Annex 1. Imperial College London report

PM2.5 exposure and reduction towards achievement of WHO standards

SNAPCS contract Report

H. ApSimon, T. Oxley, H. Woodward, D Mehlig

Centre for Environmental Policy, Imperial College London

in collaboration with

the Centre for Ecology and Hydrology, Wood Plc. &

EMRC

Contents

Glossary:

AIS: Automatic identification system for shipping

BAU: Business as usual

ECA: Emission control area

IVOC: organic compounds of intermediate volatility

Mpu: Millions of people x.µg/m^3 used as a unit for quantifying accumulated exceedance (dividing by the number of people in millions in the area to which it applies gives the average exceedance of the WHO standard for people in that area)

NAEI: National Atmospheric Emission Inventory

NECD: National Emissions Ceilings Directive

SIA: secondary inorganic aerosol

SOA: secondary organic aerosol

VOCs: volatile organic compounds

$PM_{2.5}$ exposure and reductions towards achievement of WHO standards in the UK

1. Introduction

A central objective of the UK's Clean Air Strategy is to reduce exceedance of the WHO standard of 10 µg/m^3 for $PM_{2.5}$. This report describes modelling of a range of future scenarios to explore how much this exceedance can be reduced by the year 2030 with increasing levels of effort, taking account of imported contributions from other countries and shipping as well as UK emissions. 2016 is taken as the base year and starting point against which improvements in exceedance are assessed, with UK emissions based on the NAEI. The model used to derived population exposure from each emission scenario is the UK Integrated Assessment Model, UKIAM, which has been developed at Imperial College to support Defra in establishing air pollution control strategies. The abatement scenarios are largely based on the Multi-Pollutant Measures Data-base, MPMD, put together by Wood Plc to cover potential abatement measures in the UK and their effect in reducing emissions as well as their costs.

A brief description of the modelling tools used is given below. The pollutant emissions considered are NH_3, SO_2, and NO_x, which contribute to formation of secondary particulate matter; and primary $PM_{2.5}$. This is followed by analysis of $PM_{2.5}$ concentrations and exposure of the UK population in 2016; together with source apportionment differentiating contributions from other countries and international shipping, and from UK sources. Also included are other fixed and natural contributions that are not subject to abatement. Key sources, comparison with measurements, and uncertainties are discussed.

This is followed by analysis of a Business-as-Usual scenario for the year 2030, BAU2030, reflecting NAEI projections for UK sources, and also projected changes in emissions in other countries and from international shipping. Thereafter a range of scenarios is considered with further reductions in UK emissions up to the Maximum Technical Feasible Reduction in which every conceived technical measure is taken to reduce emissions, irrespective of costs. Also considered are more realistic scenarios aimed at achieving our own UK commitments under the National Emission Ceilings Directive, NECD. This is followed by a more detailed examination for London where exceedance of the WHO standard is highest, and most difficult to eliminate.

2. Modelling approach

2.1The UK Integrated Assessment Model, UKIAM model

The UKIAM model brings together projected emissions of SO_2, NO_x, NH_3 and PM_{10}/$PM_{2.5}$ and VOCs as adjusted to represent abatement measures specified, and calculates pollutant concentrations and deposition of sulphur and nitrogen across the

UK. Exposure of the populations and monetised health impacts are assessed, and also effects on protection of natural ecosystems. In this report we are concerned only with $PM_{2.5}$ and not PM_{10}, and ignore abatement of VOCs which are more important for ozone.

For the UK unabated emissions are taken from NAEI projections, distinguishing up to 90 different point and area sources. In the work described below the reductions due to the abatement measures selected have been taken from the Multi-Pollutant Measures Database, MPMD, described below for SO_2, NO_x, and $PM_{2.5}$; and from work by Ricardo and Rothamsted on abatement of NH_3 emissions from agriculture. Some additional measures have been defined independently by Defra, based for example on the Roads to Zero programme of DfT. Also represented are imported contributions from other countries and from international shipping, contributing to formation of secondary $PM_{2.5}$ concentrations and to deposition. Shipping emissions, both domestic and international, in the seas surrounding the UK are taken from recent data compiled by Ricardo (Ricardo 2017), and projections derived by Wood Plc, and as discussed give an important but uncertain contribution. Emissions in other countries are based on data reported to the UNECE, and commitments under the National Emission Ceilings Directive, NECD.

The contribution of each source to concentrations and deposition is calculated by scaling and superimposing pre-calculated source foot-prints for each source. For international contributions from other countries, these are based on source-receptor matrices calculated with the EMEP model, which are the same as those used in the scenarios analysed by IIASA with the GAINS model to support the development of the Gothenburg protocols and the NECD. For contributions of UK sources, concentrations of secondary inorganic aerosol, SIA, and deposition of sulphur and nitrogen, are based on the FRAME model of CEH. FRAME has been used to examine the effect of reducing each pollutant from each source one at a time within a baseline scenario for 2020, with the results for changes in concentrations or deposition normalised to unit emission reductions. For concentrations of NO_x/NO_2 and primary $PM_{2.5}$ where more local scale dispersion dominates, the Gaussian PPM model of Imperial College is used, with adjustments for urban areas such as street canyon effects for road-side concentrations. Annual average $PM_{2.5}$ concentrations are calculated on a 1x1 km grid across the UK, and deposition on a 5x5 km grid. Other contributions which are not variable such as natural contributions (as provided by Ricardo), and organic aerosol (calculated with the NAME model of the Met Office), are superimposed as an additional background.

The advantage of this approach superimposing contributions derived with different models is that the model is very quick to run (~30 minutes). It also enables detailed source apportionment and sensitivity studies to specific assumptions about individual sources. The limitations include non-linear effects of chemical interactions between pollutants, where sensitivity studies with FRAME have indicated that such effects are small compared with other uncertainties in such modelling of future scenarios; but which can be important when large changes in emissions are made.

Health impacts are assessed by combining pollutant concentrations on a 1x1 km grid with the population distribution, and using monetised costs of health impacts per person per $\mu g/m^3$ of $PM_{2.5}$ and of NO_2 equivalent to those assumed in Defra's recently published damage costs.

2.2 Modelling abatement measures, the MPMD and agricultural measures

The development of scenarios requires information on abatement measures and their effect on emissions. This has used the Multi-Pollutant Measures Database (MPMD) of measures for reducing emissions of SO_2, NO_x, PM and VOCs compiled by Wood Plc, and additional information on agricultural measures to reduce emissions of NH_3.

The Multi-Pollutant Measures Database, MPMD

The Multi-Pollutant Measures Database (MPMD) is a spreadsheet-based database of measures beyond those expected to be implemented under business as usual (BAU) policies for reducing emissions of air pollutants. Potential beyond BAU measures for 2020, 2025 and 2030 have been developed for emission sources contributing to >1% of forecast national emissions according to the NAEI projections for these years. The database contains information on the extent to which the measure is applicable with BAU(/WM) and beyond BAU(/WAM) uptake based on maximum technical feasibility), the associated costs (capital cost, operating cost and total annualised cost), emission reductions (percentage and absolute) and associated damage cost avoided (benefits to society).

The database of measures is intended to provide supporting information on the costs and benefits of emission reductions for the consideration of policies such as a revised National Emission Ceilings Directive (NECD) and Gothenburg Protocol. Therefore, the main focus of the analysis has been on those pollutants regulated under the NECD; sulphur dioxide (SO_2), nitrogen oxides (NO_X), volatile organic compounds (VOCs), and particulate matter, both PM_{10} and $PM_{2.5}$. Moreover, research for MPMD measures primarily considers those targeted at reducing absolute emissions at national level, as the NECD ceilings are expressed in tonnes per year. Knock on impacts on CO_2 are also included.

The MPMD currently includes ~200 measures across ~30 sectors (including industry, transport, domestic, agriculture and others). This has been developed by Wood for Defra over the past 10 years; and in this time there have been a number of consultations to gather feedback from key stakeholders in industry, government departments and modellers, and comparisons against GAINS.

Single pollutant cost curves have been developed for a range of different scenarios. As many measures impact on more than one pollutant a multi-pollutant analysis is also performed in order to optimise packages of measures to meet the emission ceilings for SO_2, NO_X, VOC and $PM_{2.5}$ simultaneously. The latest scenarios (modelled in the scope of the WHO target for $PM_{2.5}$) focused on selecting measures that abate primary and secondary $PM_{2.5}$ with different levels of beyond BAU uptake.

Outputs from the MPMD scenario modelling are being used by Defra to inform the development of the UK Clean Air Quality Strategy and National Air Pollutant Control Programme.

Abatement of agricultural emissions of Ammonia

In parallel with the measures in the MPMD, reducing emissions of ammonia from agriculture is based on estimation of NH_3 emissions for the NAEI by Rothamsted, and review by Ricardo of associated work on abatement measures. The emissions come from animal wastes and from fertiliser use. Abatement measures include injection and incorporation of slurries and manures spread on the land, covered storage of slurries in tanks and lagoons, and reduction of emissions from animal housing; also avoidance of urea as a fertiliser, or alternatively using it in a form with urease inhibitors.

3. The current situation based on 2016

Starting with the current situation the UKIAM model has been run with updated NAEI projections for 2016, and current emissions in other European countries. In preceding work we had identified wood burning as an important source which we looked into in more detail, using emissions provided by Defra to reflect the latest assumptions on dry versus wet wood. In the current work we have also introduced some parallel updates on domestic combustion, including new source-receptor data from FRAME. But we had also identified other sources that were important and needed attention. These included international and domestic shipping, and non-exhaust emissions of primary $PM_{2.5}$, both of which have been substantially revised, and affect the results as discussed below.

Shipping

For shipping we had already used new mapping of emissions derived by Ricardo from AIS data from the Maritime and Coastguard Agency (Ricardo 2017). This gave substantially higher emissions than in the NAEI for both domestic and international shipping. In previous work we allowed for this by simple scaling of earlier dispersion modelling which implied that international shipping with 660 kt of NO_x in sea areas round the UK was very important. But we had no estimate of how shipping emissions would change over time, or how the reclassification of emissions as UK domestic including at berth emissions, “UK international” and “In transit” and their respective spatial distributions would affect contributions to $PM_{2.5}$ concentrations.

Since then we have distinguished emissions in the Emission Control Area, ECA, from other uncontrolled emissions; and with help from Wood Plc have estimated projected emissions in 2030, taking into account the mix and growth in use of different types of vessel. More importantly for 2016 CEH have calculated new source-receptor footprints with the FRAME model for the new break down of shipping emissions, and their spatial distributions. These have been used in the revised results in this report, and indicate a much lower contribution to $PM_{2.5}$ exposure from international shipping (~50%), and a smaller absolute increase in the contribution of domestic shipping which is potentially controllable. Despite the more conservative concentrations shipping is still an important contribution to $PM_{2.5}$ population exposure, corresponding in the new estimates to a UK population weighted mean concentration in 2016 of 0.4 $\mu g/m^3$ and thus to health costs of the order of £1billion per year in the UK (based on recently revised Defra damage costs).

Non exhaust emissions

Road-transport emissions are mapped across the UK road network by the BRUTAL sub-model of UKIAM, using COPERT-5 emission factors for exhaust emissions. However in previous work non- exhaust emissions of $PM_{2.5}$ were shown to be increasingly important as exhaust emissions were reduced, making a significant contribution to population exposure to $PM_{2.5}$. In previous work we had used very simple emission factors per km driven, and had included only emissions from brakes and tyres. In the current work we have followed the Tier 2 methodology in the EEA Guidebook (EEA2016), and used speed-dependent emission factors to represent increased braking in more congested urban areas and lower emissions on faster motorways: and have also added road abrasion emissions. This has had a significant effect on the current $PM_{2.5}$ concentrations. Overall the contribution of non-exhaust emissions to population weighted mean concentrations has doubled to ~0.4 $\mu g/m^3$; and the effect is especially important in urban areas with contributions of over 1 $\mu g/m^3$ in heavily trafficked areas such as inner and central London.

$PM_{2.5}$ concentrations in 2016

Figure 3.1 shows a map of the total $PM_{2.5}$ across the UK as modelled for 2016. This has been compared with available measurements (see appendix A). The areas in red and dark-red are above the WHO standard of 10 $\mu g/m^3$, and include 15 million people. Of these 6 million are in the bright red area within 1 $\mu g/m^3$ of the standard, and within the modelling uncertainty. Correspondingly 12.4 million people are in the orange area, only just below the standard as modelled. A further 13.5 million people are in the yellow area between 1 and 2 $\mu g/m^3$ below the standard, and could possibly be at risk in a year with extreme meteorology. It is clear that the exceedance is largely confined to England, and is concentrated in major cities including London.

The total concentrations shown in figure 3.1 are composed of a natural contribution that remains the same through all the scenarios except for a small change in water content; a contribution imported from other countries and from shipping; and the contribution from UK emissions. The latter has been divided between primary $PM_{2.5}$ concentrations, and secondary $PM_{2.5}$ produced from precursor gaseous emissions of SO_2, NO_x and NH_3. These separate components are shown in figure 3.2. Note these are on different scales to reflect the geographical variation in each.

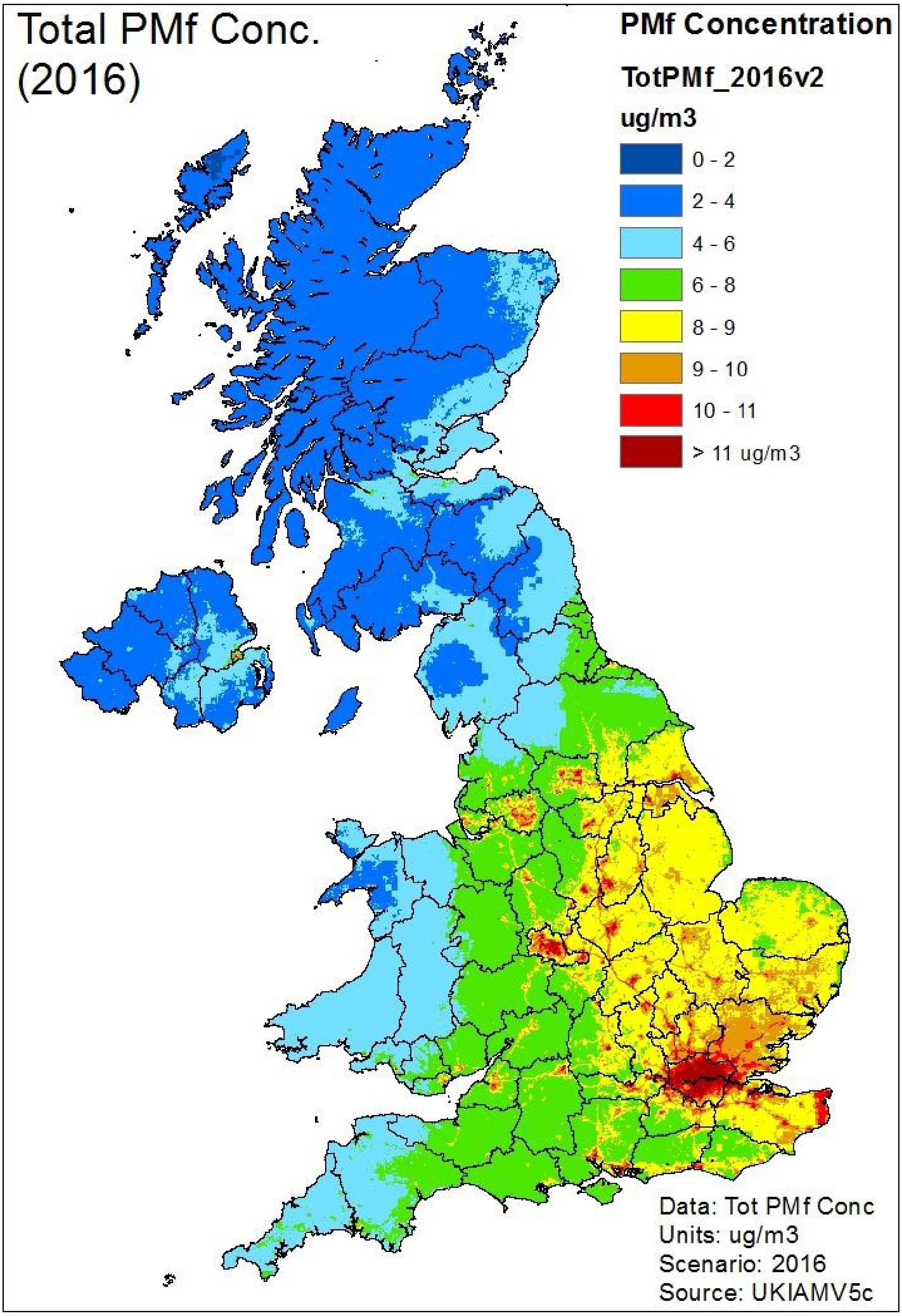
Overall there may be a tendency to underestimate concentrations due to missing sources in the NAEI such as cooking: and to additional components not included such as formation of $PM_{2.5}$ from less volatile IVOC precursors. These are also not included in the NAEI, and this is still a research area.

