect on the overall picture presented above.

The major uncertainty in emissions from wood- burning in the domestic sector has been addressed above in section 8.1 with a sensitivity study to recent revision of estimated amounts of wood burned. Whereas our work has taken NAEI 2018 emission as a starting point which appeared high with respect to wood burning compared with other estimates, recent statistics in DUKES2021 indicated a two-thirds reduction in wood used. The effect of this in giving smaller % reductions in PWMC achieved by the different scenarios is shown in Table 8.1. It also has substantial implications for the setting of limit values- see Table 8.2b. However, research currently commissioned by Defra may lead to revised emission factors and moderate this change which may give a pessimistic estimate of improvement.

Another concern is missing sources in the NAEI such as domestic and commercial cooking, which may counteract any overestimate of emissions in wood-burning, but without any reduction from abatement measures. Cooking has been taken as an illustration of a missing source, and the potential impact is one of the reasons for the suggested 1 ug.m^{-3} allowance for model underestimation in applying UKIAM modelling results to target setting.

A further consideration is the accuracy of emission reduction from the selected abatement measures, based on the work of Wood Plc and incorporated in the Scenario Modelling Tool, SMT. This can occasionally cause difficulties where abatement measures are applied to the same sources, as both measures are applied to the baseline emissions. This means when one measure would logically be applied to the results of another, the SMT is not able to take this ordering into account, requiring special attention. Further work has been started to look at the relative contributions from different sources and measures, and which are the most important and cost effective. More work is required on this topic since some measures which contribute little benefit can be very costly, and 90 to 95% of the improvement could be delivered at lower cost. This is more complicated when measures relate to both climate and net zero, and air quality

<u>Uncertainties in the impacts and benefits</u>

The assessment of health benefits as described below reflects the work of WHO and advice from COMEAP, and is based on particulate mass with no differentiation between different chemical components. The WHO guidelines are based on the latest health evidence, and are considered as part of the target setting process alongside other important factors such as the achievability, feasibility and impacts of different measures, including cost-benefit. The adoption of $PM_{2.5}$ mass reflects the epidemiological reliance on measurements which are predominantly particle mass, and it is currently not possible to consider potential differences in toxicity of different components. Nevertheless, there are indications that particular components are more toxic than others, suggesting emphasis on the corresponding source. For example, compared with ammonium sulphate and nitrate as secondary inorganic aerosol, diesel exhaust and carbonaceous particles which are generated by combustion processes have been proposed as more harmful. (see for example exploration of the implications for reducing PM in London by Oxley et al 2015, though limited by data from a single epidemiological study which essentially re-ascribed all PM health effects to black carbon). There are also toxic elements in sources such as brakes, and tyres (which are also a source of small plastic particles thought to be a significant component of particle waste exported to the ocean).

There is then the issue of basing human exposure on outdoor ground-level concentrations and data on the residential population distribution, ignoring patterns of behaviour and the large proportion of time spent indoors- a fast developing research area. But such considerations are complicated by potential changes in urban topography and life-styles over the coming decades, and factors outside the scope of this study.

Many of the factors above, apart from interannual variations in meteorology, have negative or positive effects on population weighted mean concentrations within the 1ug.m^{-3} range or considerably less, and others are indeterminate. Thus, the previously allowed margin of 1ug.m^{-3} is still suggested for model uncertainty, or 2ug.m^{-3} for years with more adverse meteorology.

References:
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Oxley, T., ApSimon, H. M., de Nazelle, A. (2015) Investigating the sensitivity of health benefits to focussed PM2.5 emission abatement strategies. Environmental Modelling & Software. 74, 268-283. ISSN: 1364-8152. Available from: https://doi.org/10.1016/j.envsoft.2015.07.011.

8.2 Assessment of health impacts and economic benefits of abatement

The analysis is based around the use of Defra's damage costs based on previous discussions, to ensure consistency with methods used elsewhere by Defra. However, the damage costs have been adjusted for this work to account for:

1. Updating damage costs to 2020 prices
2. A recommendation from COMEAP to increase the risk factor for chronic exposure to $PM_{2.5}$ from a relative risk of 1.06/10 ug.m^{-3} to 1.08/10 ug.m^{-3}.

Results are shown in Tables 8.3 and 8.4, with equivalents from the current published set of damage costs in 2017 prices shown for comparison.

Table 8.3. 'Direct' damage costs for each emitted pollutant, as £/ug.m-3/person/year.

Primary Pollutant	Sector	£2017 / popwm 1ug.m^{-3} change per person	£2020 / popwm 1ug.m^{-3} change per person
NO_2	Central	6.31	7.02
	Low	0.48	0.53
	High	24.88	27.67
SO_2	Central	0.11	0.12
	Low	0.05	0.06
	High	0.19	0.21
$PM_{2.5}$	Central	50.12	62.69
	Low	10.37	16.89
	High	156.52	178.21

The costs in Table 8.3 exclude non-health impacts such as soiling of buildings, and effects on ecosystems and carbon sequestration. Table 8.4 gives an indication of these additional damage costs in terms of £ per tonne of pollutant emitted.

Table 8.4. 'Additional' damage costs for each emitted pollutant, consistent with the quantification in the Defra damage cost tool as £/tonne.

Primary Pollutant	Sector	£2017 / tonne	£2020 / tonne
NO_x	Central	-107	-120
	Low	-51	-55
	High	-246	-281
SO_2	Central	305	325
	Low	265	279
	High	351	375
NH_3	Central	-539	-564
	Low	-227	-238
	High	-675	-707
VOC	Central	102	110
	Low	55	58
	High	205	219
$PM_{2.5}$	Central	890	933
	Low	890	933
	High	890	933

Results for NO_x and NH_3 in Table 8.4 indicate negative figures, in other words, some benefit from emissions of these pollutants. These arise as a consequence of some increase in carbon uptake linked to increased deposition of nitrogen, and in the case of NO_x, also a reduction in exposure to ozone via chemical reactions in the atmosphere. However, as is apparent in results presented below, these effects are small compared to the health damage linked to emissions of these pollutants via the formation of ammonium and nitrate aerosols and hence human exposure to $PM_{2.5}$. It is questionable whether these figures are truly negative: whilst there are some beneficial aspects of N deposition there are also adverse impacts to ecosystems, notably the loss of biodiversity as N levels in soil rise and rarer species that are adapted to an existence in low-nutrient environments can be out-competed by more common species. A higher valuation of ecological damage could change the negative figures for NO_x and NH_3 to positive: significant uncertainty in the valuation of biodiversity should be recognised given that it is based on a very limited literature.

Table 8.5. Impacts included in damage cost calculations for low, central, high estimates. 'L', 'C', 'H' within the table refer to uncertainty ranges for response functions and valuation.

		Damage cost sensitivity		
Health Pathways / CRFs for inclusion		Low	Central	High
NO_2	Respiratory hospital admission			C
NO_2	Deaths brought forward	L	C	H
NO_2	Chronic mortality	L	C	H
NO_2	Asthma (Adults)			C
NO_2	Diabetes			C
NO_2	Lung Cancer			C
NO_2	Asthma (Small Children)		C	H
NO_2	Asthma (Older Children)		C	H
O_3	Deaths brought forward	L	C	H
O_3	Respiratory hospital admission	L	C	H
O_3	Cardiovascular hospital admission	L	C	H
PM_{10}	Respiratory hospital admission	L	C	H
PM_{10}	Cardiovascular hospital admission	L	C	H
PM_{10}	Chronic Bronchitis			C
$PM_{2.5}$	Chronic mortality	L	C	H
$PM_{2.5}$	Respiratory hospital admission	L	C	H
$PM_{2.5}$	Cardiovascular hospital admission	L	C	H
$PM_{2.5}$	CHD		C	H
$PM_{2.5}$	Stroke		C	H
$PM_{2.5}$	Diabetes			C
$PM_{2.5}$	Lung Cancer		C	H
$PM_{2.5}$	Asthma (Older Children)		C	H
SO_2	Deaths brought forward	L	C	H
SO_2	Respiratory hospital admission	L	C	H
All	Productivity	L	C	H
All	Ecosystems	L	C	H

In each case in Table 8.3 the uncertainties are characterised in the Defra damage cost tool by the range between low and high costs about the central estimates. These ranges are clearly very broad, and some commentary on the way that they are compiled is necessary. Uncertainty is characterised for all impacts that contribute to the damage costs (Table 8.5).

Each damage cost sensitivity case accounts for two elements of uncertainty:

1. Confidence in the link between each air pollutant and the effect in question
2. The uncertainty range reported in the literature for each effect.

The 'Low' sensitivity case limits the health impact assessment to those effects (mortality and hospital admissions) that have been most extensively studied. It also takes adopts the lower bound estimates for response functions and valuation.

The 'Central' case accepts a broader range of impacts, and the central estimate of response and valuation functions.

The 'High' case accepts a very broad range of impacts and applies for most the upper bound response and valuation functions, or the central response and valuation functions for a few impacts where proof of causality was considered weaker.

Additional considerations are applied to the quantification of the range for NO_2 mortality reflecting the difficulty in separating out the impacts of individual pollutants in epidemiological studies when people are always exposed to a range of pollutants simultaneously. This generates a proportionally much broader range for NO_2 than is present for $PM_{2.5}$.

It is necessary to consider whether the Low, Central and High sensitivity cases are equally plausible or not, given that no guidance is provided. The Low and High cases both take extreme positions for the following reasons:

- With respect to the Low case:
    - The mortality response function for $PM_{2.5}$ (which contributes a large part of the overall benefits) is well characterised from a very large number of epidemiological studies carried out in numerous countries. It has also been subject to intense discussion and review over many years. It indicates that $PM_{2.5}$ has a significant impact on mortality. An increase in mortality requires an accompanying increase in morbidity (otherwise, what causes the mortality burden?), and this cannot be explained through the rather modest number of hospital admissions accounted for in the analysis. The Low case therefore omits a significant morbidity burden.
    - Further to this, it is unrealistic for all response functions to be best represented by the lower bound: it is to be expected that there will be some cancelling of error when a number of impacts are added together.
- With respect to the High case:
    - A very broad range of impacts have been included for the High case, some of which are the subject of limited literature. The assumption of causality for some of these effects is weaker than for those effects included in the Central estimate.
    - It is unrealistic for all response functions to be best represented by the upper bound: Like for the Low sensitivity case, it is to be expected that there will be

some cancelling of error when a number of impacts are added together. This may be more pronounced for the High sensitivity case given the larger number of effects included in the analysis.

Considerably greater weight should therefore be given to the Central case than either the Low or High cases. For this reason, the results presented here focus on the Central case, though uncertainties in the analysis are noted.

Pollutant damage by scenario

Estimated net present values for pollutant damage in the Baseline, Medium, High, Speculative and Net Zero[2] scenarios are shown in Table 8.6. For each scenario, damage is aggregated over different periods (2023 to 2030, 2023 to 2040 and 2023 to 2050) to show the growth in damage over time. Effects linked to $PM_{2.5}$ exposure (associated with emissions of primary $PM_{2.5}$ and formation of secondary $PM_{2.5}$ formed through reaction of NH_3, NO_x and SO_2 in the atmosphere) dominate the analysis, providing approximately 90% of the total quantified damage. Most of the remaining damage is linked to exposure to NO_2, with the additional impacts on ecosystems, soiling of buildings, etc. accounting for under 1% of impacts.

The decline in health damage linked to $PM_{2.5}$ exposure under each scenario is shown in Figure 8.2. Values are not adjusted to reflect the increase in willingness to pay over time as incomes increase or discounting of future values, in order to better demonstrate the underlying impact of changes in exposure on health. The following are apparent:

1. Most of the projected decline in damage is achieved within the first 10 years of the scenarios.
2. After a slower start, the Net Zero scenario follows a similar trajectory to the Medium scenario. The better performance of the High and Speculative scenarios demonstrates that climate policies, though useful, do not provide the full benefits that could be anticipated from air quality policies.
3. Under the Baseline scenario there is a slight increase in damage in the final years linked to growth in the population. Other scenarios maintain a flat trajectory in the final years.

[2] For Net Zero, only effects linked to $PM_{2.5}$ exposure have been modelled

Table 8.6. Net present value of health and other damage in England linked to pollutant emissions under the Baseline, Medium, High, Speculative and Net Zero scenarios for the periods 2023 to 2030, 2023 to 2040 and 2023 to 2050. Units, £million.

BASELINE	**2023-2030**	**2023-2040**	**2023-2050**
$PM_{2.5}$ concentration	209,966	431,019	625,280
NO_2 concentration	21,288	41,758	60,190
Additional impacts unaccounted for above linked to emissions of:			
NH_3	(838)	(1,607)	(2,151)
SO_2	167	301	398
NOx	(376)	(709)	(974)
Primary $PM_{2.5}$	404	759	1,016
VOC	451	871	1,181
Total	**231,062**	**472,393**	**684,941**
MEDIUM	**2023-2030**	**2023-2040**	**2023-2050**
$PM_{2.5}$ concentration	204,588	412,790	587,275
NO_2 concentration	20,265	36,793	46,961
Additional impacts unaccounted for above linked to emissions of:			
NH_3	(796)	(1,511)	(2,013)
SO_2	166	298	385
NOx	(361)	651)	(850)
Primary $PM_{2.5}$	374	666	854
VOC	446	860	1,165
Total	**224,682**	**449,243**	**633,777**
HIGH	**2023-2030**	**2023-2040**	**2023-2050**
$PM_{2.5}$ concentration	201,276	399,238	563,802
NO_2 concentration	20,040	35,646	44,767
Additional impacts unaccounted for above linked to emissions of:			
NH_3	(772)	(1,447)	(1,918)
SO_2	165	296	381
NOx	(365)	(656)	(846)
Primary $PM_{2.5}$	344	571	710
VOC	445	54	1,156
Total	**221,133**	**434,502**	**608,053**
SPECULATIVE	**2023-2030**	**2023-2040**	**2023-2050**
$PM_{2.5}$ concentration	195,843	380,584	534,662
NO_2 concentration	19,230	32,602	40,623
Additional impacts unaccounted for above linked to emissions of:			
NH_3	(765)	(1,427)	(1,882)
SO_2	164	285	364
NOx	(353)	(613)	(787)
Primary $PM_{2.5}$	325	509	628
VOC	442	842	1,136
Total	**214,888**	**412,782**	**574,745**
NET ZERO	**2023-2030**	**2023-2040**	**2023-2050**
$PM_{2.5}$ concentration	210,253	422,121	3,389,268,400
NO_2 concentration	-	-	-
Additional impacts unaccounted for above linked to emissions of:			
NH_3	-	-	-
SO_2	-	-	-
NOx	-	-	-
Primary $PM_{2.5}$	-	-	-
VOC	-	-	-
Total	**210,253**	**422,121**	**3,389,268,400**

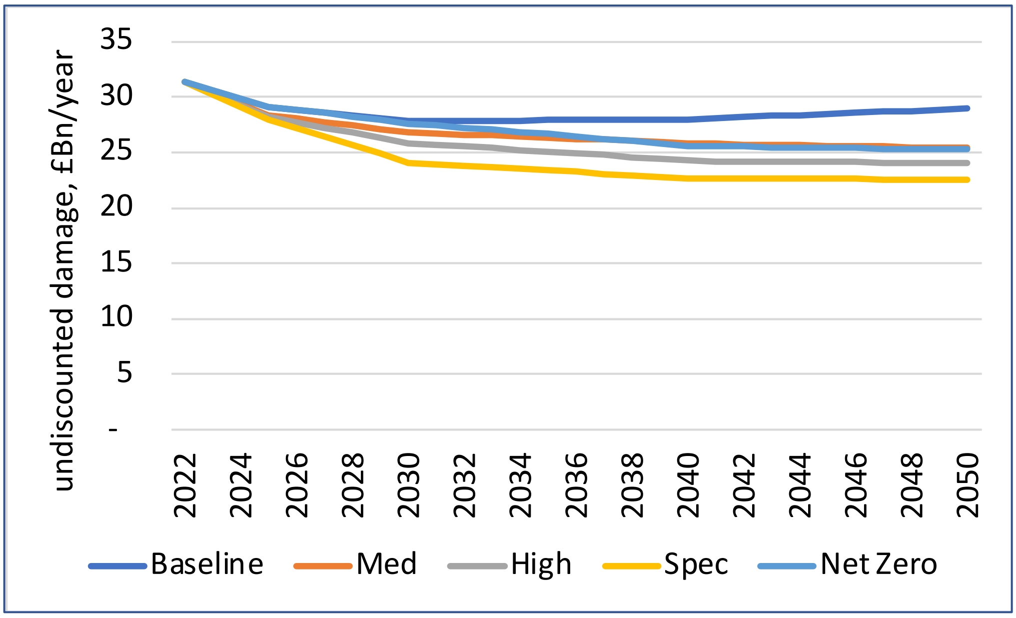


Figure 8.2. Decline in health damage linked to $PM_{2.5}$ exposure under each scenario from 2023 to 2050. Undiscounted, units £billion/year.

Figure 8.2 shows a maximum reduction in $PM_{2.5}$ health impacts against the Baseline of 13% and 17% for the High scenario and 19% and 22% for the Spec scenario, for 2040 and 2050 respectively. As a fraction of the contribution from UK anthropogenic sources (transport, heating, etc.) the reduction naturally increases, for example for the High 2050 scenario from 17% to 38% (Figure 8.3).

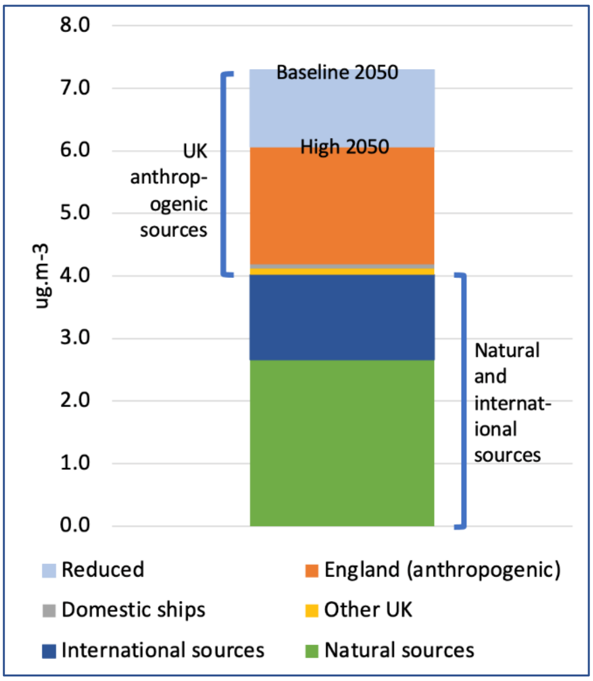


Figure 8.3. Contribution of sources to population weighted mean $PM_{2.5}$ exposure in England in 2050 under the High 2050 scenario, with reduction from Baseline 2050 shown.

Whilst the UK has some control over UK anthropogenic sources it would not be possible to eliminate these entirely, even in the very long term. For example, there will always be some need for combustion (e.g. related to incineration of hazardous chemicals and clinical waste) though associated emissions are minimised using appropriate controls. Some emissions, for example related to tyre, brake and road wear, are unavoidable despite abatement. However, it is also important to appreciate that the UK has at least some influence over emissions from natural and international sources. Natural sources, for example, will be affected by climate change, by agricultural practices and by land management more generally. International sources (anthropogenic emissions from other countries) can be influenced through negotiations for example on the UN/ECE Convention on Long-Range Transboundary Air Pollution.

Impacts by scenario

It is possible to back-calculate from estimates of economic damage to quantify health and other impacts. Results are presented for health effects in Table 8.7 addressing:

- Chronic mortality (life years lost)
- Acute deaths (deaths)
- Asthma (cases)
- Lung cancer (cases)
- CHD (cases)
- Stroke (cases)
- Respiratory hospital admissions (cases)
- Cardiovascular hospital admissions (cases)

These results are based on the Central sensitivity case. Diabetes and chronic bronchitis are not included in the table as they are not included in the Central damage costs, only the High.

Table 8.8 then provides results for non-health damage (productivity, ecosystems, materials damage and soiling of buildings with particulate matter). These results are provided only in monetary terms.

Table 8.7. Estimated health impacts by scenario (not discounted).