The natural irreducible contribution (Figure 3.2A - upper left hand map)

From figure 3.2 it is clear that the natural contribution in the top left map accounts for over a third of the WHO standard over large parts of England; and is up to half the WHO standard in London with high urban dust. There are large uncertainties in the contribution of natural sources (sea salt, and natural rural and urban dusts which have been provided by Ricardo having been used in the PCM model), which is higher over parts of the eastern side of the country due to soil properties generating more dust. The secondary organic aerosol, SOA, is included with the natural contributions. It is taken from modelling with the NAME model of the Meteorological Office, and is predominantly due to biogenic emissions that are assumed to remain unchanged over time. (There is a small contribution from anthropogenic VOCs, but based on the EMEP model the contribution from UK emissions is less than 0.1 $\mu g/m^3$, and has been ignored). A small amount due to water content is also included, and is assumed to vary with the hygroscopic secondary inorganic aerosol as in the EMEP model. This is the only part of this natural contribution that changes over time.

The importance of the natural irreducible component is illustrated in Appendix B with a map in which it has been removed, and which can be compared with figure 3.1 It is clearly important to address the considerable uncertainties in this component.

Figure 3.1 $PM_{2.5}$ concentrations in 2016 across the UK



The imported contribution (Figure 3.2B - upper right hand map)

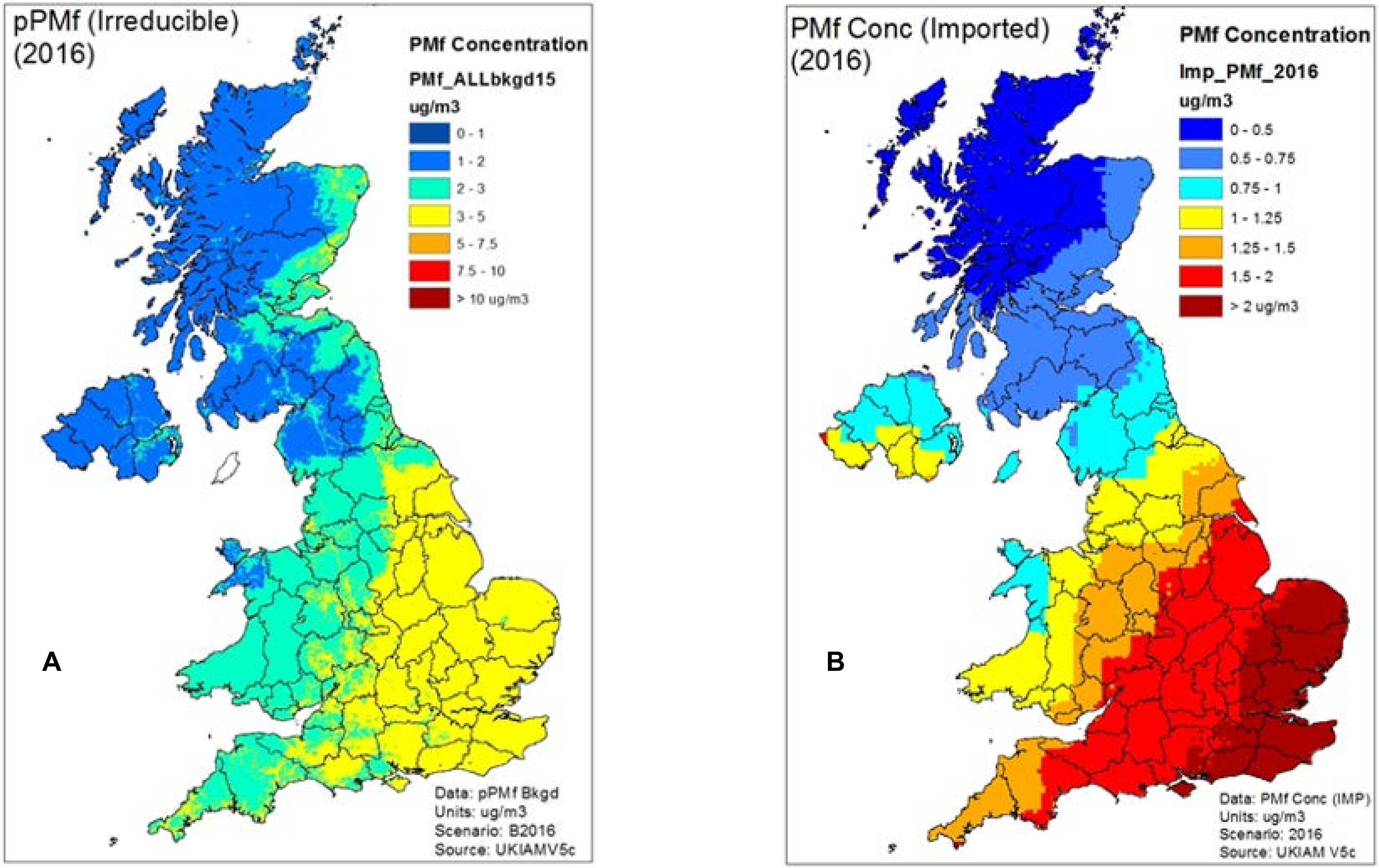
The imported contribution from other countries and from shipping is shown in the top right map in figure 3.2, and has a strong gradient from higher concentrations in the south east to small values in northern parts. The major component of this is due to emissions in other countries, particularly France and northern Europe, giving a contribution of 0.9 $\mu g/m^3$ to the UK population weighted mean concentration. However an important component is from international shipping, due to 660 kt of NO_x including high emissions through the English Channel and into the North Sea. These give a smaller contribution of 0.33 $\mu g/m^3$ to the UK population weighted mean concentration, but reduce less over time.

Contribution of UK emissions to secondary $PM_{2.5}$ concentrations (Figure 3.2D - lower right hand map)

Due to major reductions in SO_2 and NO_x emissions in the UK the contribution of SIA concentrations due to UK precursor emissions has decreased, with the highest values in central and eastern England where chemical reactions involving NH_3 emissions and NO_x chemistry lead to enhanced values. This contributes to the higher overall $PM_{2.5}$ concentrations over rural parts of eastern England. Over recent decades the sulphate content of the aerosol has reduced, with ammonia largely forming ammonium nitrate. The contribution from NH_3 emissions is predominantly due to agricultural sources and anaerobic digestion: and has reduced little compared with other pollutants over recent decades. (NB The simplifying assumptions about linear scaling with emission reductions in UKIAM should be noted with respect to interactive chemistry between components. This becomes more important the larger the % emission changes made relative to 2020, the year for which the FRAME source-receptor relationships were calculated).

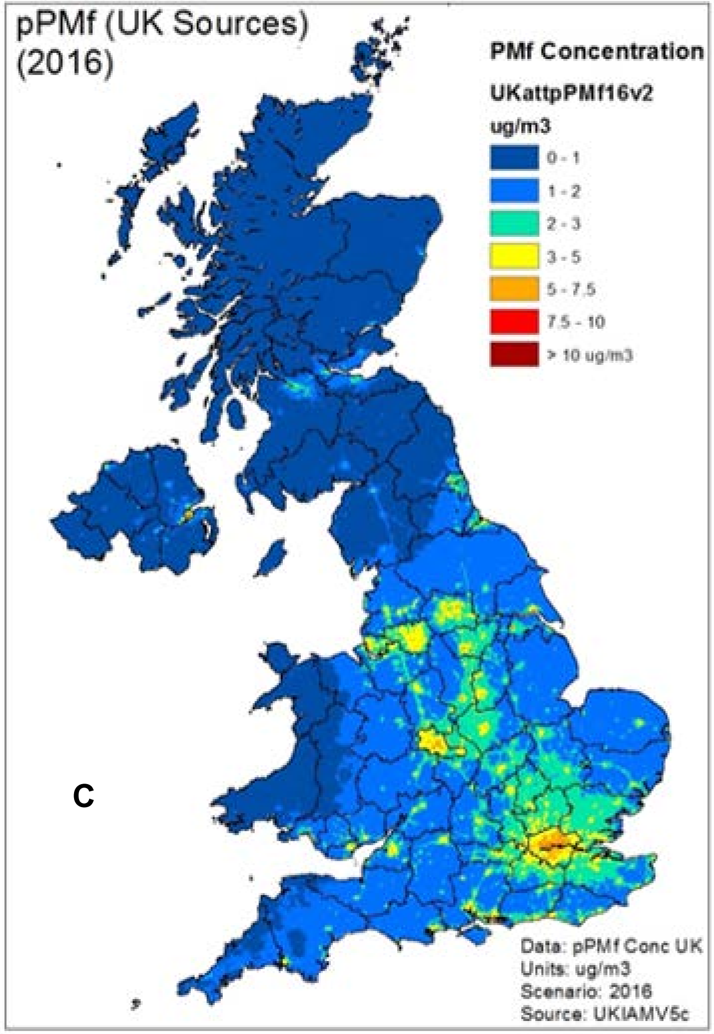
Note that there was a big reduction in UK emissions of SO_2 and NO_x between 2015 and 2016, with large changes in coal consumption in power stations. A sensitivity study showed a significant effect on SIA concentrations.

Figure 3.2 Contributions from A) natural sources,B) imported $PM_{2.5}$, C) UK primary and D) UK secondary $PM_{2.5}$

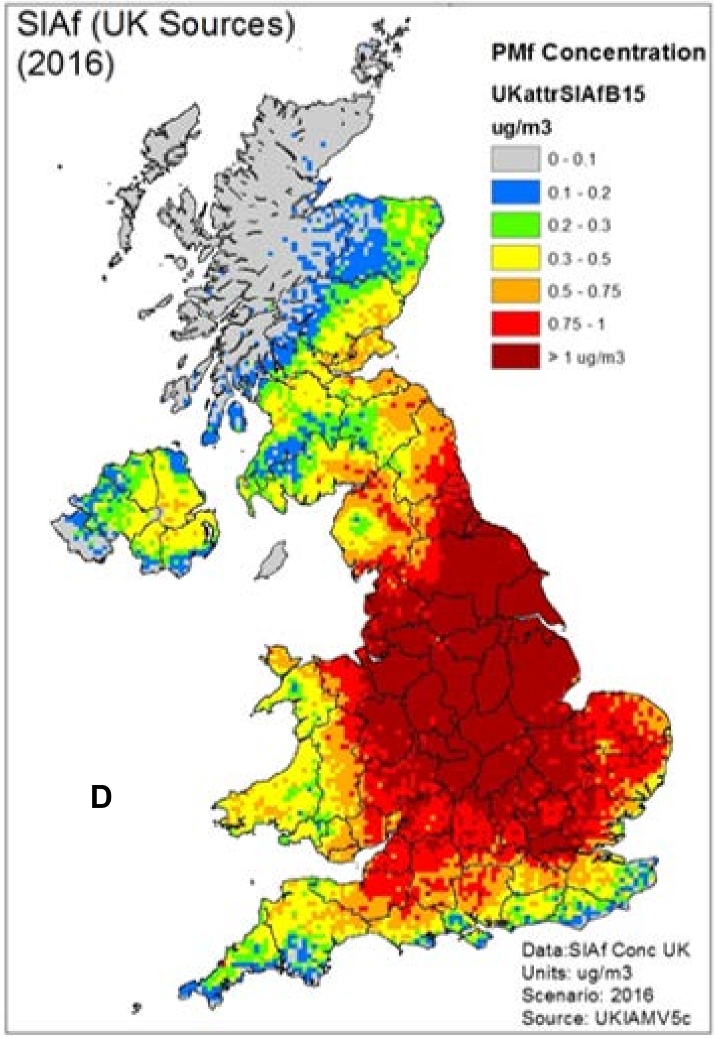


Data: pPMf Bkgd
Units: ug/m3
Scenario: B2016
Source: UKIAMV5c

Data: PMf Conc (IMP)
Units: ug/m3
Scenario: 2016
Source: UKIAM V5c


C

pPMf (UK Sources)
(2016)
PMf Concentration
UKattpPMf16v2
ug/m3
0 - 1
1 - 2
2 - 3
3 - 5
5 - 7.5
7.5 - 10
> 10 ug/m3
Data: pPMf Conc UK
Units: ug/m3
Scenario: 2016
Source: UKIAMV5c


D

SIAf (UK Sources)
(2016)
PMf Concentration
UKattrSIAfB15
ug/m3
0 - 0.1
0.1 - 0.2
0.2 - 0.3
0.3 - 0.5
0.5 - 0.75
0.75 - 1
> 1 ug/m3
Data:SIAf Conc UK
Units: ug/m3
Scenario: 2016
Source: UKIAMV5c

Contribution from UK primary PM2.5 concentrations (Figure 3.2C - lower left hand map)

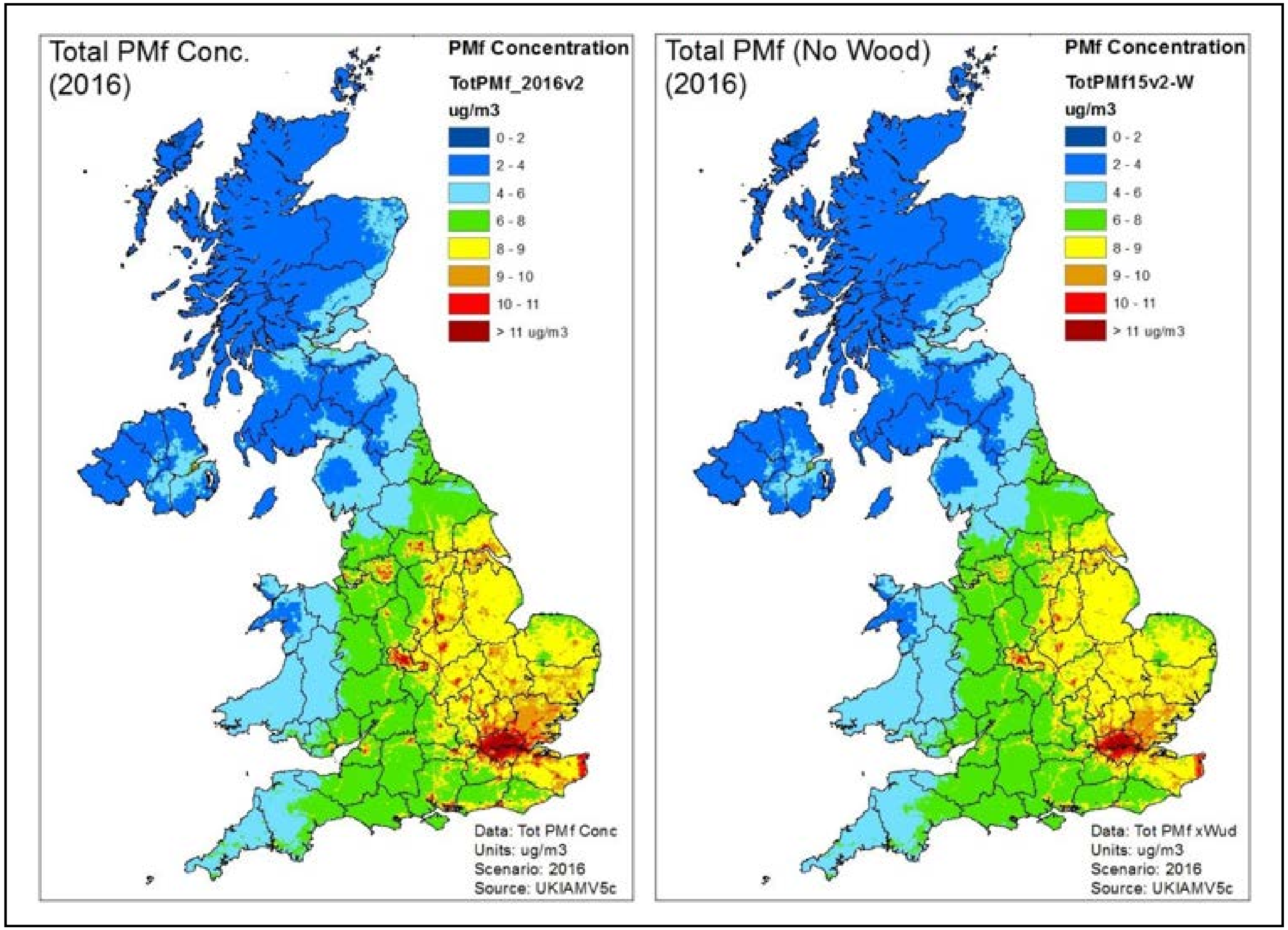
From figure 3.2 the largest contribution is from UK primary $PM_{2.5}$ emissions. This has been greatly affected by the growth in wood burning, accounting for 26.6 kt of $PM_{2.5}$ emitted in 2016 and anticipated to increase in future if not controlled. This was the topic of a previous report to Defra in February 2018 on domestic combustion, and wood-burning in particular, where emissions are very dependent on the wood burned, and very much higher if the wood is wet and not properly cured (ApSimon and Oxley 2018).