BASELINE	Units	2023 to 2030	2023 to 2040	2023 to 2050
Chronic mortality	life years lost	2,429,274	5,336,322	8,310,667
Acute deaths	acute deaths	(6)	56	81
Asthma	new cases	97,002	211,652	329,269
Lung cancer	new cases	24,463	53,984	84,133
CHD	new cases	227,533	502,098	782,521
Stroke	new cases	60,140	132,712	206,831
Respiratory hospital admissions	cases	78,163	174,338	272,525
Cardiovascular hospital admissions	cases	49,567	109,592	170,919
MED	**Units**	**2023 to 2030**	**2023 to 2040**	**2023 to 2050**
Chronic mortality	life years lost	2,361,131	5,063,289	7,641,507
Acute deaths	acute deaths	43	292	634
Asthma	new cases	93,974	198,511	295,046
Lung cancer	new cases	23,830	51,618	78,682
CHD	new cases	221,641	480,100	731,821
Stroke	new cases	58,583	126,897	193,431
Respiratory hospital admissions	cases	76,681	169,549	262,040
Cardiovascular hospital admissions	cases	48,325	105,020	160,454
HIGH	**Units**	**2023 to 2030**	**2023 to 2040**	**2023 to 2050**
Chronic mortality	life years lost	2,323,089	4,890,123	7,315,268
Acute deaths	acute deaths	18	249	628
Asthma	new cases	92,528	191,750	282,145
Lung cancer	new cases	23,434	49,848	75,376
CHD	new cases	217,961	463,635	701,064
Stroke	new cases	57,610	122,545	185,301
Respiratory hospital admissions	cases	75,023	162,986	250,729
Cardiovascular hospital admissions	cases	47,485	101,336	153,654
SPEC	**Units**	**2023 to 2030**	**2023 to 2040**	**2023 to 2050**
Chronic mortality	life years lost	2,255,628	4,636,514	6,900,131
Acute deaths	acute deaths	61	362	772
Asthma	new cases	89,665	180,808	264,745
Lung cancer	new cases	22,784	47,434	71,336
CHD	new cases	211,912	441,182	663,495
Stroke	new cases	56,011	116,610	175,371
Respiratory hospital admissions	cases	73,381	156,712	239,686
Cardiovascular hospital admissions	cases	46,198	96,567	145,629

Table 8.8. Estimated damage to productivity, materials and ecosystems, £million net present value.

BASELINE	Units	2023 to 2030	2023 to 2040	2023 to 2050
Productivity	£M	£5,443	£10,276	£13,773
Ecosystems	£M	(£543)	(£1,057)	(£1,424)
Material damage	£M	£90	£160	£207
Building soiling	£M	£404	£759	£1,016
MED	**Units**	**2023 to 2030**	**2023 to 2040**	**2023 to 2050**
Productivity	£M	£5,310	£9,878	£13,042
Ecosystems	£M	(£506)	(£978)	(£1,315)
Material damage	£M	£91	£165	£212
Building soiling	£M	£374	£666	£854
HIGH	**Units**	**2023 to 2030**	**2023 to 2040**	**2023 to 2050**
Productivity	£M	£5,223	£9,565	£12,550
Ecosystems	£M	(£482)	(£916)	(£1,226)
Material damage	£M	£90	£162	£210
Building soiling	£M	£344	£571	£710
SPEC	**Units**	**2023 to 2030**	**2023 to 2040**	**2023 to 2050**
Productivity	£M	£5,090	£9,151	£11,949
Ecosystems	£M	(£478)	(£909)	(£1,210)
Material damage	£M	£91	£160	£204
Building soiling	£M	£325	£509	£628

Benefits relative to the Baseline scenario

Net present value of benefits for each scenario is shown in Table 8.9, again over the time periods 2023-30, 2023-40 and 2023-50.

Table 8.9. Net present value of benefits for England relative to the Baseline scenario for the periods 2023 to 2030, 2023 to 2040 and 2023 to 2050. Units, £million.

Total estimates of benefits by scenario			
	2023-2030	**2023-2040**	**2023-2050**
Medium	6,380	23,150	51,163
High	9,930	37,891	76,887
Speculative	16,174	59,611	110,196
Benefits associated with reduced $PM_{2.5}$ exposure			
	2023-2030	**2023-2040**	**2023-2050**
Medium	5,378	18,229	38,005
High	8,690	31,780	61,478
Speculative	14,123	50,434	90,618
Net zero	448	8,488	24,105

Effects of $PM_{2.5}$ exposure under the 2030 scenarios

Data for $PM_{2.5}$ exposure in 2030 were provided above for some additional scenarios, NECR+EV, H2030LS and H2030LSC where the latter two include stronger abatement measures in London. Associated health impacts have been quantified and economic equivalents are shown in Table 8.10:

Table 8.10. Damage, and benefits relative to baseline, associated with PM $_{2.5}$ exposure for scenarios for 2030 for England and London. Units: £million, benefits discounted.

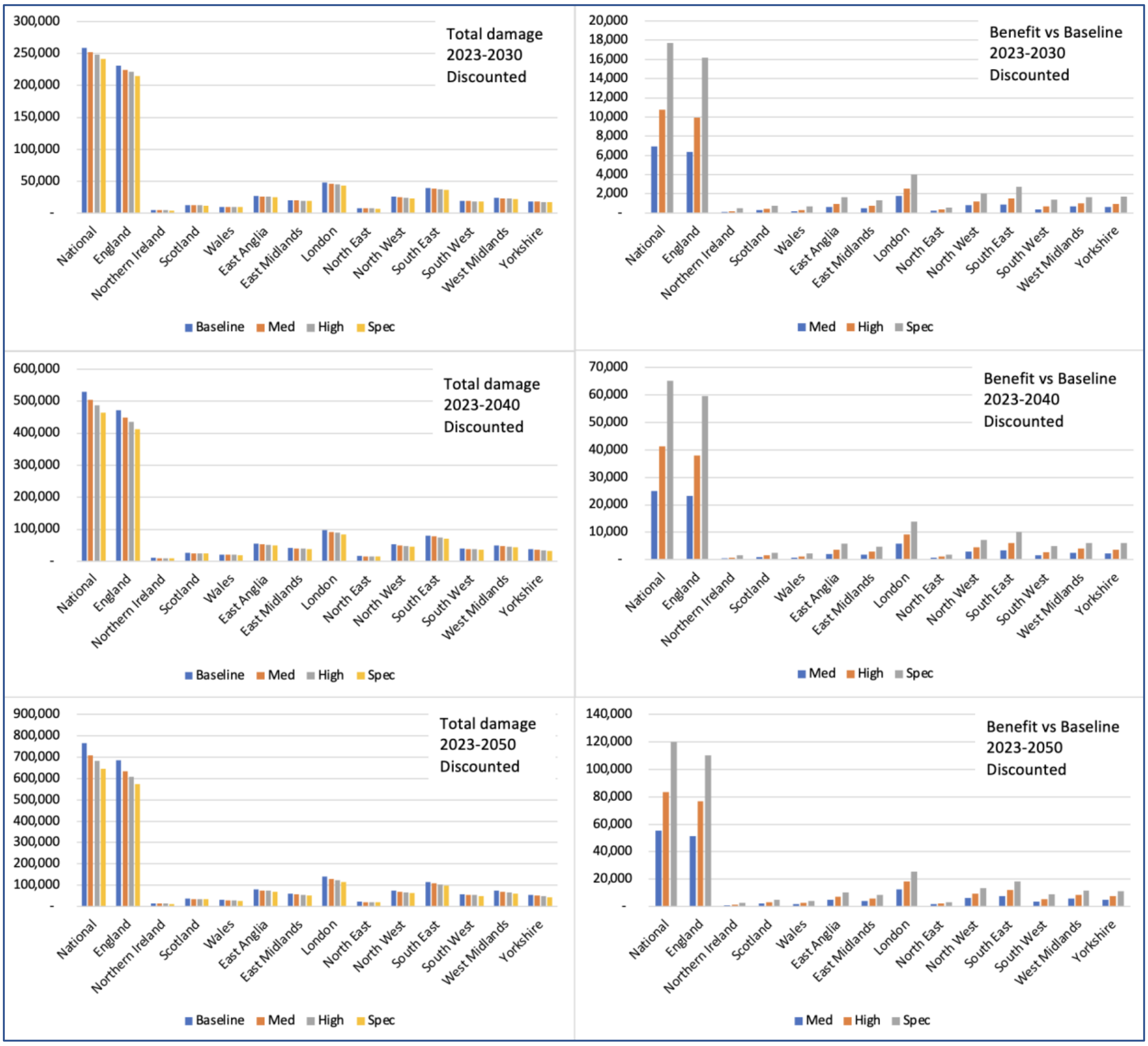
	England			London	
	Damage	Benefit vs Baseline		Damage	Benefit vs Baseline
Baseline	23,900			4,875	
Medium	23,049	851		4,664	211
High	22,197	1,703		4,476	399
Speculative	20,699	3,201		4,141	734
Net zero	23,754	146		4,801	74
NECR+EV	21,594	2,306		4,393	482
H2939LS	21,910	1,990		4,254	621
H2030LSC	21,864	2,036		4,210	665

The tables above indicate substantial benefits, increasing with the extent of abatement in successive scenarios. Detailed inspection of the scenarios has shown a large variation in the benefit to cost ratio between different individual measures, with some measures even having a negative cost and others dominating in the overall costs. It is also evident that some measures contribute very little to the improvement in $PM_{2.5}$ exposure. This has been illustrated by looking at what measures can be omitted while still producing 95% or even 99% of the reduction in cumulative exposure to $PM_{2.5}$. This suggests that slightly revised scenarios excluding these measures can generate almost the same improvements at significantly lower cost. Some of these measures seem more relevant to climate policy, generating only small or zero benefits for air quality, and hence care is needed in what proportion of their costs are attributed to air pollution. It has not been possible to go into this thoroughly here, and further work is required including consideration of uncertainties.

Regional analysis

Analysis above provides results for England only. Results are also available for the UK nationally, the Devolved Administrations and the regions of England. Total damage and benefits for these areas are presented in Figure 8.4.

Figure 8.4. Total damage and benefits for the periods 2023-2030, 2023-2040, 2023-2050 for the UK, England, Northern Ireland, Scotland and Wales, and the regions of England. Units: £million net present value.



8.3 Index of deprivation and deprived groups

Current analysis of future scenarios for Defra has concentrated on overall reduction of population exposure (reflected in population weighted mean concentrations, PWMC), and convergence towards attaining a limit on the maximum concentration such as the WHO guideline (indicated by calculating the population weighted mean exceedance, PWME). However, there are also equity issues and concerns about higher concentrations coinciding with more deprived members of society. This research note describes initial development of an approach to investigate this based on the Index of Multiple Deprivation, IMD.

The index of multiple deprivation

The index of multiple deprivation is derived for England from statistical data as a weighted average of seven different components, as summarised below.

Summary taken from the English Indices of deprivation 2019 research report (Noble et al. 2019):

About the English Indices of Deprivation 2019 (IoD2019)

The Indices of Deprivation 2019 provide a set of relative measures of deprivation for small areas (Lower-layer Super Output Areas) across England, based on seven domains of deprivation. The domains were combined using the following weights to produce the overall Index of Multiple Deprivation:

- Income Deprivation (22.5%)
- Employment Deprivation (22.5%)
- Education, Skills and Training Deprivation (13.5%)
- Health Deprivation and Disability (13.5%)
- Crime (9.3%)
- Barriers to Housing and Services (9.3%)
- Living Environment Deprivation (9.3%)

The Living Environment Deprivation domain contains an indicator for air quality; there is therefore a degree of statistical bias when looking at the relation between the IMD and exposure. However, this bias was investigated in the NETCEN (2006) report and found to be of little significance, largely due to the very small proportion allocated to the air quality index in the overall calculation of the IMD. We therefore use the IMD unadjusted for this bias.

The map in Figure 8.5 shows the Index of Multiple Deprivation produced in 2019 at Lower-layer Super Output Area (LSOA) level across England (Noble et al 2019). The areas have been ranked and divided into 10 equal groups (deciles). Areas shaded dark blue are the most deprived 10 per cent of LSOAs in England, while areas shaded bright yellow are the least deprived 10 per cent. As was the case in earlier versions of the index, 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 (see smaller inset map).

It is noted that one of the subsets relates to health deprivation and it may be interesting to investigate relationships with air pollution for this too, but this preliminary investigation applies only to the overall IMD which also only covers England.

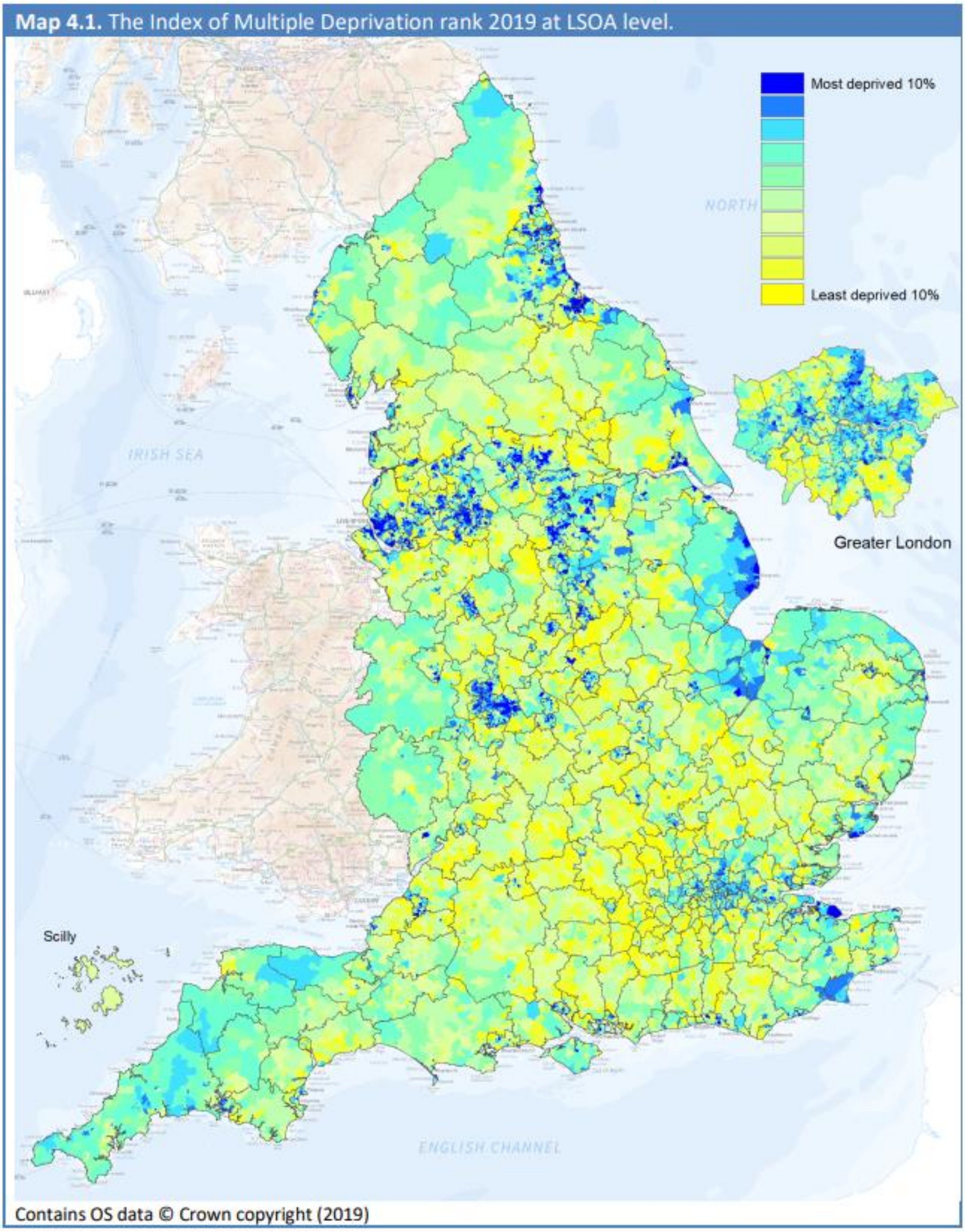


Figure 8.5: Map Index of Multiple Deprivation as shown in the English Indices of deprivation 2019 research report (Noble et al. 2019).

Relationship with $PM_{2.5}$ concentrations

The relationship with $PM_{2.5}$ concentrations can be investigated by overlaying the map of the IMD on the pollutant concentrations calculated by UKIAM on the 1x1km^2 grid used for deriving population exposure and health impacts. The individual tiles of the IMD may overlap different grid-cells; and have been apportioned in GIS according to the respective areas of overlap. In this way we can integrate across the map area of England to calculate the population weighted mean concentration for each decile of the IMD.

These can then be plotted as in the graphs below (Figure 8.6) ranging from the most deprived in decile 1 on the left, to the least deprived decile 10 on the right. The illustration is for emissions in 2018 based on the NAEI. The plot for PWMC is on the left. It is interesting to see that, across England as a whole, the highest exposure does not coincide with the most deprived sector, but with the neighbouring deciles. 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 will not pick up on these instances as the LSOAs are ordered by the average deprivation in each area, and the resolution of the concentration map used is not sufficiently high.

Here we are interested in the degree of inequality between the different deciles, rather than the absolute concentrations. We therefore plot the Delta PWMC, the right-hand figure, calculated by subtracting the mean concentration from the PWMC for each decile. The delta plot brings out the difference between the deciles more clearly and is used for the remaining analysis.

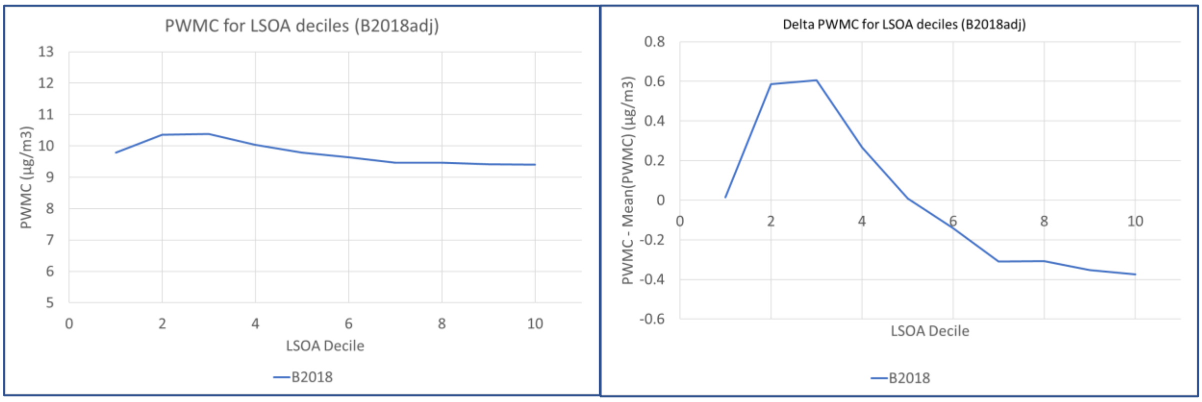


Figure 8.6: B2018adj PWMCs and Delta PWMCs in relation to Indices of Deprivation in England

Equivalent graphs have been explored for different sub-regions, and rural versus urban comparisons showing a wide variability. This can be useful to illustrate comparison with just London for example (Figure 8.7), where the highest concentration does coincide with the lowest decile (orange line).

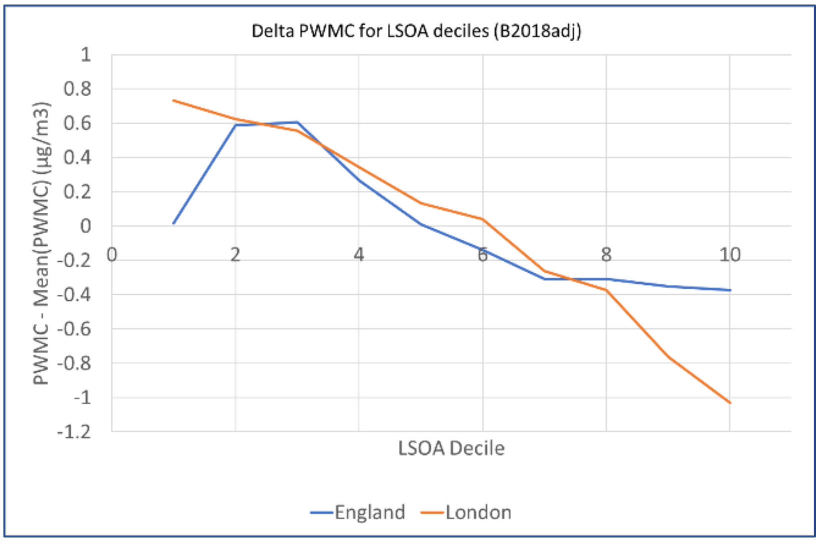


Figure 8.7: B2018adj Delta PWMCs in relation to Indices of Deprivation in London

This approach can also be used to compare scenarios as shown in Figure 8.8 illustrating the improvement in the baseline scenario between 2018 and 2050. A significant improvement is seen between 2018 and 2025, with a clear reduction in the degree of exposure bias towards the more deprived deciles. From 2025 onwards, there is little change in the bias for the baseline, with a marginal increase in the bias towards more deprived areas from 2030 to 2050.