After producing that report we reconsidered the modelling of domestic emissions from burning wood and coal. Previously we had modelled dispersion in the same way as for domestic gas and oil used for cooking and heating, where emissions take place from vents in the building, which is then treated as a volume source. But for coal and wood the emissions take place from a chimney with some additional plume rise, so that they disperse downwind above the buildings, and also avoid the "urban drag" effects of buildings and streets in slowing removal from the local area. This reduces exposure in the local grid square by a factor of approximately 2, though this is an average factor, which will vary with the characteristics of individual buildings and stoves. Introducing this factor reduces concentrations from wood- burning, which we previously consider too high; and they are now more consistent with observations by Kings College (2017). These indicated winter concentrations ranging from 0.2 to 2.7 $\mu g/m^3$ in different cities, with the highest values in London and Birmingham. Bearing in mind that these concentrations are for winter and almost absent in summer, the UKIAM modelled annual values over London now range up to 1 to 1.2 $\mu g/m^3$ which matches the observations much better.

The importance of wood-burning is illustrated in figure 3.3, comparing the map of total $PM_{2.5}$ with a map in which the contribution from wood has been removed. This has a significant effect on the population exceeding 10 $\mu g/m^3$, which is reduced from 15 million to 9.2 million. Peaks in the contribution to concentrations from wood-burning are highly correlated with larger populations in urban areas, and hence the improvements from reducing wood-burning are most apparent where $PM_{2.5}$ concentrations and exceedance of the WHO standard are highest.

Another important source similarly concentrated in urban areas is non-exhaust emissions, which are difficult to reduce but contribute to high concentrations in hot-spots with high traffic- as illustrated in a later section on London. Averaged over the UK these contribute 0.4 $\mu g/m^3$ to population weighted mean concentrations, but over London this increases to 0.86 $\mu g/m^3$.

Figure 3.3. Total $PM_{2.5}$ concentrations in 2016 with and without wood-burning included



Population weighted mean concentrations

Table 3.1 gives a break-down of the different contributions to $PM_{2.5}$ exposure in terms of population weighted mean concentrations, averaged over the whole country and over sub-populations in urban (including London) and rural areas, in London where the concentrations are highest, and in the devolved administrations. This shows how much higher the mean exposure is in London and urban areas, and lower in Scotland as compared with the national average, and gives a direct comparison of different contributions. The natural component is clearly very important, and the primary component due to UK sources, especially for London. Imported contributions are mainly secondary SIA, and roughly equal to the UK contribution to SIA. A little over a quarter of the imported SIA comes from international shipping in the sea areas round the UK, contributing 0.4 $\mu g/m^3$ over London.

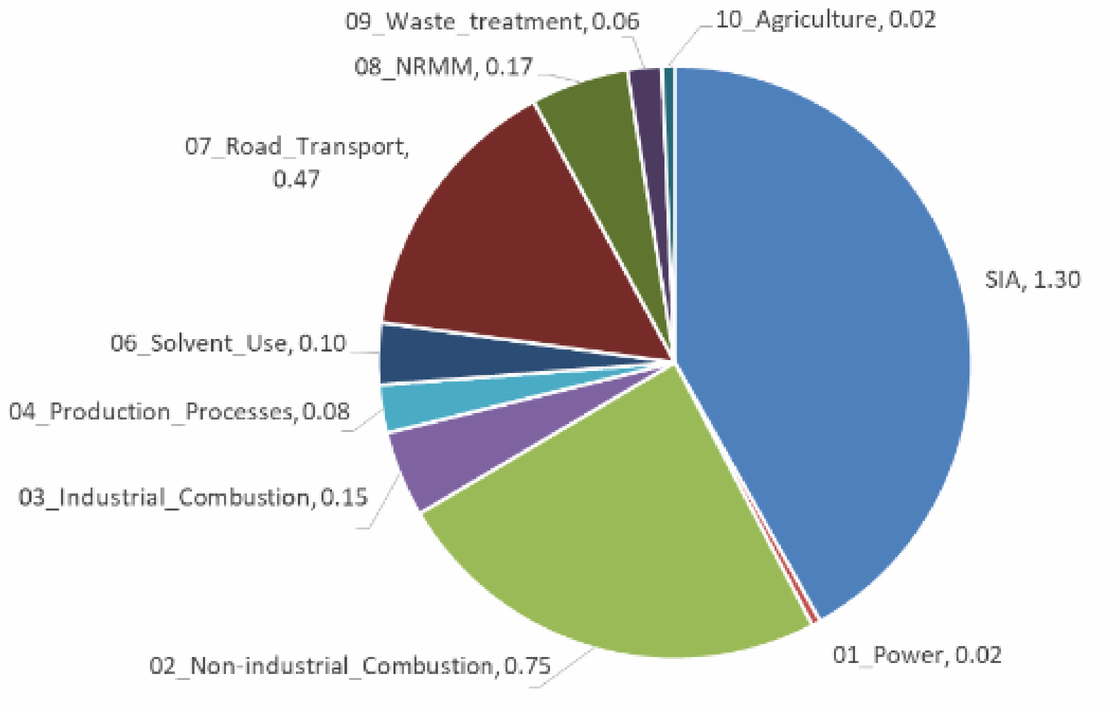
More information on the source apportionment of the UK contributions, with the primary PM broken down by SNAP sector, is given in the pie charts in figure 3.4. The role of domestic combustion and transport is clear, with transport especially important across London where a large contribution comes from non-exhaust emissions (0.86 $\mu g/m^3$ averaged across the GLA area).

Table 3.1 Population weighted mean concentrations nationally and for different regions of the UK

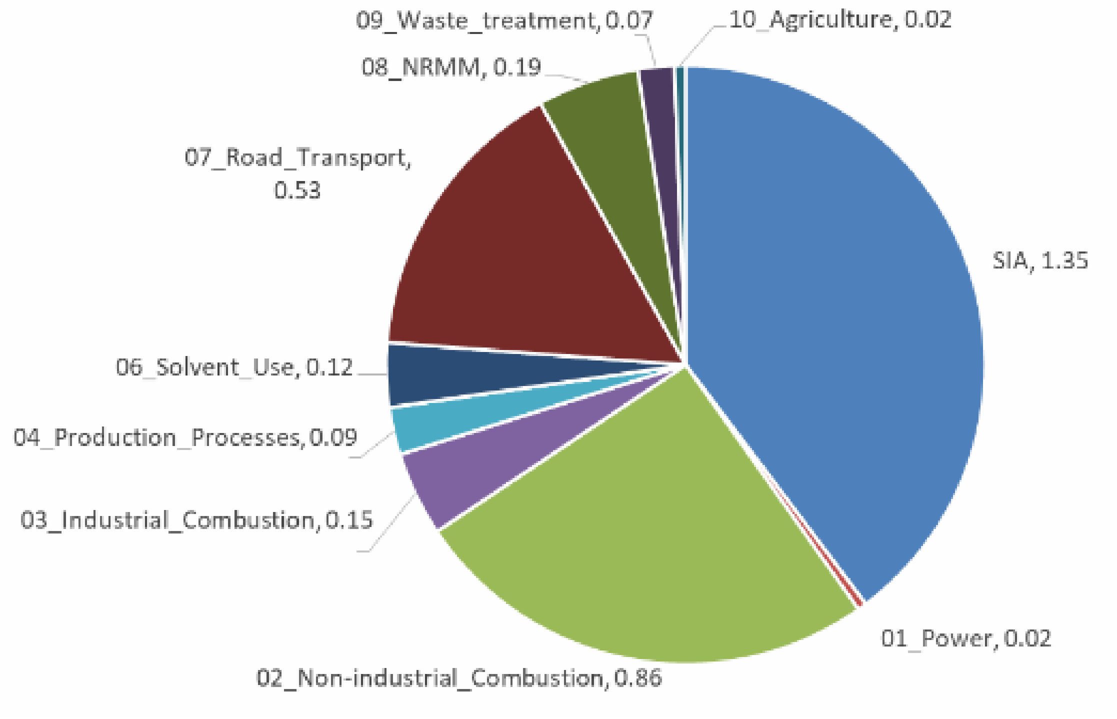
		National	Urban	Rural	London	England	Scotland	Wales	Northern Ireland
Natural PM2.5	**Dusts & Salt**	1.367	1.362	1.384	1.650	1.393	1.283	1.233	1.145
	Water	0.782	0.799	0.725	0.865	0.830	0.478	0.695	0.437
SOA	**(v3)**	0.869	0.890	0.796	1.152	0.937	0.438	0.762	0.327
Primary PM2.5	**UK Sources**	1.938	2.195	1.049	3.295	2.095	1.004	1.295	1.396
	DomShips	0.009	0.010	0.007	0.008	0.008	0.014	0.008	0.008
	Int'l Ships	0.006	0.007	0.006	0.012	0.007	0.002	0.004	0.003
	Europe	0.186	0.189	0.178	0.268	0.202	0.062	0.139	0.160
NH4	**UK Sources**	0.302	0.312	0.269	0.383	0.336	0.106	0.190	0.099
SO4		0.179	0.185	0.161	0.186	0.200	0.064	0.113	0.046
NO3		0.763	0.792	0.660	1.092	0.846	0.264	0.491	0.292
SIA	**DomShips**	0.059	0.059	0.056	0.062	0.062	0.038	0.048	0.043
	Int'l Ships	0.336	0.340	0.320	0.419	0.368	0.107	0.295	0.145
	Europe	0.908	0.919	0.866	1.169	0.967	0.443	0.758	0.645
TOTAL PM2.5	**All Sources**	**7.706**	**8.060**	**6.479**	**10.562**	**8.249**	**4.304**	**6.030**	**4.746**

Figure 3.4 2016 contribution of UK sources only to $PM_{2.5}$ for (a) national, (b) urban, (c) rural and (d) London, distinguishing SIA from primary PM emission contributions by SNAP sector. NB the SIA is only that due to UK sources, and excludes imported SIA from other countries and international shipping.

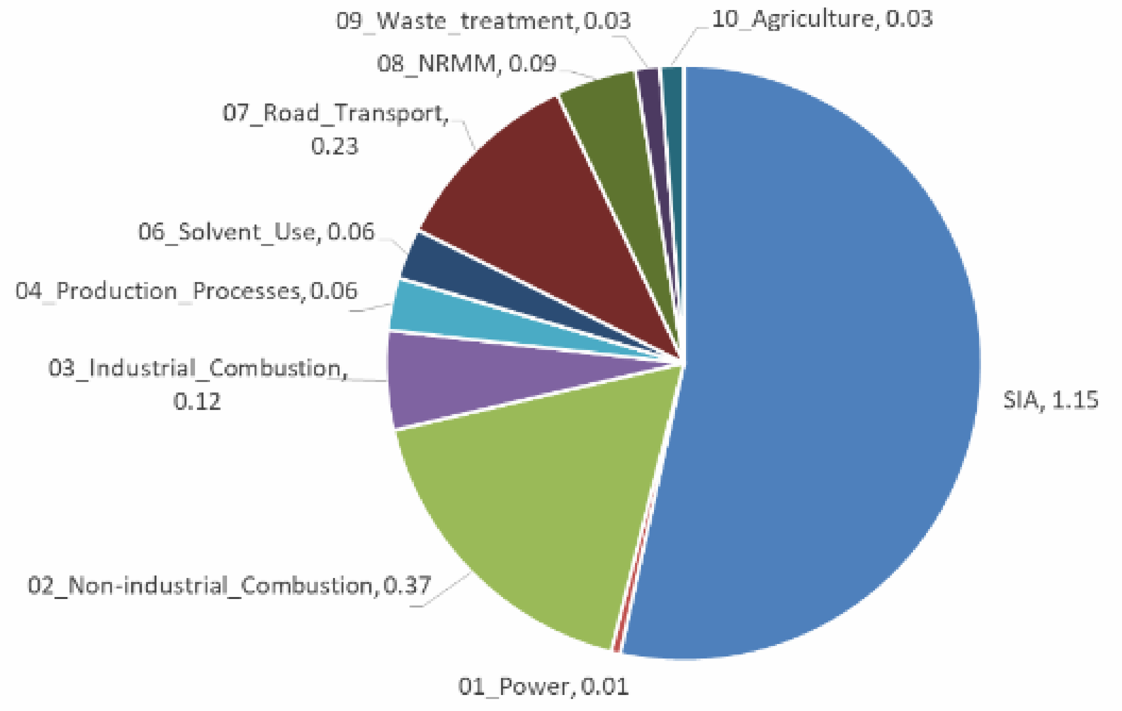
(a) National



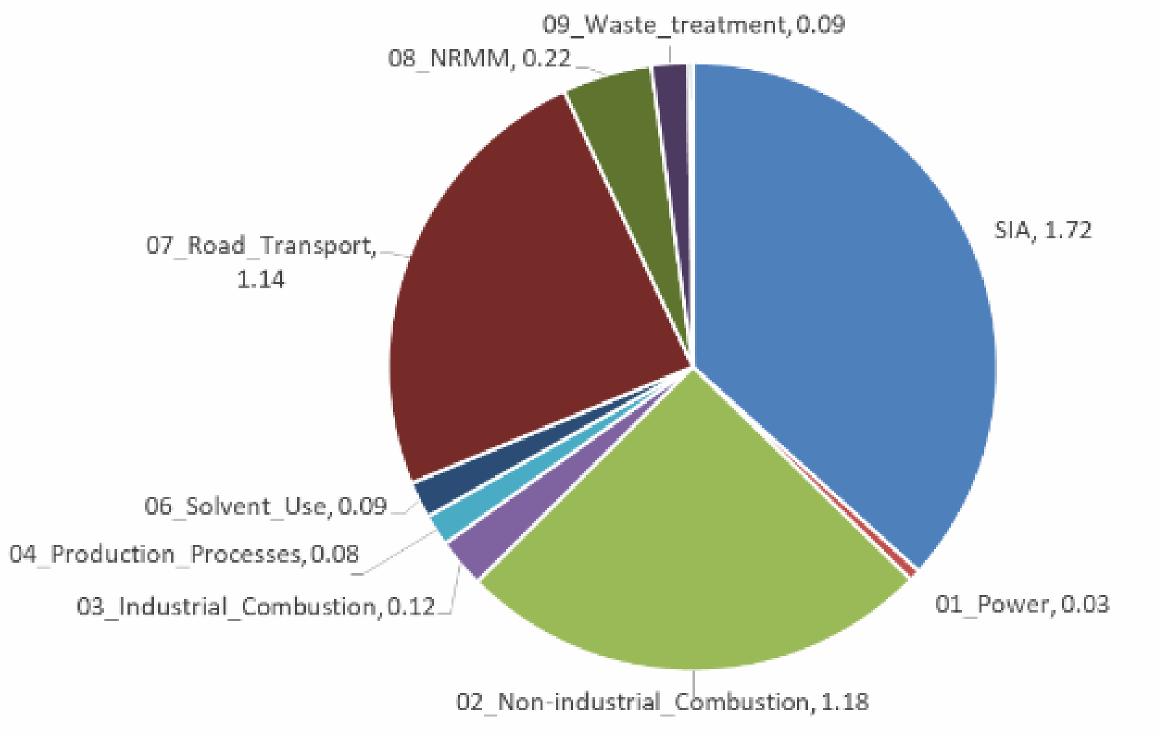
(b) Urban



(c) Rural



(d) London



Population exposure in 2016

The main purpose of this study is to assess how exceedance of the WHO standard of 10 µg/m^3 may be reduced. One way of quantifying this is to consider the number of people exposed above the standard. Figure 3.5 shows a graph of the population exceeding different threshold levels of PM$_{2.5}$ indicating a population of 14.8 million (8.6 to to 27 million allowing for +/- 1 µg/m^3 uncertainty) above the WHO standard in 2016. The dotted line shows the corresponding graph without any contribution from wood-burning- again illustrating the importance of this source.