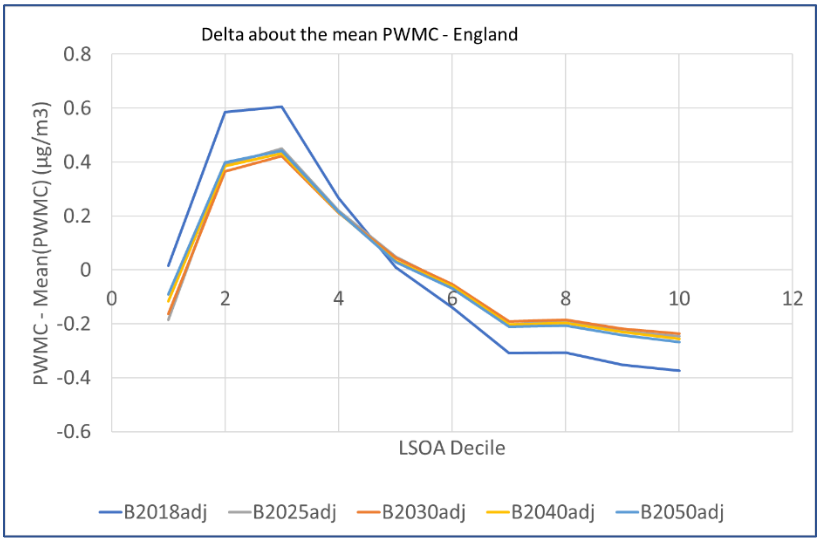


Figure 8.8: Baseline Delta PWMCs in relation to Indices of Deprivation in England for each year.

Extending the analysis to the medium, high and speculative scenarios we see a progressive reduction in exposure bias with scenario ambition, as shown in Figure 8.9. For 2030, the improvement is limited for the medium and high scenarios. However, by 2050 a significant improvement is seen for all scenarios. This may be a reflection of the time taken for the enforcement of certain measures to translate to emission reductions. For example, NO_x

reduction due to the phase out of ICE vehicles is limited in 2030, but leads to a larger reduction by 2040.

Further analysis is underway to explore how the abatement of specific SNAP sectors contribute to the overall bias in exposure. Early results show that domestic and commercial combustion (SNAP2) and road transport (SNAP7) contribute the greatest proportion to the inequality in exposure across the deprivation deciles.

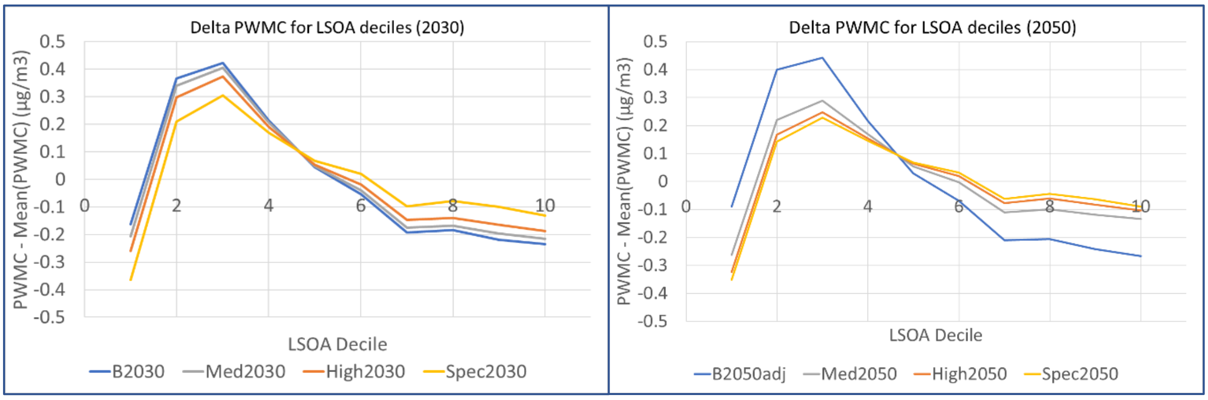


Figure 8.9: Delta PWMCs in relation to Indices of Deprivation in England for each scenario for 2030 and 2050.

<u>Index of exposure inequality</u>

We have also started investigating an approach for deriving a quantitative value as an indicator of the degree of bias in exposure towards less or more deprived areas. This is based on the Gini index as a recognised statistical technique (e.g. NETCEN 2006), but adapted to use cumulative exposure instead of number of people above a threshold (which can be an unstable indicator sensitive to very small changes in modelled concentrations). This approach generates a single number where +ve values indicate a bias towards higher exposure in more deprived regions, and negative values the opposite. The greater the magnitude of the indicator, the greater the level of inequality (see addendum for an explanation of how the index is derived). For the baseline years this index of exposure bias decreases from 0.83ug.m^{-3} for 2018 to 0.45ug.m^{-3} for 2030 (Table 8.11), indicating that the degree of bias in exposure towards the more deprived areas has nearly halved. In London, the rate of improvement is lower with a reduction from 1.61ug.m^{-3} for 2018 to 1.17ug.m^{-3} for 2030. From 2030 onwards the indicator increases slightly rather than decreases, indicating that there is no further benefit towards reducing the exposure bias after 2030 as also seen in Figure 8.8.

Higher values for the index are seen in London across all scenarios for 2030, 2040 and 2050 (Table 8.12). For the 2050 speculative scenario, representing the greatest emission reductions, the index for England is reduced substantially relative to the baseline, however still remains relatively high for London. Future work could investigate the impact of London-specific measures in addition to the use of the sub-index on health as opposed to the compound Index of Multiple Deprivation.

Table 8.11: Index of exposure inequality for baseline scenario.

Unit=ug/m3	England	London
B2018adj	0.83	1.61
B2025adj	0.47	1.24
B2030adj	0.45	1.17
B2040adj	0.50	1.19
B2050adj	0.54	1.20

Table 8.12: Index of exposure inequality for all scenarios 2030, 2040 and 2050.

Unit=ug/m3	England	London
B2030adj	0.45	1.17
Med2030	0.40	1.13
High2030	0.31	1.06
Spec2030	0.20	0.91
B2040adj	0.50	1.19
Med2040	0.30	1.00
High2040	0.16	0.90
Spec2040	0.10	0.85
B2050adj	0.54	1.20
Med2050	0.20	0.89
High2050	0.10	0.82
Spec2050	0.05	0.78

<u>Extending inequality analysis to health impact assessment</u>

Description of the effects of air pollution on inequality based on population exposure only provides a partial impression of health inequalities linked to air pollution exposure. There is significant evidence, as shown by the following examples, that the prevalence and incidence of health impacts associated with air pollution is greater amongst deprived populations than those that are less deprived.

- Mortality
  - Stillbirth: Factor 2 -3 difference in stillbirth rates between most and least deprived in UK https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6747680/
  - Life expectancy: In 2017 to 2019 the difference in life expectancy (LE) at birth between the least and most deprived areas in England was 9.4 years for males and 7.6 years for females https://www.ons.gov.uk/peoplepopulationandcommunity/healthandsocialcare/healthinequalities/bulletins/healthstatelifeexpectanciesbyindexofmultipledeprivationimd/2017to2019
- Morbidity
  - Healthy life expectancy: Difference of 19.0 years for males and 19.3 years for females among those living in the most deprived areas of England compared with the least. https://www.ons.gov.uk/peoplepopulationandcommunity/healthandsocialca

re/healthinequalities/bulletins/healthstatelifeexpectanciesbyindexofmultipledeprivationimd/2017to2019
  - Stroke: inverse social gradient in disability after stroke. https://www.ahajournals.org/doi/10.1161/01.str.0000157597.59649.b5
  - Dementia: areas with a higher number of deprived households tend to have higher age-standardised rates of dementia. https://commonslibrary.parliament.uk/dementia-age-and-deprivation-differences/
  - Respiratory health/hospital admissions: IMD was significantly and independently associated with emergency hospitalization. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5914553/
  - Diabetes: those in lower socio-economic position groups having a higher prevalence and incidence of diabetes. https://www.nice.org.uk/guidance/ph35/evidence/ep-3-socioeconomic-status-and-risk-factors-for-type-2-diabetes-pdf-433771165
  - Asthma: Asthma is more prevalent within more deprived communities, and those living in more deprived areas of England are more likely to go to hospital for their asthma. https://www.asthma.org.uk/support-us/campaigns/publications/inequality/

The usual approach to quantification of health impacts in the UK is to apply national average estimates of prevalence and incidence (as appropriate). This approach is used in the calculation of the Defra damage costs, as an example. This could be adjusted to take account of variation in prevalence and incidence with deprivation. Considering the case of London as an example, the graph above indicates a near straight line relationship of deprivation decile with $PM_{2.5}$ levels. Accounting for variation in incidence of impacts with deprivation in this case seems unlikely to affect the overall estimate of health impact significantly, but would (following the cited data that suggests health is negatively associated with deprivation) affect the distribution of damage, with the highest health benefits arising from air quality improvements in deprived areas.

References:

Noble, S., McLennan, D., Noble, M., Plunkett, E., Gutacker, N., Silk, M., Wright, G. (2019). *English Indices of deprivation*. Ministry of Housing, Communities & Local Government research report. Available from: https://www.gov.uk/government/statistics/english-indices-of-deprivation-2019 [Accessed 25 February 2022].

NETCEN (2006) *Air quality and social deprivation in the UK: an environmental analysis.* Defra. Report AEAT/ENV/R/2170. Available from: https://uk-air.defra.gov.uk/assets/documents/reports/cat09/0701110944_AQinequalitiesFNL_AEAT_0506.pdf [Accessed 25 February 2022].

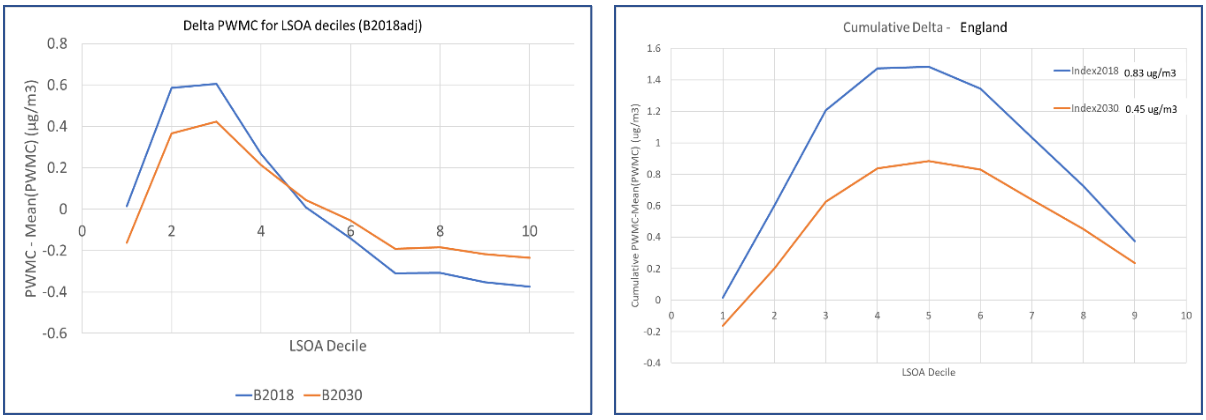
Addendum– Derivation of index of exposure inequality

The delta PWMC plot is a useful way of showing the inequality in exposures across deciles, e.g. the left hand plot of Addendum Figure 4 below. On the right hand side is a plot of the cumulative exposure about the mean for each decile. This plot is similar to the cumulative population plots which are used to derive the Gini Index, a recognised index of inequality. Calculating the area of this graph gives a value that represents the shape of the left hand plot of the delta, i.e. the degree of inequality across the deciles. If the lower deciles have higher concentrations in the delta plot you get a positive number, if the higher deciles have higher concentrations in the delta plot you get a negative value. If it's perfectly equal across deciles you get 0. The value associated to each curve is included on the plot below. The index captures the degree of bias towards either the less or more deprived areas.

$$\text{Exposure Index} = \text{Area under cumuative curve of } \Delta\text{PWMC}$$

Where $\Delta\text{PWMC} = \text{PWMC} - \text{mean(PWMC)}$.

This index can be shown to be equivalent to the covariance of the ΔPWMC and the decile number.



Delta PWMCs and cumulative Delta PWMC in relation to Indices of Deprivation in England for B2018 and B2030

8.4 Protection of ecosystems and effects of eutrophication

In addition to impacts on human health, anthropogenic emissions of NH_3, NO_x and SO_2 have a significant impact on the health of ecosystems through direct effects from atmospheric concentrations and wet and dry deposition. This impact includes both acidification and the eutrophication of soils and freshwater, leading to a loss of species. Due to the vastly reduced rate of SO_2 emissions over the last 30-40 years and reduction of acidification, the impact of eutrophication through the deposition of reactive nitrogen in wet (NO_3^-, NH_4^+) and dry (NH_3, HNO_3, NO_x) forms has become a more urgent problem. As well as contributing to $PM_{2.5}$ through formation of SIAs, a co-benefit of the mitigation of NH_3 and NO_x is a reduction in the rate of deposition of these pollutants and therefore improvements in the outlook of nitrogen-sensitive habitats with respect to eutrophication.

Here we apply the exceedance score methodology (Woodward et al. 2022) outlined in section 5.3 to estimate the degree of improvement in the protection of ecosystems from the impact of eutrophication. The method makes use of the deposition estimates of two inherently different models along with the maximum and minimum critical load (CL) values for different nitrogen-sensitive habitats to derive an exceedance score. This score ranges from highly unlikely to be in exceedance (P0) to highly likely to be in exceedance (P5).

Figure 8.10 shows the proportion of the area of nitrogen-sensitive habitats in each exceedance score for the 2018 baseline in addition to the 2030 and 2050 scenarios. The national outlook is significantly more positive than that for England only, where the majority of nitrogen-sensitive habitat area is likely (P4), or highly likely (P5), in exceedance. This difference is largely due to considerably lower exceedances in Scotland where deposition rates are lower. A modest improvement is seen for the Medium scenario relative to the baseline, with a slightly greater improvement for the High and Speculative scenarios.

The difference between scenarios is seen more clearly in Figure 8.11, showing the increase in the percentage area of habitats considered likely (P1) or highly likely (P0) to be protected relative to the B2030adj scenario. A gradual improvement is seen with each level of ambition, with a significant improvement between the 2030 and 2050 scenarios. By 2050, the Speculative scenario achieves similar improvements to that of the most ambitious agriculture scenario considered in Section 5.3 where the impact of dietary change on NH_3 emissions is considered. In the case of the Speculative scenario, this improvement is achieved by 2050 through a significant reduction in NH_3 emissions (45kT) combined with a large reduction in NO_x emissions.

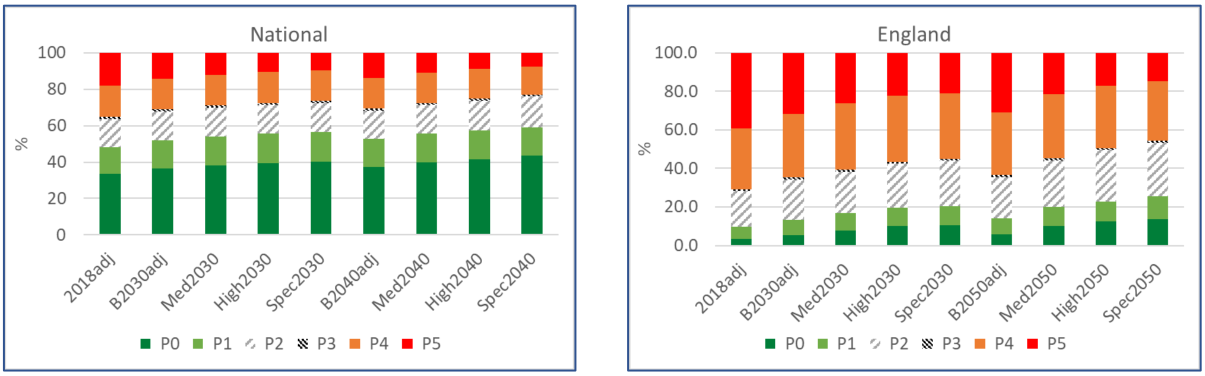


Figure 8.10: Percentage area of all N-sensitive habitats assigned to each exceedance score for (a) UK and (b) England for the B2018adj, 2030 scenarios and 2050 scenarios.

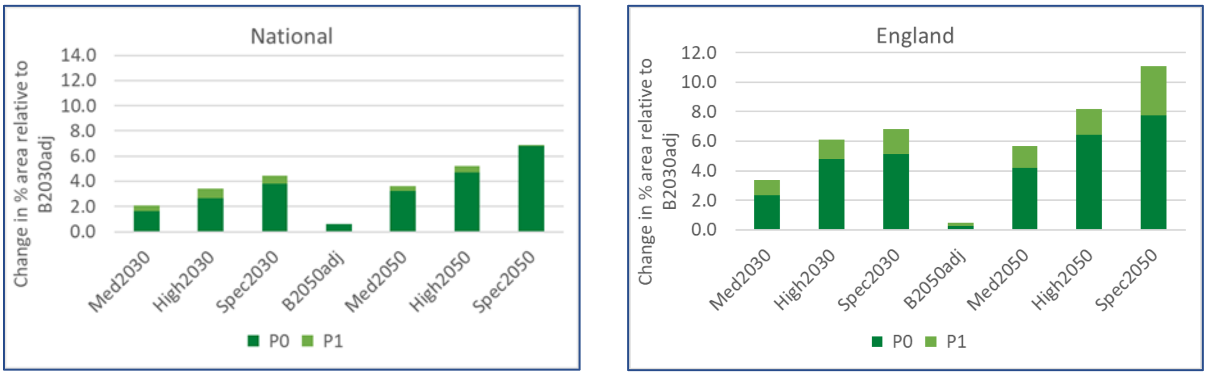


Figure 8.11: Difference in percentage area of all N-sensitive habitats assigned to the likely or highly likely protected scores relative to B2030adj for (a) UK and (b) England.

The Clean Air Strategy specifies a target of a 17% reduction in the deposition of reactive nitrogen onto priority sensitive habitats by 2030. As UKIAM is a national scale model we do not estimate the deposition and associated critical load exceedances on these specific sites; a limitation was lack of data on where the sensitive ecosystems are located within them, and sometimes these sites are quite large so that finding exceedance somewhere within a site could be pessimistic. Hence, we have concentrated on the national mapping of all N-sensitive habitats rather than just the protected sites. As there is a correlation between the N-sensitive habitat areas and the location of protected sites, we expect the relative reduction in N deposition due to national measures to be similar for both.

None of the scenarios considered achieve a 17% reduction in N deposition on N-sensitive habitat areas by 2030, with the greatest reduction for the Speculative scenario at 16.2%. However, the High and Speculative scenarios do achieve this target by 2040 with 18.5% and 20.1% reductions, respectively. These numbers should be considered as crude estimates only. Each site will require a local assessment to determine whether the target is reached, however these reductions give an indication of the degree to which these national emission reductions can contribute towards achieving this target.

The Government's 25 year environment plan (Defra, 2018) states a target of restoring 75% of protected sites in England to a favourable condition. While again the analysis has not been limited to protected sites only, it is clear from Figure 8.10 that none of the scenarios considered achieve this target. Greater reductions in national NH_3 emissions are likely to be required. However, reducing national emissions only is unlikely to be enough; local measures to reduce emissions near these protected sites are also likely to be necessary (Dragositis et al. 2020).

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9. Conclusions

The aim of this work has been to provide support to Defra in setting targets for reducing fine particulate pollution $PM_{2.5}$ in England as required in the Environment Act. This has involved modelling future scenarios for the UK up to 2050, combining both imported contributions from other countries and shipping, and due to UK pollutant emissions of primary $PM_{2.5}$ and gaseous SO_2, NO_x and NH_3 as precursors of secondary inorganic particulate matter, SIA. We have used the UKIAM model developed previously to investigate how the UK could best achieve compliance with national emissions ceiling requirements; but adapted and developed to assess total $PM_{2.5}$ concentrations and exposure. This is a simplified model, but very fast to run, enabling investigation of a large number of potential future scenarios; and also giving detailed source apportionment. To check its suitability UKIAM has been compared with the more sophisticated EMEP4UK model, which has also investigated such factors as the effects of meteorology on interannual variability.

There are inevitably a large number of uncertainties, complicated by interaction of air quality abatement with climate, transport and agricultural policies. As an initial step individual studies have been undertaken of the transport, domestic, agriculture, and energy and industry sectors, to identify the key sources and uncertainties, and how they might be affected by external factors. This has included electrification of the fleet with respect to road transport; and in the domestic sector the important contribution from wood-burning with huge uncertainties. There have been major changes in estimates of wood-burning as we concluded this work, which we have tried to allow for with sensitivity studies. Many emissions are highly uncertain, and some sources, such as commercial and domestic cooking, are missing in the National Atmospheric Emission Inventory, NAEI, as the starting point for this study. Whereas the main aim in setting targets for $PM_{2.5}$ reduction is the benefit for human health, there are also side effects of emission abatement such as the improvement in protection of natural ecosystems from reducing agricultural emissions of ammonia.