Figure 3.5 Distribution of population exposure 2016

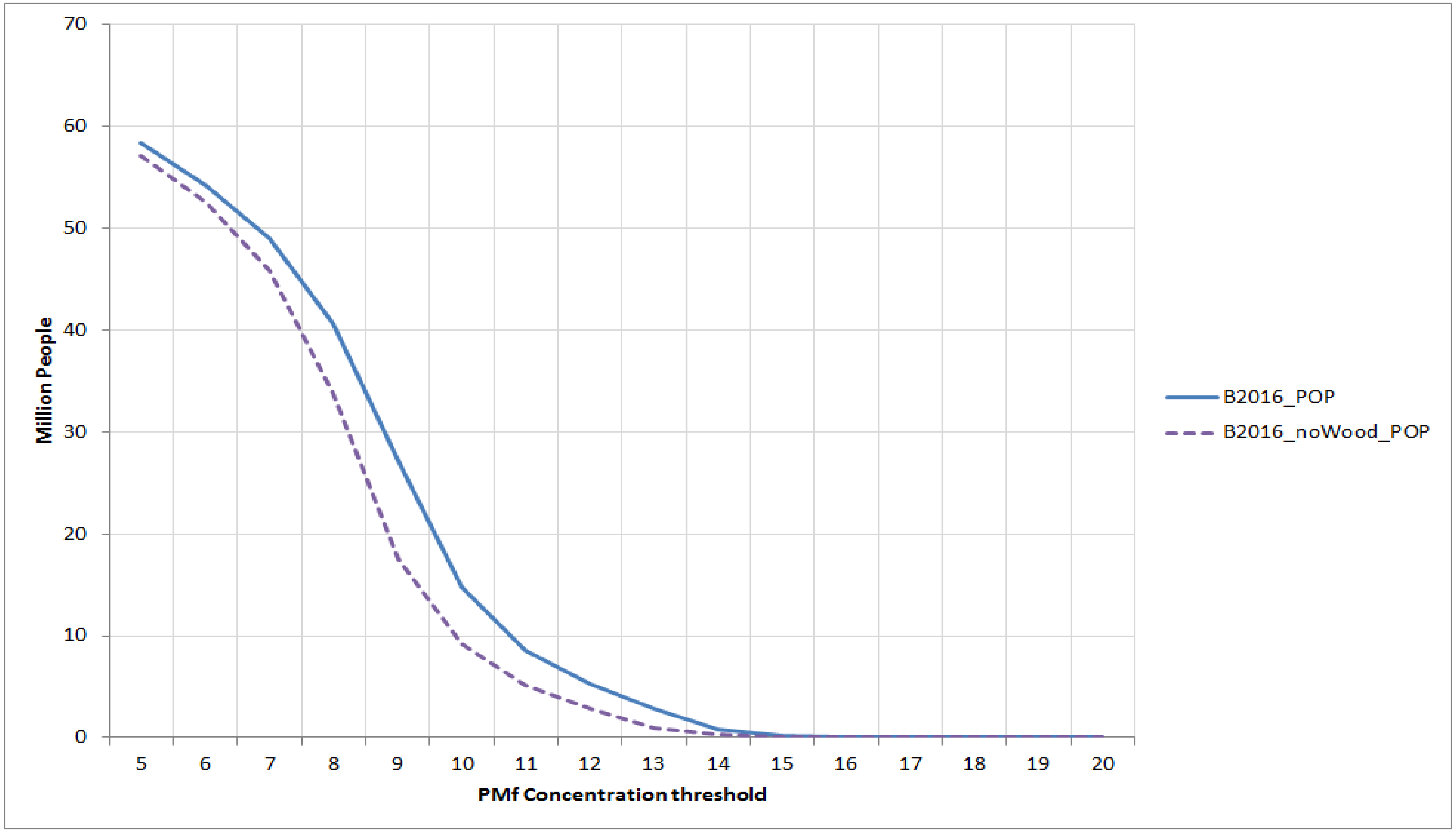


Table 3.2 Population exceeding threshold concentrations of PM$_{2.5}$ (millions)

B2016	Conc.	National	England	Scotland	Northern_I	Wales	London	Urban	Rural
total_pmf_2030	5	58.290	52.618	2.193	0.818	2.661	8.178	46.648	11.640
total_pmf_2030	6	54.106	51.386	0.330	0.425	1.964	8.178	43.993	10.111
total_pmf_2030	7	48.950	47.716	0.030	0.202	1.002	8.178	40.598	8.352
total_pmf_2030	8	40.660	40.103	0.006	0.123	0.428	8.178	34.947	5.713
total_pmf_2030	9	27.157	26.858	0.003	0.106	0.190	8.154	25.008	2.149
total_pmf_2030	10	14.795	14.729	0.003	0.025	0.038	7.827	14.262	0.533
total_pmf_2030	11	8.560	8.541	0.003	0.014	0.003	6.617	8.399	0.160
total_pmf_2030	12	5.213	5.202	0.003	0.005	0.003	4.792	5.154	0.059
total_pmf_2030	13	2.824	2.821	0	0	0.003	2.706	2.800	0.024
total_pmf_2030	14	0.809	0.806	0	0	0.003	0.731	0.796	0.013
total_pmf_2030	15	0.243	0.241	0	0	0.003	0.196	0.231	0.012
total_pmf_2030	16	0.063	0.060	0	0	0.003	0.028	0.051	0.012
total_pmf_2030	17	0.025	0.023	0	0	0.003	0	0.021	0.004
total_pmf_2030	18	0.022	0.022	0	0	0.000	0	0.019	0.003
total_pmf_2030	19	0.021	0.021	0	0	0.000	0	0.018	0.003
total_pmf_2030	20	0.016	0.016	0	0	0.000	0	0.013	0.003

Table 3.2 gives a breakdown of population exposure against concentration thresholds for different regions of the UK, and for urban versus rural populations. As expected from the population weighted mean concentrations in the previous table, the population exceeding the WHO standard is much higher in London and urban regions where exposure to local primary PM sources is superimposed on smoother distributions of back-ground concentration (which are higher in the south and east of England). Exceedance of the WHO standard is predominantly a problem for England. Apart from this there are small areas of Wales in the more industrial areas in the south, and a small population in N Ireland centred on Belfast. In Scotland virtually all the population is well below the WHO standard.

For the urban population a large proportion lies in the concentration band between 10 and 13 µg/m^3. London, and also Birmingham and the Manchester area, account for most of the population exposed to the highest concentrations.

Accumulated exceedance

An alternative way of assessing scenarios and setting quantitative targets for improvement is provided by "accumulated exceedance" of the WHO standard of 10 µg/m^3. This is calculated by summing the population multiplied by the excess concentration over all grid-cells in which the standard is exceeded.

$$\text{Accumulated exceedance} = \sum \text{population x Max } (0; C\text{-}T)$$

where the sum is over 1x1 km grid squares in UKIAM, C is the $PM_{2.5}$ concentration in µg/m^3, and T is the threshold (equal to 10 µg/m^3 for the WHO standard.) It will be argued later in this report that this is a much more stable basis for setting targets given model uncertainties.

An alternative way of quantifying exceedance in an area is to divide accumulated exceedance by the number of people in millions in the area to which it applies (i.e. in the whole country or sub-region) to give the average exceedance for people in that area in units of µg/m^3.

Figure 3.6 shows a graph of accumulated exceedance against different threshold concentrations for 2016. The accumulated exceedance above the threshold of 10 µg/m^3 is 24.6 million people.µg/m^3 (13 to 45 Mpu allowing for +/- 1 µg/m^3 of model uncertainty). Again the dashed line represents the case when wood-burning is omitted.

Table 3.3 gives a break-down of accumulated exceedance by region for 2016. Again this indicates that most of the exceedance is in England and in urban areas, with very small contributions from Scotland, Wales and N Ireland. The average exceedance per person in London is just over 2 µg/m^3 giving an indication of the amount of reduction required.

Figure 3.6: Accumulated exceedance versus threshold in 2016 (in millions of people .µg/m^3, Mpu)

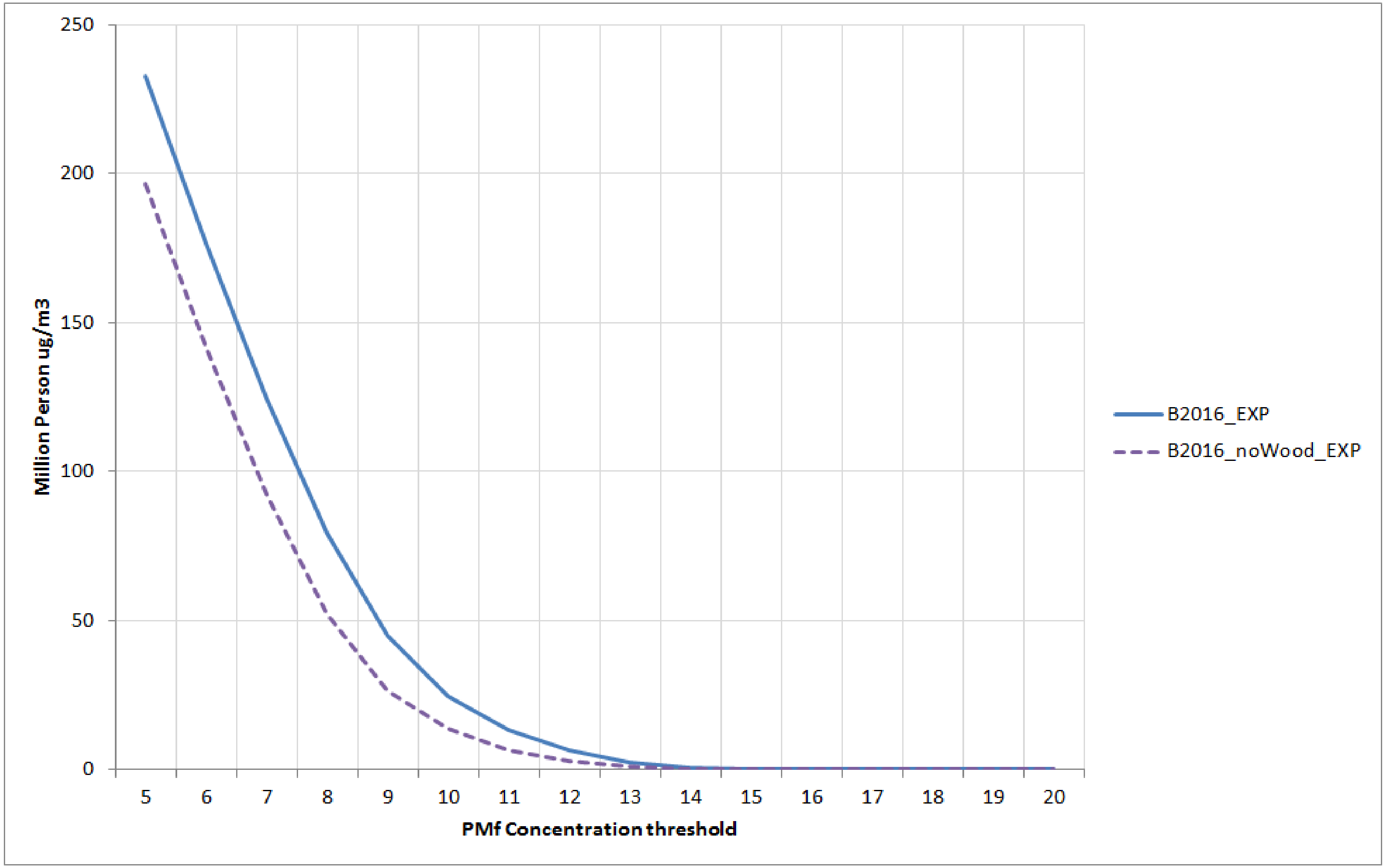


Table 3.3: Accumulated exceedance for different regions

B2016	Conc.	National	England	Scotland	Northern_I	Wales	London	Urban	Rural
total_pmf_2030	5	232.749	225.264	1.317	1.273	4.895	59.716	199.803	32.948
total_pmf_2030	6	176.512	173.113	0.164	0.657	2.579	51.538	154.465	22.050
total_pmf_2030	7	124.731	123.275	0.025	0.353	1.079	43.360	111.974	12.759
total_pmf_2030	8	79.599	78.991	0.013	0.193	0.403	35.181	73.919	5.680
total_pmf_2030	9	45.161	44.936	0.009	0.080	0.136	27.007	43.485	1.676
total_pmf_2030	10	24.626	24.564	0.006	0.024	0.032	18.963	24.106	0.520
total_pmf_2030	11	13.327	13.295	0.004	0.009	0.019	11.635	13.107	0.220
total_pmf_2030	12	6.547	6.530	0.001	0.000	0.016	5.884	6.430	0.118
total_pmf_2030	13	2.575	2.561	0	0	0.014	2.129	2.496	0.079
total_pmf_2030	14	0.841	0.830	0	0	0.011	0.484	0.781	0.060
total_pmf_2030	15	0.395	0.386	0	0	0.009	0.095	0.347	0.048
total_pmf_2030	16	0.267	0.261	0	0	0.006	0.007	0.231	0.036
total_pmf_2030	17	0.232	0.229	0	0	0.003	0	0.207	0.025
total_pmf_2030	18	0.209	0.207	0	0	0.002	0	0.188	0.021
total_pmf_2030	19	0.188	0.185	0	0	0.002	0	0.170	0.018
total_pmf_2030	20	0.170	0.168	0	0	0.002	0	0.155	0.015

4. The BAU scenario for 2030

The next step is to consider a Business As Usual scenario up to 2030 (BAU2030) to investigate expected changes with current energy, transport and agricultural projections as represented in the NAEI. In addition there are changes in imported contributions as other countries comply with their emissions ceilings under the NECD, and the volume of international shipping grows but in compliance with regulations in the ECA areas. Relative to 2016 UK emissions of NH3 are barely reduced (0.82%) but SO_2, NO_x and $PM_{2.5}$ emissions are reduced by 54.5%, 43% and 16.2% respectively.

Figure 4.1 shows a map of calculated PM2.5 concentrations for the BAU2030 scenario. Comparison with concentrations in 2016 (figure 3.1) shows very big improvements with the red areas exceeding the WHO standard contracted down almost entirely to major cities, and much smaller areas in orange that are below but close to the standard.

The maps in figure 4.2 show how the imported contribution, and the contributions due to UK primary $PM_{2.5}$ emissions and UK SIA, have reduced. The natural contribution is unchanged except for a small change in water content.

Figure 4.1 Total $PM_{2.5}$ concentrations for BAU2030 scenario

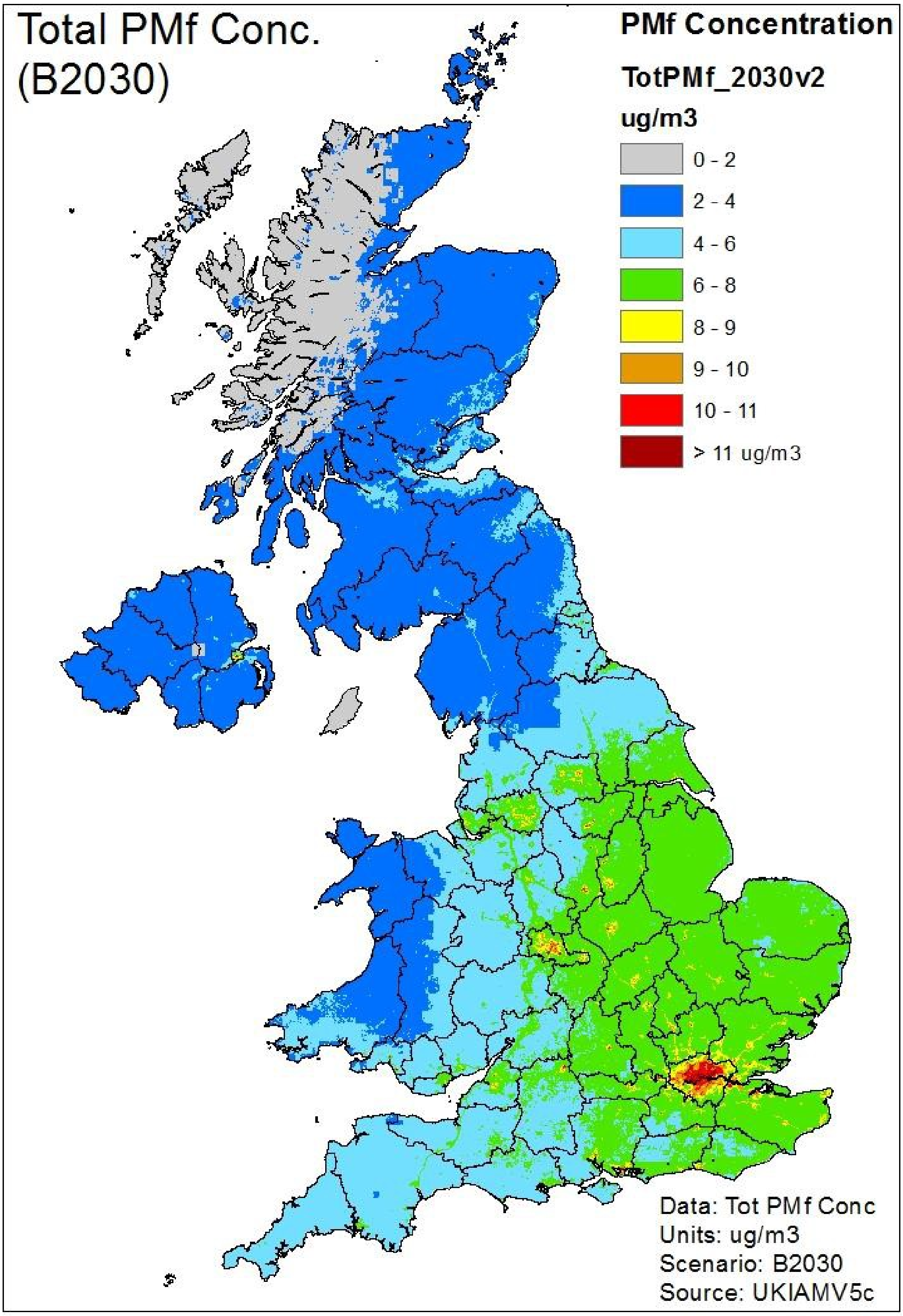
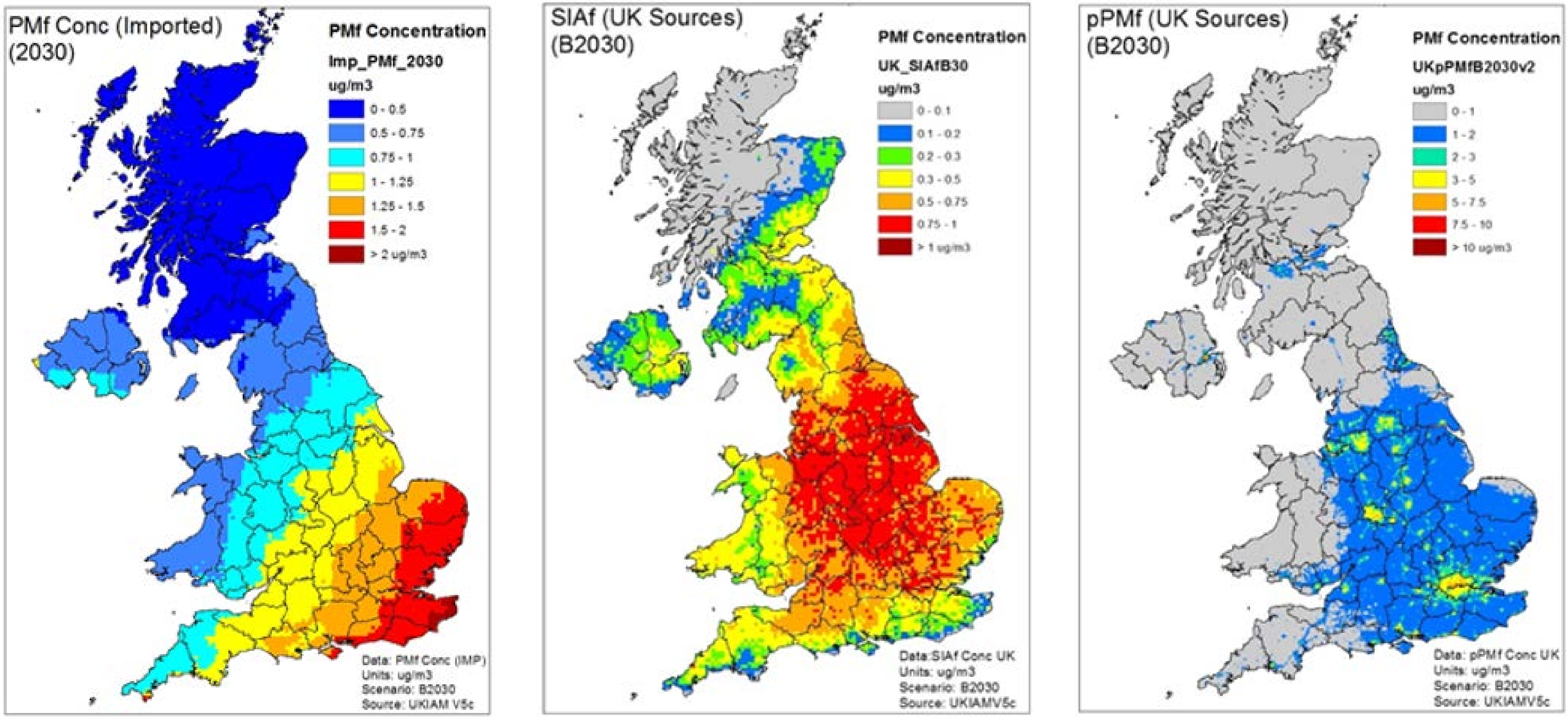


Figure 4.2 Imported and UK SIA contributions, and UK Primary $PM_{2.5}$ for BAU2030



The imported contribution is now considerably reduced due to emission reductions in other countries, and the SIA due to UK sources is also now below 1 except in a few isolated grid-squares. The contribution from primary $PM_{2.5}$ emissions in the UK is still the largest anthropogenic component, with peaks of concentration in London, Birmingham and other cities.

Table 4.1 gives a more detailed break-down of source apportionment for population weighted mean concentrations in different regions. This shows that for the imported contribution the reductions in other countries to comply with the NECD in 2030 has reduced this by a third from 2016; whereas the contribution from international shipping has remained much the same with growth in activity balancing control measures in ECA areas. Nationally the UK contribution to SIA (excluding domestic shipping) has fallen from 1.25 to 0.76 $\mu g/m^3$, a reduction of almost 40%. But the UK primary NAEI contribution has only fallen from 1.94 $\mu g/m^3$ to 1.75 $\mu g/m^3$ and is still contributing nearly 3 $\mu g/m^3$ in London.

Table 4.1 Source-apportionment for the BAU2030 scenario

BAU2030		**National**	**Urban**	**Rural**	**London**	**England**	**Scotland**	**Wales**	**Northern Ireland**
Natural PM2.5	**Dusts & Salt**	1.367	1.362	1.384	1.650	1.393	1.283	1.233	1.145
	Water	0.414	0.422	0.388	0.459	0.437	0.265	0.375	0.258
SOA	**(v3)**	0.869	0.890	0.796	1.152	0.937	0.438	0.762	0.327
Primary PM2.5	**UK Sources**	1.750	1.986	0.931	2.912	1.892	0.918	1.144	1.234
	DomShips	0.008	0.008	0.006	0.008	0.007	0.011	0.005	0.005
	Int'l Ships	0.006	0.006	0.005	0.012	0.007	0.002	0.002	0.002
	Europe	0.114	0.116	0.110	0.163	0.124	0.041	0.085	0.097
NH4	**UK Sources**	0.187	0.193	0.165	0.255	0.208	0.066	0.123	0.058
SO4		0.083	0.087	0.072	0.108	0.092	0.033	0.061	0.021
NO3		0.495	0.512	0.434	0.671	0.551	0.164	0.316	0.162
SIA	**DomShips**	0.047	0.047	0.044	0.050	0.049	0.029	0.037	0.034
	Int'l Ships	0.316	0.321	0.300	0.400	0.346	0.101	0.274	0.137
	Europe	0.610	0.618	0.582	0.789	0.648	0.319	0.498	0.439
TOTAL PM2.5	**All Sources**	**6.266**	**6.570**	**5.217**	**8.631**	**6.690**	**3.669**	**4.916**	**3.919**

Figure 4.3 Contributions of UK sources to national population exposure in BAU 2030 scenario

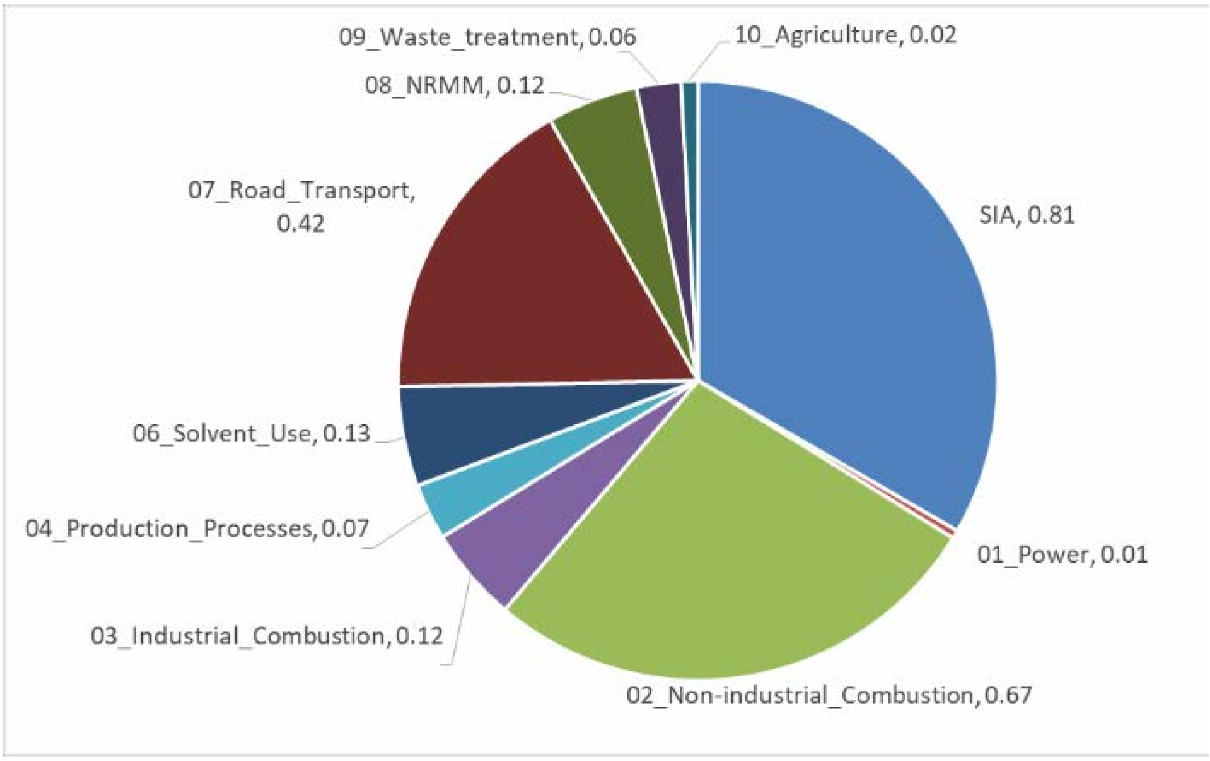


Figure 4.3, giving the break-down of the relative contributions of UK sources to population exposure, shows how the proportion in blue due to SIA has shrunk; with primary emissions, particularly domestic combustion and transport, increasingly important (compare with figure 3.3).

Population exposure for BAU2030 scenario

Figure 4.4 shows the distribution of population exceeding different threshold concentrations in red for the BAU2030, compared with the blue graph for 2016; with a regional break-down in table 4.2 The population exceeding 10 µg/m^3 has fallen from 15 million (8.6 to 27 million) in 2016 to 4.4 million (1.5 to 8.5 million) in 2030 - a big improvement as expected.

Figure 4.4 Population exposure distribution for BAU2030 scenario compared with 2016.

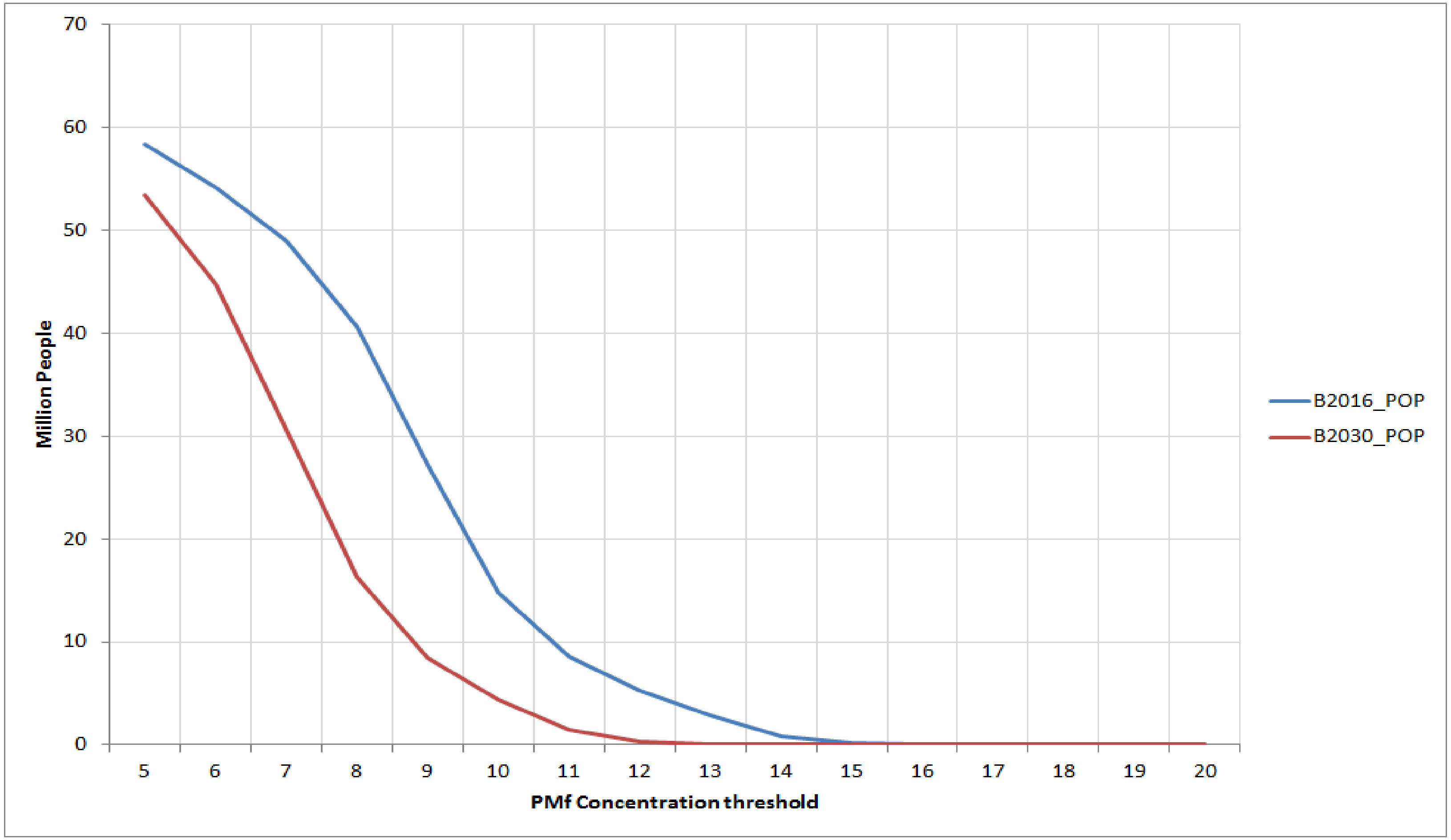


Table 4.2. Population (millions) exceeding different thresholds for BAU2030 scenario by region

BAU2030	Conc.	National	England	Scotland	Northern_I	Wales	London	Urban	Rural
total_pmf_2030	5	53.361	50.689	0.516	0.436	1.720	8.178	43.642	9.717
total_pmf_2030	6	44.817	43.863	0.049	0.201	0.704	8.178	38.028	6.789
total_pmf_2030	7	30.565	30.192	0.006	0.121	0.246	8.165	27.903	2.662
total_pmf_2030	8	16.221	16.068	0.003	0.084	0.066	7.782	15.591	0.630
total_pmf_2030	9	8.475	8.447	0.003	0.014	0.011	6.324	8.309	0.166
total_pmf_2030	10	4.377	4.358	0.003	0.014	0.003	3.955	4.306	0.071
total_pmf_2030	11	1.460	1.450	0.003	0.005	0.003	1.337	1.439	0.021
total_pmf_2030	12	0.312	0.306	0.003	0	0.003	0.229	0.299	0.012
total_pmf_2030	13	0.070	0.067	0	0	0.003	0.011	0.057	0.012
total_pmf_2030	14	0.046	0.043	0	0	0.003	0	0.041	0.005
total_pmf_2030	15	0.034	0.032	0	0	0.003	0	0.030	0.005
total_pmf_2030	16	0.029	0.028	0	0	0.002	0	0.026	0.003
total_pmf_2030	17	0.019	0.017	0	0	0.002	0	0.016	0.003
total_pmf_2030	18	0.017	0.016	0	0	0.002	0	0.014	0.003
total_pmf_2030	19	0.016	0.016	0	0	0.000	0	0.013	0.003
total_pmf_2030	20	0.015	0.015	0	0	0.000	0	0.012	0.003

Accumulated exceedance for BAU2030 scenario

Figure 4.5 shows a graph of accumulated exceedance with a regional break-down in table 4.3 below. The accumulated exceedance of the 10 μg/m^3 WHO standard has fallen from 24.6 MPu in 2016 (13.3 to 45.1 allowing for +/- 1 μg/m^3 uncertainty) to 4.0 Mpu^3 (1.2 to 10) in the BAU2030 scenario - a bigger % reduction than in the number of people exceeding the standard, and reflecting overall reduction in exposure rather than changes near the threshold. There is still a small tail in exposure at high concentrations at urban sites outside London, which needs more detailed investigation.