To investigate what reductions in $PM_{2.5}$ might be feasible we have considered a broad range of future emission scenarios. The scenarios were based on emission trajectories produced by applying abatement measures identified by Wood Plc through stakeholder engagement and literature review, applied to a NAEI 2018 baseline using the Scenario Modelling Tool, SMT. Emission scenarios from the SMT have been mapped on to around ninety different sources distinguished in UKIAM for London, the rest of England, Scotland, Wales and N Ireland, coupled with the detailed modelling of road transport included in UKIAM across the UK road network. The scenarios span different levels of ambition - the medium, high and speculative scenarios, each extending from 2018 as the base year up to 2050. Comparison with a scenario aimed at achieving the 2030 national emissions ceiling requirements in 2030, coupled with progress towards electrification of the fleet, produces results very similar to the high scenario for 2030. In addition, a net zero scenario has been modelled based on data supplied to Defra from BEIS for energy projections to achieve net zero climate commitments in 2050. This does not include air pollution abatement measures, and achieves relatively modest improvements, emphasizing the need for additional action to reduce air pollution. Large improvements in $PM_{2.5}$ concentration are indicated by 2030 even in the baseline, but these are enhanced with increasingly stronger abatement in the scenarios above, and with further improvements by 2040 and 2050.

However, the highest concentrations are in London, and additional work has been undertaken to investigate this and how it may be reduced, including stronger measures to reduce traffic within the extended ULEZ area of inner London. Throughout the work we have tried to consider the many uncertainties and indicate sensitivity to the assumptions made. This has built on previous work on, for example, uncertainties in emissions of primary $PM_{2.5}$, and comparison of the London Atmospheric Emissions Inventory, LAEI and the national NAEI underpinning our scenario analysis. This helped to identify the potential contribution of cooking as well as emphasizing the uncertainties for wood burning as an important source.

There are two different $PM_{2.5}$ targets proposed. The first is aimed at overall reduction of population exposure which we consider by calculating the population weighted mean concentrations for England. The second is a limit value on the maximum concentrations in England. This has led to the investigation of hybrid scenarios with stronger measures to improve concentrations in London as compared with the rest of England. This is shown to be an effective way of improving the higher concentrations in London to converge towards improved concentrations achieved elsewhere in England.

Using population weighted mean concentrations as an indicator of improvements in population exposure it has been suggested that % reductions are a better indicator than absolute reductions in concentration, being more consistent between different regions. Recognising the large contribution from wood-burning as a source of $PM_{2.5}$ and our concerns that this was overestimated in the NAEI, we have undertaken sensitivity studies to account for a recent downward revision of estimates of wood burned, assuming that this reduces the improvement due to abatement measures for wood-burning. This reduces the percentage improvements in population weighted mean concentrations both for England and for London by between 3 and 7%. These sensitivity studies may tend towards being pessimistic but represent a safety margin for uncertainty. The results for the different scenarios are given in Table 8.1 with the estimates based on lower wood burning in italics, giving a range for each scenario.

The results indicate that by combining the high scenario with additional measures a reduction in population exposure of 24 to 25% could be achieved by 2030 both in London and the rest of England even allowing for the more pessimistic assumptions in the sensitivity study. By 2040 this increases to 29 to 30% reduction in population exposure, again taking the more pessimistic assumptions in the sensitivity study.

Towards the setting of limit values we have estimated population weighted mean exceedance, PWME, of different threshold values from 8 to 12 $ug.m^{-3}$. These have been tabulated in a traffic light format, with different levels of exceedance from red for high exceedance to green for zero or negligible exceedance for the different scenarios and years- see Table 8.2a. This table illustrates the higher levels of exceedance in London, and the improvements when additional measures including behavioural change and traffic reduction are taken to reduce concentrations there. As these results are based on NAEI emissions and are subject to the same uncertainties as the mean population exposure above, we have undertaken the same sensitivity study with respect to wood-burning emissions and their abatement. The resulting exceedance values with these more pessimistic assumptions are compared with the original estimates for selected scenarios in Table 8.2b, giving significant increases in PWME for the sensitivity study.

These results imply that even with the more adverse assumptions in the sensitivity study, the calculated concentrations in London away from major roads or other hot-spots, lie below $10ug.m^{-3}$ for the high scenario with additional measures in London by 2040. Outside London, or for the more optimistic estimates based on the original NAEI emissions, this could be achieved earlier by 2030.

It needs to be recognised that in this analysis there are very many uncertainties and assumptions, which, as far as possible, we have tried to identify and assess what effects they may have. These include the limited spatial resolution of $1x1km^2$ of the UKIAM model in picking out local hot-spots, where we have attempted to use more detailed spatial resolution in independent modelling with the ADMS model to illustrate how there can still be much higher $PM_{2.5}$ values in grid squares giving local enhancement close to major roads. Attention has been drawn to uncertainties in emissions of primary $PM_{2.5,}$ including non-exhaust emissions, and wood-burning where further work is required reflecting other research in progress: also to missing sources such as cooking.

There are also other considerations in deriving effective strategies for $PM_{2.5}$ abatement. These include the benefits, especially for health, based here on reduction of total $PM_{2.5}$ concentrations by mass and the advice of COMEAP. Assessment of the monetised benefits of the abatement scenarios indicates that these are very substantial as reported in section 8.2. For the high scenario the net present value for the total benefits over the period 2023 to 2030 is estimated at almost £10 billion, increasing to £38 billion over the extended period to 2040. Most of this benefit is attributable to the reduction in health effects from $PM_{2.5}$ exposure of the population. Additional work is in progress in Defra to compare these benefits with the costs of abatement, taking into account corresponding reductions in greenhouse gases as many measures address improvements both for climate and air quality. Further work is suggested here on the abatement scenarios, some of which include measures which contribute little to improving $PM_{2.5}$ while adding substantial costs; whereas other measures with low or even negative costs can be highly cost-effective. Sensitivity studies could be useful here towards achieving much the same improvement at lower cost.

An interesting aspect has been the use of the deprivation index to illustrate the convergence between exposure in some of the more deprived areas and the least deprived areas, reflecting reductions in primary $PM_{2.5}$ emissions in more polluted urban areas, including traffic. This has been explored in section 8.3 and shows a stronger relationship for London than for England as a whole.

But there are other co-benefits and synergies, especially with climate and transport policies which require consideration in more depth. There are also wider environmental benefits, including for eutrophication and effects on natural ecosystems, where future changes in agriculture including land-use change and climate measures will also be important. Also, although not considered in this report, there is an international aspect with reciprocal benefits of emission reduction in the UK for other countries, and commitments to reduce transboundary air pollution in Europe. With regard to imported contributions the importance of shipping in the seas round the UK has been noted, and further work is required here on the limited extent of the emission control area for international shipping, and IMO plans to reduce CO_2 emissions.

Finally, another area needing further work is the measurement network, and how this can be used to check future progress as well as improve modelling work as undertaken in this report. This is particularly important in relation to assessing exceedance of a limit value, and specifying where such limit values apply, especially for London with large spatial variability and complex problems of urban topography and dispersion.

Appendix: supplementary data

A) National emission data by SNAP sector for different scenarios

B) Reductions in PWMC of NO_2 for different scenarios

A) National emission data by SNAP sector for different scenarios

National emissions for baseline scenario

	2018				2025				2030				2040				2050			
SNAP	**NH_3**	**SO_2**	**NOx**	**$PM_{2.5}$**	**NH_3**	**SO_2**	**NOx**	**$PM_{2.5}$**	**NH_3**	**SO_2**	**NOx**	**$PM_{2.5}$**	**NH_3**	**SO_2**	**NOx**	**$PM_{2.5}$**	**NH_3**	**SO_2**	**NOx**	**$PM_{2.5}$**
1	0.3	57.9	150.5	3.5	0.3	30.7	114.4	3.5	0.3	29.0	100.7	2.8	0.3	28.7	96.4	2.7	0.3	28.7	96.4	2.7
2	2.5	33.1	46.1	47.0	2.9	14.0	37.6	28.5	2.9	11.3	37.9	28.6	2.5	4.8	38.8	28.7	2.1	2.9	38.8	28.7
3	0.4	40.9	133.7	18.5	0.4	26.8	122.0	14.9	0.4	20.3	118.0	13.8	0.4	20.0	116.1	13.6	0.4	20.0	116.1	13.6
4	2.6	8.8	10.8	7.5	2.5	9.7	8.3	6.7	2.5	9.3	7.7	6.6	2.5	9.2	7.7	6.6	2.5	9.2	7.7	6.6
5	0.0	0.6	2.0	0.5	0.0	0.4	1.5	0.4	0.0	0.2	0.8	0.2	0.0	0.2	0.7	0.2	0.0	0.2	0.7	0.2
6	1.2	0.0	0.0	1.2	1.3	0.0	0.0	1.1	1.3	0.0	0.0	1.1	1.3	0.0	0.0	1.1	1.3	0.0	0.0	1.1
7	4.4	1.3	254.9	15.8	4.8	1.3	110.6	12.5	4.9	1.3	62.5	10.3	4.7	1.1	64.8	12.6	4.3	1.1	71.1	13.8
8	0.0	2.7	82.6	6.2	0.0	2.7	67.1	3.5	0.0	2.7	62.8	3.3	0.0	2.7	62.9	3.4	0.0	2.7	62.9	3.4
9	22.3	0.6	1.3	1.7	22.5	0.6	1.3	1.7	22.5	0.6	1.3	1.7	23.5	0.6	1.3	1.7	23.5	0.6	1.3	1.7
10	231.7	0.0	26.9	2.8	230.9	0.0	27.2	2.8	229.7	0.0	27.1	2.8	229.7	0.0	27.1	2.8	229.7	0.0	27.1	2.8
11	9.0	0.0	0.2	3.3	9.2	0.0	0.2	3.2	9.4	0.0	0.2	3.1	9.4	0.0	0.1	3.1	9.4	0.0	0.1	3.1
TOTAL	**274.3**	**145.9**	**709.0**	**108.0**	**274.9**	**86.2**	**490.1**	**78.8**	**274.1**	**74.8**	**419.0**	**74.4**	**274.3**	**67.2**	**415.9**	**76.3**	**273.5**	**65.3**	**422.2**	**77.5**