Figure 4.5. Accumulated exceedance for BAU2030 scenario (Mpu)

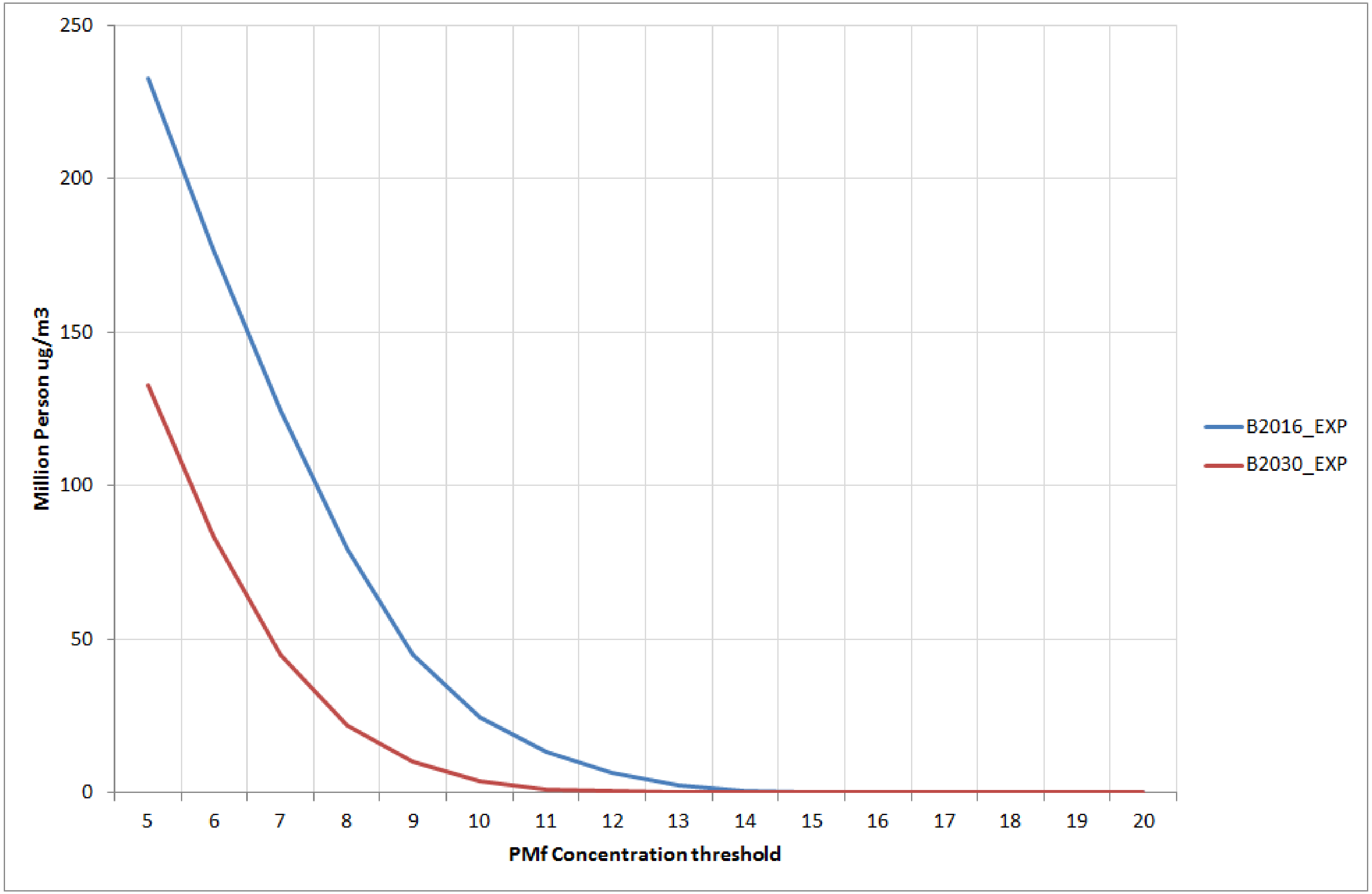


Table 4.3 Accumulated exceedance for BAU2030 scenario by region (Mpu)

BAU2030	Conc.	National	England	Scotland	Northern_I	Wales	London	Urban	Rural
total_pmf_2030	5	132.961	130.245	0.224	0.626	1.865	40.009	117.810	15.151
total_pmf_2030	6	83.455	82.413	0.039	0.328	0.675	31.831	76.647	6.809
total_pmf_2030	7	45.132	44.718	0.018	0.172	0.224	23.654	43.166	1.967
total_pmf_2030	8	22.103	21.970	0.012	0.066	0.055	15.614	21.545	0.558
total_pmf_2030	9	10.332	10.272	0.010	0.024	0.027	8.462	10.102	0.230
total_pmf_2030	10	4.031	3.992	0.007	0.010	0.022	3.274	3.910	0.121
total_pmf_2030	11	1.166	1.142	0.004	0.001	0.019	0.643	1.089	0.077
total_pmf_2030	12	0.517	0.499	0.001	0	0.017	0.093	0.455	0.063
total_pmf_2030	13	0.354	0.341	0	0	0.014	0.006	0.304	0.050
total_pmf_2030	14	0.295	0.284	0	0	0.011	0	0.255	0.040
total_pmf_2030	15	0.255	0.247	0	0	0.009	0	0.220	0.035
total_pmf_2030	16	0.225	0.219	0	0	0.006	0	0.194	0.031
total_pmf_2030	17	0.202	0.198	0	0	0.005	0	0.174	0.028
total_pmf_2030	18	0.184	0.181	0	0	0.003	0	0.159	0.025
total_pmf_2030	19	0.167	0.165	0	0	0.002	0	0.146	0.022
total_pmf_2030	20	0.152	0.150	0	0	0.002	0	0.134	0.018

5. Scenarios with further abatement of UK emissions

The BAU2030 still leaves considerable exceedance of the WHO standard. So the next step is to explore how convergence towards achieving the WHO standard of 10 µg/m^3 for $PM_{2.5}$ can be improved by further abatement of UK emissions, keeping the same background from imported and natural sources. Results are presented here from analysis of four scenarios.

The first two scenarios analysed, “central” and “high” are both aimed at attaining the UK emission ceilings specified in the NECD. The “high” scenario involves high levels of deployment of the most cost- effective measures in order to attain the ceilings. The “central” scenario spreads the effort more with lower levels of deployment over a wider range of measures and sources. This again attains the NECD ceilings but at a greater cost. The central scenario has formed the basis for NAPCP (National Air Pollution Control Plan) reporting. These scenarios achieve similar reductions relative to 2016 (20.23% in NH_3, 54.82% in SO_2, 50.16% in NO_x and 48.07% in primary $PM_{2.5}$ emissions for the central scenario: and 20.25% in NH_3, 57.16% in SO_2, 51.66% in NO_x and 48.96% in primary $PM_{2.5}$ emissions for the high scenario). Both scenarios have been modelled in order to see if the way in which emission reductions are spread across different sources has much effect. However since the two scenarios give similar results, only the central scenario is described in full below.

As will be seen these central and high scenarios improve exposure to $PM_{2.5}$, but still leave exceedance of the WHO standard in London and hot-spots in some other cities. The last two scenarios are therefore hypothetical scenarios aimed at exploring how much more emission reduction would actually be needed to remove this remaining exceedance, and whether this is possible. Here we examine two extreme scenarios, one exploring what could be achieved theoretically if every measure identified in the MPMD could be implemented fully irrespective of costs, only avoiding conflicting measures that cannot be deployed simultaneously. This is named the “central+” scenario with reductions in emissions of 20.23% in NH_3, 74.1% in SO_2, 54.83% in NO_x and 50.41% in primary $PM_{2.5}$ relative to 2016. The second extreme scenario goes even beyond this adding in additional or stronger emission reductions, for example taking into account potential synergies with other policies such as the DfT Roads to Zero plan for electric vehicles. This is considered the “Maximum Technically Feasible Scenario”, MTFR with emission reductions relative to 2016 of 22.5% in NH_3, 79.05% in SO_2, 63% in NO_x and 55.85% in primary $PM_{2.5}$.

Central and High scenarios

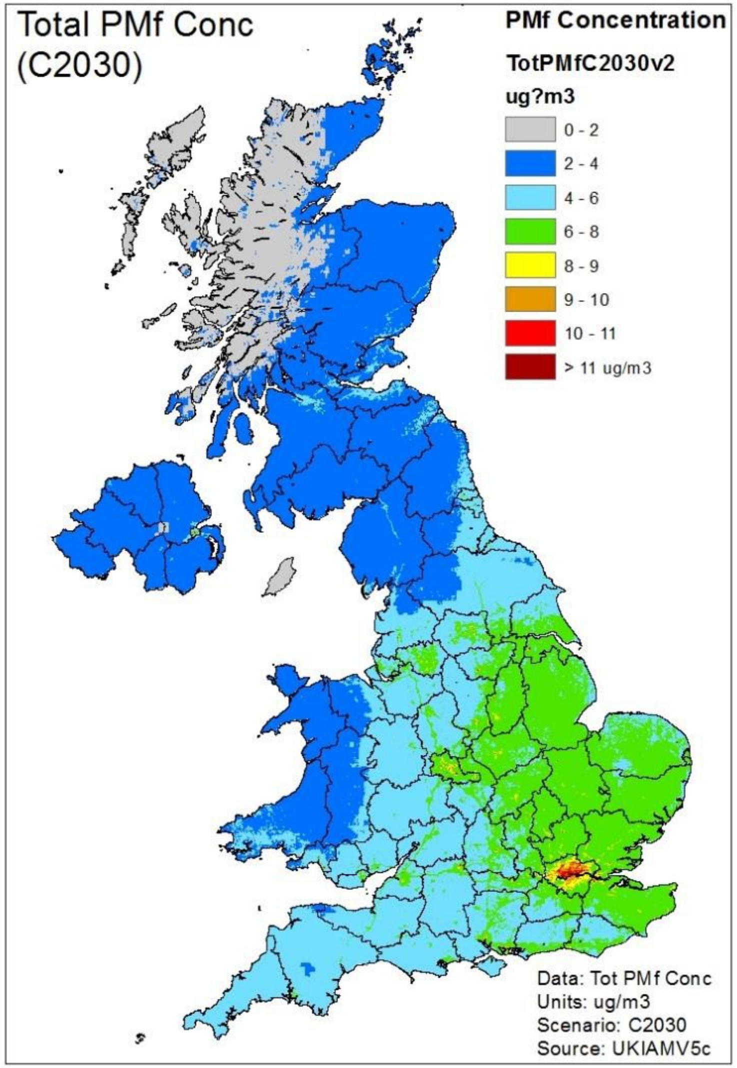
Figure 5.1 shows maps of total $PM_{2.5}$ concentrations for the central scenario, accompanied by maps of the contributions of UK sources to primary $PM_{2.5}$

concentrations and to SIA. Maps for the high scenario are almost identical. Exceedance is now almost entirely confined to London, but with areas close to the WHO standard in other urban areas. There is further improvement relative to the BAU2030, explained by the improvements in SIA and reduction in the yellow area of primary $PM_{2.5}$ above 3 μg/m^3 (or 30% of the WHO standard) attributed to UK emissions in these scenarios.

Table 5.1 gives a breakdown of source attribution for the central and high scenarios. Again these show minimal differences, suggesting that the exact way the NECD ceilings are met does not have significant effect on $PM_{2.5}$ concentrations and exposure.

Figure 5.1 CENTRAL 2030 scenario

Total PM$_{2.5}$ concentration



Contributions of UK emissions to primary PM$_{2.5}$ and to SIA for the central scenario

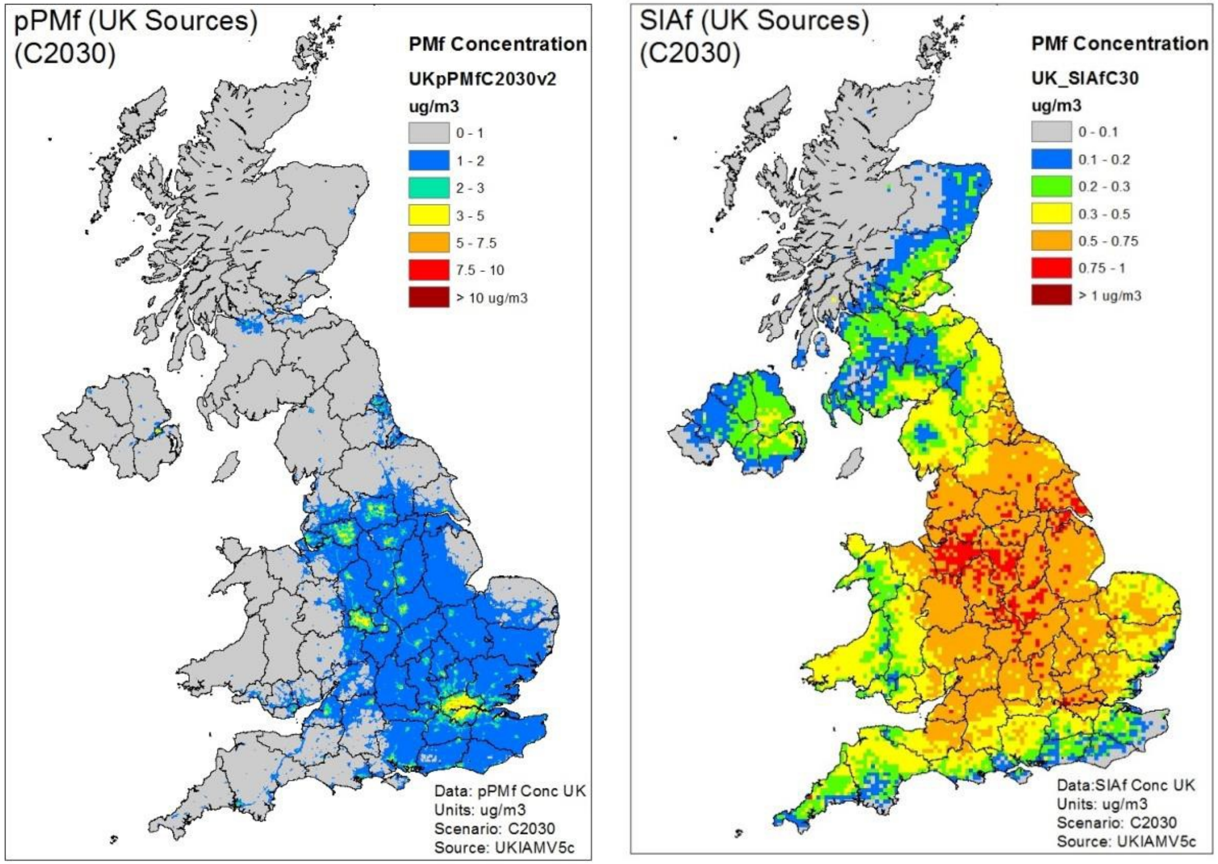


Table 5.1 Source attribution for central and high scenarios

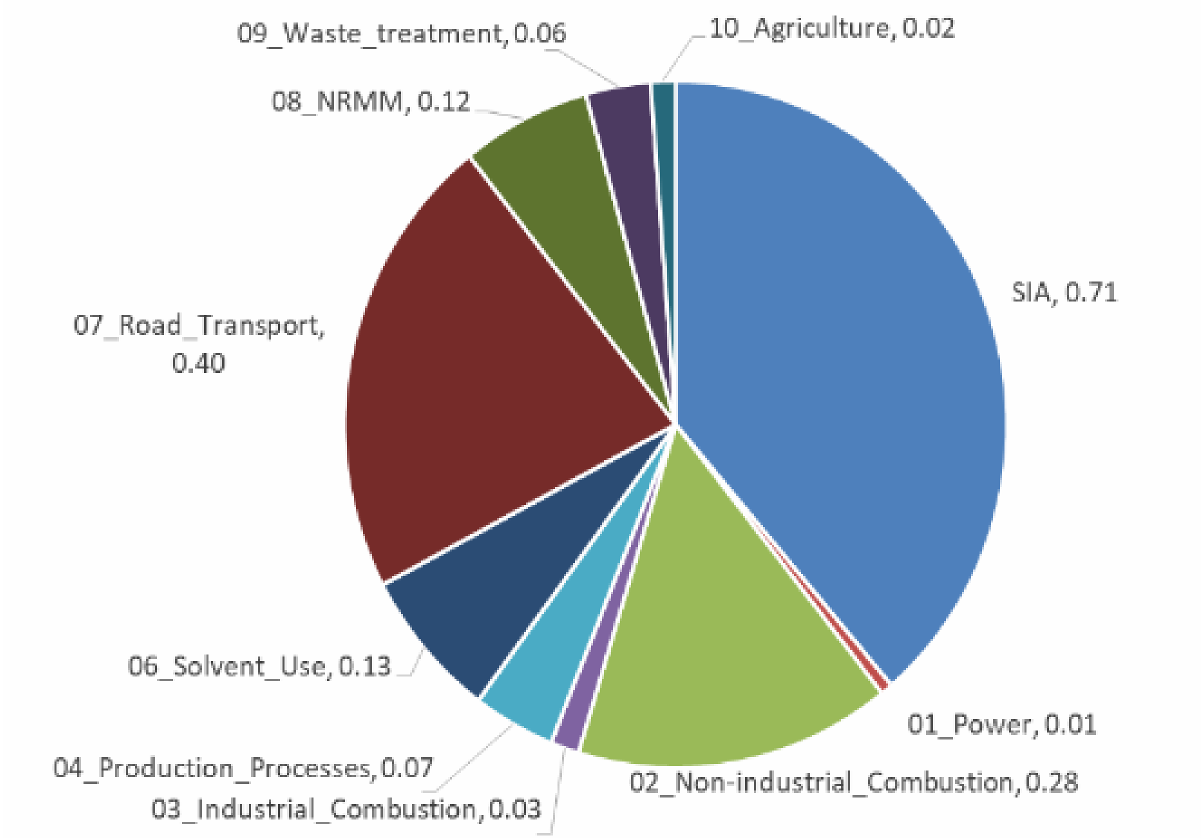
Central 2030		**National**	**Urban**	**Rural**	**London**	**England**	**Scotland**	**Wales**	**Northern Ireland**
Natural PM2.5	**Dusts & Salt**	1.367	1.362	1.384	1.650	1.393	1.283	1.233	1.145
	Water	0.414	0.422	0.388	0.459	0.437	0.265	0.375	0.258
SOA	**(v3)**	0.869	0.890	0.796	1.152	0.937	0.438	0.762	0.327
Primary PM2.5	**UK Sources**	1.255	1.429	0.651	2.231	1.363	0.669	0.778	0.753
	DomShips	0.008	0.008	0.006	0.008	0.007	0.011	0.005	0.005
	Int'l Ships	0.006	0.006	0.005	0.012	0.007	0.002	0.002	0.002
	Europe	0.114	0.116	0.110	0.163	0.124	0.041	0.085	0.097
NH4	**UK Sources**	0.166	0.173	0.143	0.238	0.184	0.059	0.110	0.052
SO4		0.077	0.080	0.066	0.102	0.085	0.030	0.056	0.019
NO3		0.439	0.457	0.378	0.610	0.488	0.148	0.285	0.146
SIA	**DomShips**	0.029	0.029	0.029	0.027	0.030	0.021	0.026	0.029
	Int'l Ships	0.316	0.321	0.300	0.400	0.346	0.101	0.274	0.137
	Europe	0.607	0.615	0.579	0.785	0.645	0.319	0.497	0.438
TOTAL PM2.5	**All Sources**	**5.668**	**5.909**	**4.834**	**7.838**	**6.046**	**3.387**	**4.489**	**3.410**

High 2030		**National**	**Urban**	**Rural**	**London**	**England**	**Scotland**	**Wales**	**Northern Ireland**
Natural PM2.5	**Dusts & Salt**	1.367	1.362	1.384	1.650	1.393	1.283	1.233	1.145
	Water	0.414	0.422	0.388	0.459	0.437	0.265	0.375	0.258
SOA	**(v3)**	0.869	0.890	0.796	1.152	0.937	0.438	0.762	0.327
Primary PM2.5	**UK Sources**	1.245	1.419	0.646	2.216	1.353	0.664	0.771	0.744
	DomShips	0.006	0.006	0.004	0.006	0.005	0.009	0.003	0.004
	Int'l Ships	0.006	0.006	0.005	0.012	0.007	0.002	0.002	0.002
	Europe	0.114	0.116	0.110	0.163	0.124	0.041	0.085	0.097
NH4	**UK Sources**	0.163	0.170	0.141	0.235	0.181	0.058	0.108	0.051
SO4		0.076	0.079	0.065	0.101	0.084	0.030	0.055	0.019
NO3		0.428	0.445	0.369	0.593	0.476	0.144	0.278	0.142
SIA	**DomShips**	0.022	0.023	0.021	0.024	0.024	0.013	0.017	0.016
	Int'l Ships	0.316	0.321	0.300	0.400	0.346	0.101	0.274	0.137
	Europe	0.606	0.614	0.578	0.784	0.644	0.319	0.497	0.438
TOTAL PM2.5	**All Sources**	**5.635**	**5.874**	**4.806**	**7.797**	**6.010**	**3.367**	**4.461**	**3.380**

Figure 5.2 gives a more detailed breakdown for the central scenario of the contributions from different sectors to primary $PM_{2.5}$ concentrations and the contribution to SIA. The pie chart for the high scenario is almost identical with a very slightly larger reduction in SIA. Compared with the BAU 2030 scenario there are significant reductions from non-industrial combustion including measures for wood-burning and domestic combustion, and also stricter controls on industrial combustion. The SIA is reduced but is now a larger proportion of the whole.

Figure 5.2 Source apportionment pie charts for the central scenario

CENTRAL SCENARIO



“Central +” 2030 scenario

The central+ scenario is a hypothetical scenario deploying all abatement measures in the MPMD to the maximum irrespective of cost. The resulting emission reductions relative to 2016 are 20.23% in NH_3, 74.1% in SO_2, 54.83% in NO_x and 50.41% in primary $PM_{2.5}$. A map of the resulting $PM_{2.5}$ concentrations is shown in figure 5.3 together with maps of the UK contributions to primary $PM_{2.5}$ concentrations and to

SIA.

There are clearly some further improvements compared with the central scenario in figure 5.1, also reflected in the UK primary and SIA components. But these improvements are modest compared with the improvements between the BAU2030 scenario and the central scenario aimed at compliance with the NECD. There is still a major area of red indicating significant exceedance over London.

Table 5.2 gives a breakdown of source apportionment for this “central+” scenario, and figure 5.4 gives more detail on the source apportionment for UK sources. Compared with the central scenario there is a small improvement in non-industrial combustion and in SIA, but that from road transport remains obstinately large. Overall the benefit of the additional measures beyond the central scenario is small with improvements of just ~0.1 $\mu g/m^3$ in population weighted mean concentration of $PM_{2.5}$ both nationally and for the London population.

Figure 5.3 CENTRAL+ 2030 scenario

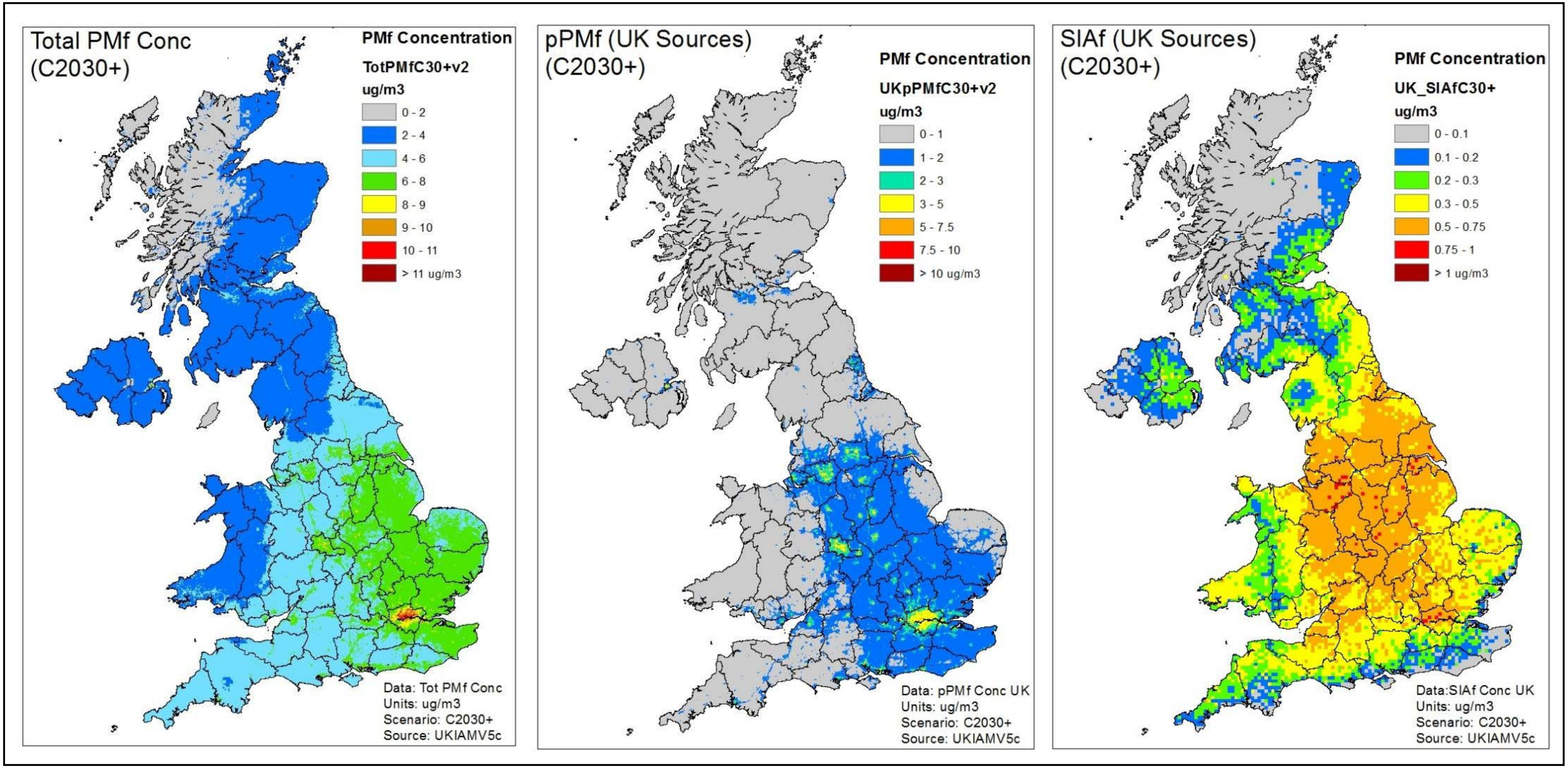
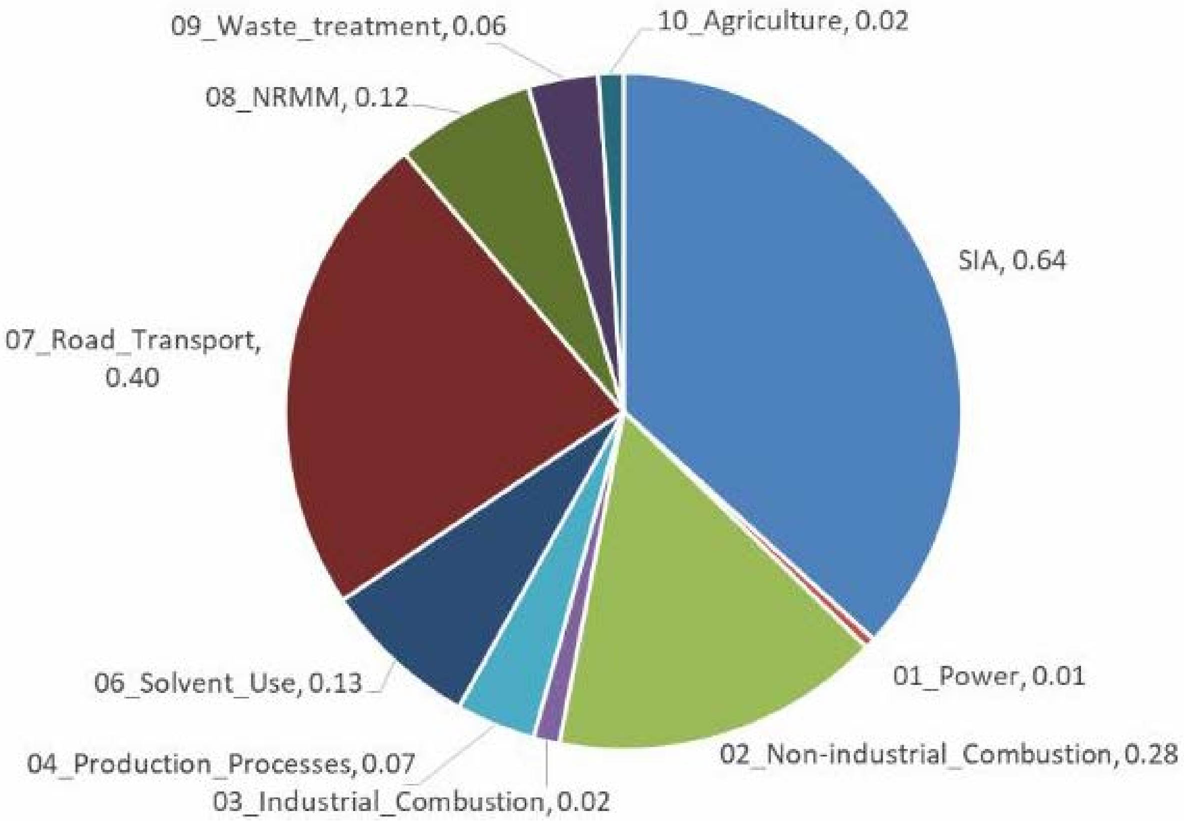


Table 5.2: Source apportionment for the Central+ scenario

Central+		National	Urban	Rural	London	England	Scotland	Wales	Northern Ireland
Natural PM2.5	Dusts & Salt	1.367	1.362	1.384	1.650	1.393	1.283	1.233	1.145
	Water	0.414	0.422	0.388	0.459	0.437	0.265	0.375	0.258
SOA	(v3)	0.869	0.890	0.796	1.152	0.937	0.438	0.762	0.327
Primary PM2.5	UK Sources	1.232	1.404	0.635	2.209	1.338	0.659	0.757	0.743
	DomShips	0.007	0.008	0.006	0.008	0.007	0.011	0.005	0.005
	Int'l Ships	0.006	0.006	0.005	0.012	0.007	0.002	0.002	0.002
	Europe	0.114	0.116	0.110	0.163	0.124	0.041	0.085	0.097
NH4	UK Sources	0.148	0.154	0.126	0.218	0.164	0.050	0.098	0.045
SO4		0.058	0.061	0.049	0.084	0.064	0.021	0.043	0.014
NO3		0.410	0.426	0.353	0.573	0.456	0.134	0.265	0.132
SIA	DomShips	0.026	0.026	0.024	0.031	0.028	0.015	0.018	0.010
	Int'l Ships	0.316	0.321	0.300	0.400	0.346	0.101	0.274	0.137
	Europe	0.606	0.614	0.577	0.784	0.643	0.318	0.497	0.437
TOTAL PM2.5	**All Sources**	**5.573**	**5.810**	**4.752**	**7.743**	**5.943**	**3.339**	**4.412**	**3.353**

Figure 5.4 Source apportionment of UK contributions to $PM_{2.5}$ exposure for the Central+ scenario



MTFR scenario

In the MTFR (Maximum Technically Feasible Reduction) scenario an attempt has been made to include extra emission reductions reflecting the potential additional impact of synergies with other policies, such as the Roads to Zero ambition of DfT. This includes more electric cars and vans in the fleet, and also some reductions for non-road transport. As indicated above this gives emission reductions relative to 2016 of 22.5% in NH_3, 79.05% in SO_2, 63% in NO_x and 55.85% in primary $PM_{2.5}$, rather more than the Central+ scenario.