National emissions for medium, high and speculative scenarios

Medium

	2025				2030				2040				2050			
SNAP	**NH_3**	**SO_2**	**NOx**	**PM2.5**	**NH_3**	**SO_2**	**NOx**	**PM2.5**	**NH_3**	**SO_2**	**NOx**	**PM2.5**	**NH_3**	**SO_2**	**NOx**	**PM2.5**
1	0.3	30.5	112.5	3.4	0.3	28.9	98.7	2.7	0.3	27.9	93.7	2.5	0.3	18.0	87.2	2.1
2	2.8	13.7	37.0	27.9	2.8	10.8	36.4	25.1	2.4	4.4	35.3	21.0	2.0	2.0	10.1	16.5
3	0.4	26.8	122.0	11.8	0.4	20.3	117.8	8.9	0.4	20.0	114.7	8.9	0.4	19.9	102.1	8.9
4	2.5	9.7	8.3	6.3	2.5	9.3	7.7	6.0	2.5	9.2	7.6	6.0	2.5	9.2	7.1	6.0
5	0.0	0.4	1.5	0.4	0.0	0.2	0.8	0.2	0.0	0.2	0.7	0.2	0.0	0.2	0.7	0.2
6	1.3	0.0	0.0	1.1	1.3	0.0	0.0	1.1	1.3	0.0	0.0	1.1	1.3	0.0	0.0	1.1
7	4.7	1.3	102.1	11.5	3.6	1.1	51.3	10.8	1.2	0.8	8.0	10.3	0.8	0.3	0.7	11.2
8	0.0	2.7	66.3	3.4	0.0	2.7	61.7	3.1	0.0	2.7	51.7	0.8	0.0	2.6	41.4	0.8
9	22.5	0.6	1.3	1.7	22.6	0.6	1.3	1.7	22.5	0.6	1.3	1.7	22.5	0.6	1.3	1.7
10	216.2	0.0	27.2	2.8	213.6	0.0	27.2	2.8	213.6	0.0	27.2	2.8	211.7	0.0	27.2	2.8
11	9.2	0.0	0.2	3.2	9.4	0.0	0.2	3.1	9.4	0.0	0.2	3.1	9.4	0.0	0.2	3.1
TOTAL	**260.1**	**85.8**	**478.3**	**73.4**	**256.6**	**74.0**	**403.0**	**65.5**	**253.8**	**65.8**	**340.2**	**58.4**	**250.9**	**52.8**	**277.8**	**54.3**

High

	2025				2030				2040				2050			
SNAP	**NH_3**	**SO_2**	**NOx**	**PM2.5**	**NH_3**	**SO_2**	**NOx**	**PM2.5**	**NH_3**	**SO_2**	**NOx**	**PM2.5**	**NH_3**	**SO_2**	**NOx**	**PM2.5**
1	0.3	30.4	110.6	3.2	0.3	28.8	96.9	2.6	0.3	27.8	91.7	2.4	0.3	17.9	85.2	2.0
2	2.8	13.5	36.5	27.4	2.1	10.1	33.8	17.9	1.8	3.8	24.3	9.6	1.5	1.7	8.8	8.6
3	0.4	26.8	121.9	10.6	0.4	20.3	117.7	6.8	0.4	20.0	107.9	7.0	0.4	19.9	102.1	6.9
4	2.5	9.7	8.3	6.2	2.5	9.3	7.7	5.9	2.5	9.2	7.1	5.9	2.5	9.2	7.1	5.9
5	0.0	0.4	1.5	0.4	0.0	0.2	0.8	0.2	0.0	0.2	0.7	0.2	0.0	0.2	0.7	0.2
6	1.3	0.0	0.0	1.1	1.3	0.0	0.0	1.1	1.3	0.0	0.0	1.1	1.3	0.0	0.0	1.1
7	4.7	1.2	101.1	11.3	3.2	1.1	50.1	10.2	0.9	0.7	7.7	9.6	0.7	0.7	0.7	10.2
8	0.0	2.7	66.7	3.3	0.0	2.6	60.8	3.0	0.0	2.6	55.4	0.8	0.0	2.4	29.5	0.5
9	22.5	0.6	1.3	1.7	22.5	0.6	1.3	1.6	22.5	0.6	1.3	1.3	22.5	0.6	1.2	1.0
10	209.7	0.0	27.2	2.8	202.0	0.0	27.7	2.8	198.7	0.0	27.7	2.8	196.9	0.0	27.7	2.8
11	9.2	0.0	0.2	3.2	9.4	0.0	0.2	3.1	9.4	0.0	0.2	3.1	9.4	0.0	0.2	3.1
TOTAL	**253.5**	**85.4**	**475.3**	**71.3**	**243.9**	**73.0**	**397.0**	**55.1**	**237.9**	**64.9**	**324.0**	**43.6**	**235.5**	**52.7**	**263.2**	**42.1**

Speculative																	
		2025				2030				2040				2050			
	SNAP	NH_3	SO_2	NOx	PM2.5	NH_3	SO_2	NOx	PM2.5	NH_3	SO_2	NOx	PM2.5	NH_3	SO_2	NOx	PM2.5
	1	0.3	30.4	110.6	3.2	0.3	28.8	98.1	2.6	0.3	18.0	86.6	2.0	0.3	18.0	86.3	2.0
	2	2.8	13.6	36.7	27.6	0.4	9.5	22.2	5.9	0.3	3.5	21.8	4.8	0.3	1.5	6.7	3.8
	3	0.4	26.8	121.8	10.6	0.4	20.3	110.2	6.8	0.4	20.0	107.9	7.0	0.4	19.9	102.1	6.9
	4	2.5	9.7	8.3	6.3	2.5	9.3	7.2	6.1	2.5	9.2	7.1	6.1	2.5	9.2	7.1	6.1
	5	0.0	0.4	1.5	0.4	0.0	0.2	0.8	0.2	0.0	0.2	0.7	0.2	0.0	0.2	0.7	0.2
	6	1.3	0.0	0.0	1.1	1.3	0.0	0.0	1.1	1.3	0.0	0.0	1.1	1.3	0.0	0.0	1.1
	7	4.6	1.2	99.0	10.8	3.5	1.1	48.7	9.8	1.1	0.7	7.4	7.7	0.7	0.7	0.7	6.7
	8	0.0	2.7	66.6	3.2	0.0	2.4	46.3	0.6	0.0	2.4	29.4	0.5	0.0	2.4	29.0	0.5
	9	22.5	0.6	1.3	1.7	22.6	0.6	1.3	1.5	22.6	0.6	1.2	1.0	22.6	0.6	1.2	1.0
	10	205.2	0.0	27.6	2.8	200.3	0.0	27.6	2.8	191.5	0.0	27.8	2.8	191.5	0.0	27.8	2.8
	11	9.2	0.0	0.2	3.2	9.4	0.0	0.2	3.1	9.4	0.0	0.2	3.1	9.4	0.0	0.2	3.1
	TOTAL	**249.0**	**85.5**	**473.6**	**71.0**	**240.8**	**72.3**	**362.7**	**40.5**	**229.6**	**54.5**	**290.2**	**36.2**	**229.1**	**52.4**	**261.6**	**34.1**

National emissions in 2030

	Medium 2030				High 2030				Speculative 2030				NECR 2030			
SNAP	NH_3	SO_2	NOx	PM2.5	NH_3	SO_2	NOx	PM2.5	NH_3	SO_2	NOx	PM2.5	NH_3	SO_2	NOx	PM2.5
1	0.3	28.9	98.7	2.7	0.3	28.8	96.9	2.6	0.3	28.8	98.1	2.6	0.3	28.8	80.7	2.6
2	2.8	10.8	36.4	25.1	2.1	10.1	33.8	17.9	0.4	9.5	22.2	5.9	1.1	9.6	25.3	12.3
3	0.4	20.3	117.8	8.9	0.4	20.3	117.7	6.8	0.4	20.3	110.2	6.8	0.4	18.6	66.8	7.3
4	2.5	9.3	7.7	6.0	2.5	9.3	7.7	5.9	2.5	9.3	7.2	6.1	2.5	3.1	4.6	6.3
5	0.0	0.2	0.8	0.2	0.0	0.2	0.8	0.2	0.0	0.2	0.8	0.2	0.0	0.2	0.8	0.2
6	1.3	0.0	0.0	1.1	1.3	0.0	0.0	1.1	1.3	0.0	0.0	1.1	1.3	0.0	0.0	1.1
7	3.6	1.1	51.3	10.8	3.2	1.1	50.1	10.2	3.5	1.1	48.7	9.8	4.9	0.6	52.6	11.2
8	0.0	2.7	61.7	3.1	0.0	2.6	60.8	3.0	0.0	2.4	46.3	0.6	0.0	2.7	62.8	3.1
9	22.6	0.6	1.3	1.7	22.5	0.6	1.3	1.6	22.6	0.6	1.3	1.5	22.7	0.6	1.3	1.7
10	213.6	0.0	27.2	2.8	202.0	0.0	27.7	2.8	200.3	0.0	27.6	2.8	180.2	0.0	27.2	2.8
11	9.4	0.0	0.2	3.1	9.4	0.0	0.2	3.1	9.4	0.0	0.2	3.1	9.4	0.0	0.2	3.1
TOTAL	**256.6**	**74.0**	**403.0**	**65.5**	**243.9**	**73.0**	**397.0**	**55.1**	**240.8**	**72.3**	**362.7**	**40.5**	**223.0**	**64.4**	**322.3**	**51.7**

B) Reductions in PWMC of NO_2 for different scenarios

	reduction in PWMC NO2 relative to 2018 ug/m3				
2030	National	Urban	Rural	London	England
baseline	5.0	5.5	3.1	8.0	5.4
medium	5.4	6.1	3.3	9.1	5.9
high	5.5	6.2	3.3	9.4	6.0
spec	6.1	6.9	3.6	10.3	6.6
NECR+EV	6.0	6.7	3.7	9.8	6.5
NZ	5.8	6.5	3.5	9.6	6.3
2040					
baseline	5.0	5.6	3.1	8.1	5.5
medium	6.6	7.4	4.0	11.0	7.2
high	7.0	7.8	4.2	11.5	7.6
spec	7.7	8.6	4.6	12.3	8.3
NZ	7.9	8.8	4.7	13.0	8.6
2050					
baseline	4.9	5.4	3.1	8.0	5.3
medium	8.2	9.2	4.7	13.8	8.9
high	8.5	9.5	4.9	14.2	9.2
spec	8.6	9.6	5.0	14.3	9.3
NZ	8.4	9.4	4.9	14.0	9.1