The resulting map of concentrations is shown in figure 5.5 together with the UK contributions to primary $PM_{2.5}$ concentrations and SIA. There is some slight further improvement with a reduction of 0.13 μg/m^3 in population weighted mean concentration relative to the Central+ scenario from these additional emission reductions. But the red area over London remains an intractable problem, still with considerable exceedance.

Figure 5.5 MTFR 2030

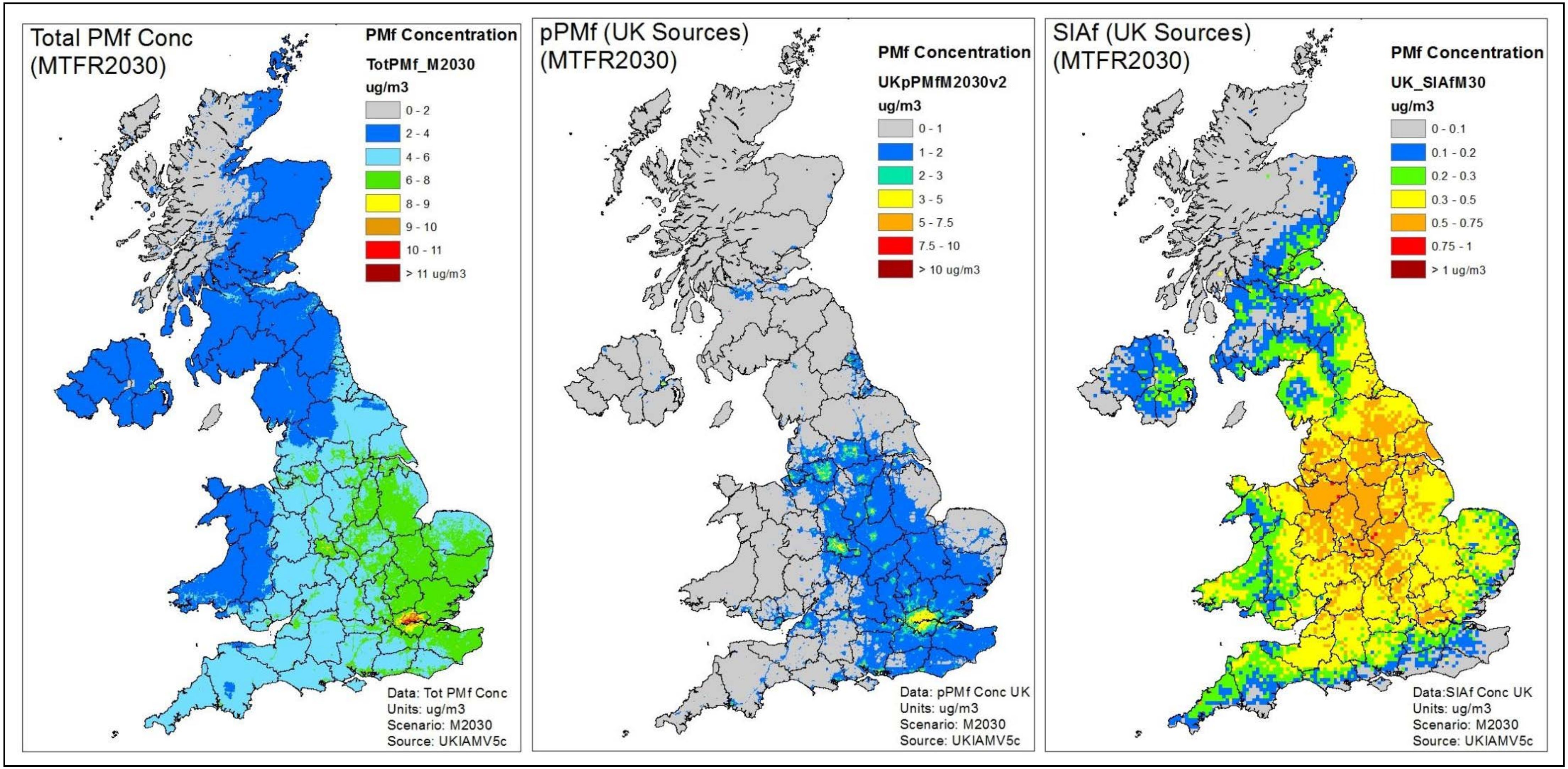


Table 5.3 gives the corresponding source-apportionment for this MTFR scenario, and figure 5.6 the break-down of UK contributions, showing a reduction in primary PM from non-road-transport emissions as well as a small reduction in SIA. Compared with the Central+ scenario there is a marginal improvement of about 0.2 µg/m^3 in population weighted mean concentration, but the contribution of primary road transport emissions remains very dominant, and this is even more important for heavily trafficked urban areas (see later section on London). The difficulty is that a large proportion of these emissions are non-exhaust emissions for which no control measures are yet defined.

Figure 5.6 Source apportionment of UK contributions

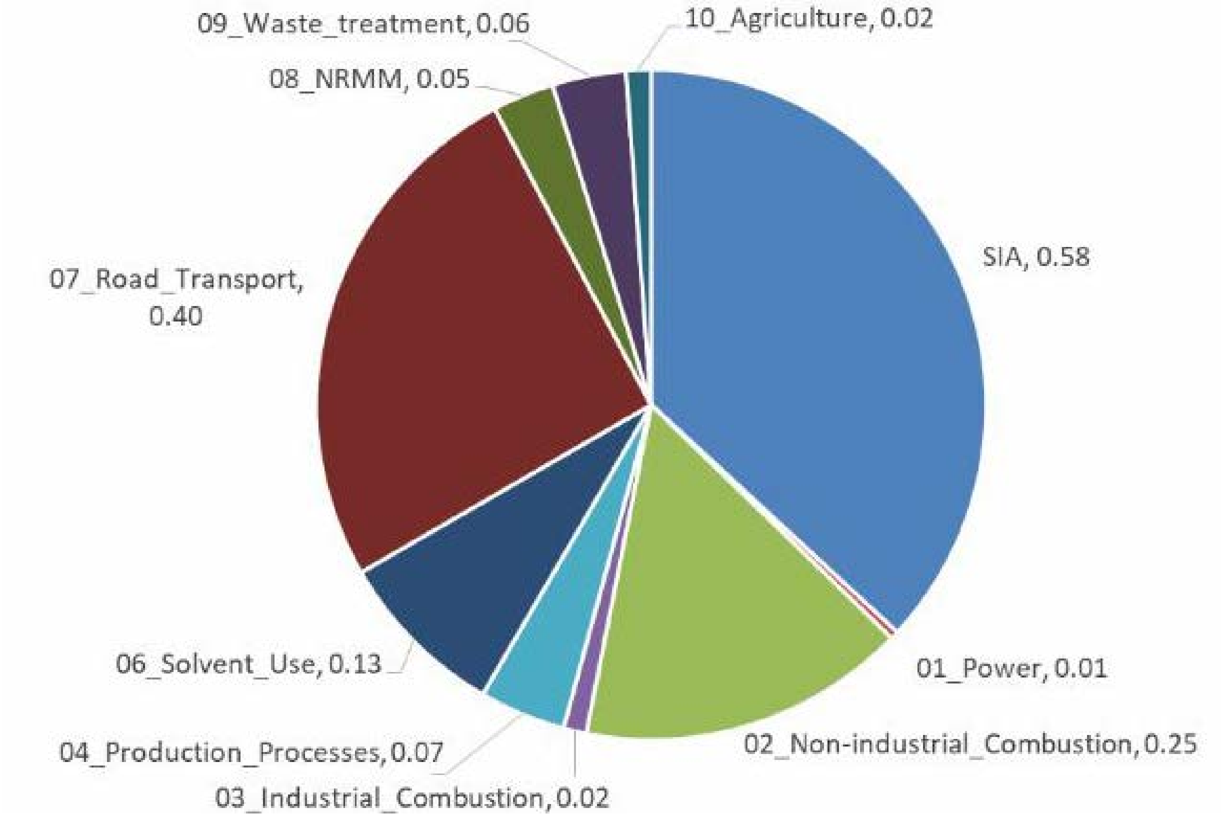


Table 5.3 Source apportionment for MTFR scenario

MTFR		National	Urban	Rural	London	England	Scotland	Wales	Northern Ireland
Natural PM2.5	**Dusts & Salt**	1.367	1.362	1.384	1.650	1.393	1.283	1.233	1.145
	Water	0.414	0.422	0.388	0.459	0.437	0.265	0.375	0.258
SOA	**(v3)**	0.869	0.890	0.796	1.152	0.937	0.438	0.762	0.327
Primary PM2.5	**UK Sources**	1.128	1.286	0.581	2.058	1.226	0.605	0.689	0.674
	DomShips	0.006	0.006	0.005	0.005	0.005	0.010	0.005	0.005
	Int'l Ships	0.006	0.006	0.005	0.012	0.007	0.002	0.002	0.002
	Europe	0.114	0.116	0.110	0.163	0.124	0.041	0.085	0.097
NH4	**UK Sources**	0.138	0.144	0.118	0.204	0.154	0.047	0.091	0.041
SO4		0.051	0.054	0.043	0.072	0.057	0.019	0.038	0.012
NO3		0.385	0.400	0.330	0.544	0.428	0.125	0.246	0.123
SIA	**DomShips**	0.009	0.009	0.008	0.008	0.009	0.007	0.007	0.006
	Int'l Ships	0.316	0.321	0.300	0.400	0.346	0.101	0.274	0.137
	Europe	0.604	0.612	0.576	0.781	0.641	0.318	0.496	0.436
TOTAL PM2.5	**All Sources**	**5.408**	**5.629**	**4.643**	**7.509**	**5.763**	**3.260**	**4.305**	**3.263**

6. Exceedance of the WHO standard of 10 μg/m^3

The next question is how exceedance of the WHO standard improves through the different scenarios. This is addressed below, both by quantifying the numbers of people exceeding the WHO standard, and then by comparing accumulated exceedance.

Population exceeding the standard

Figure 6.1 shows graphs of the number of the UK population exceeding different threshold concentrations for each of the scenarios modelled in the preceding sections. Table 6.1 below gives numbers of the population above 9 and 11 μg/m^3 as well as above the WHO standard of 10 μg/m^3 as a sensitivity study to model uncertainties: and also gives a regional break-down.

The top blue graph (national) in figure 6.1 shows the starting point in 2016 with 15 (8.5 to 27) million people in the UK exceeding the standard. The lower exceedance for the purple line shows the reduction when wood-burning is removed to show the importance of this source. There is a large improvement in the 2030 baseline (B2030) reflecting emission reductions in other countries as well as in the UK. This gives 4.4 (1.5 to 8.5) million people still exceeding the standard, an improvement of 70% relative to 2016. Beyond this the Central and High scenarios (C2030 and H2030) almost coincide on top of each other with some further improvement, reducing the population above the standard to 1.8 (0.37 to 4.7) and 1.6 (0.35 to 4.6 respectively), an improvement of 88 to 89 % relative to 2016. Beyond this there is a marginal improvement to 1.4 (0.3 to 4.3) million with the additional measures in the C+ scenario; and then to 0.95 (0.2 to 3.5) million for the MTFR scenario. These numbers are dominated by the population of England. London is a particular problem with most of its population exceeding the WHO standard in 2016, but with major improvements to 1.5 to 1.7 million for the central and high scenarios aimed at compliance with the NECD (a reduction of ~80% relative to 2016). This reduces to 0.87 (0.13 to 3.3) million for the extreme MTFR scenario, indicating that even these extreme measures would not entirely eliminate exceedance in London.

Figure 6.1 UK population exceeding different threshold concentrations (millions of people)

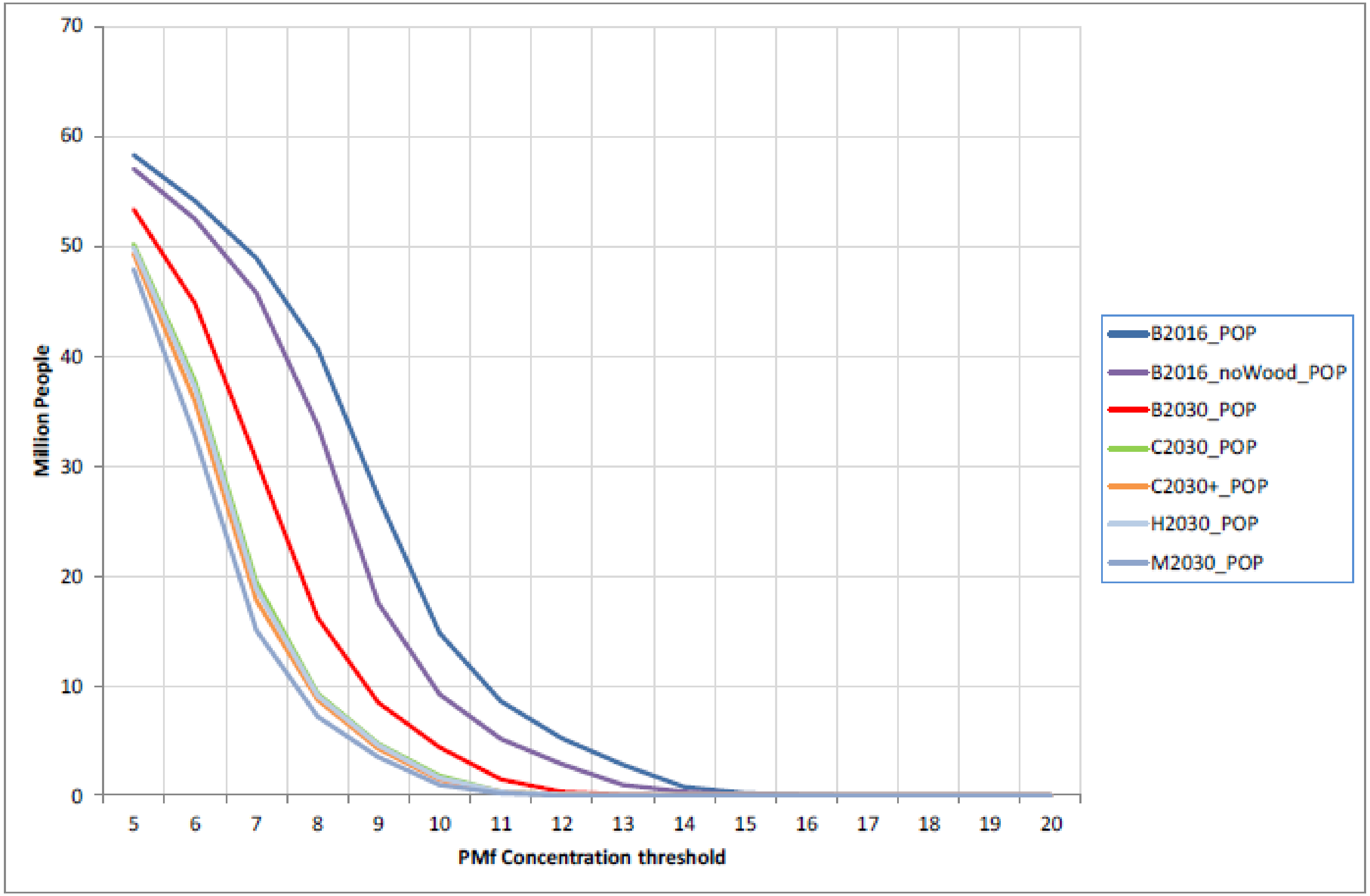


Table 6.1 Regional break-down of population (millions) exceeding thresholds of 10 (+/-1) µg/m^3

B2016	Conc.	National	England	Scotland	Northern_I	Wales	London	Urban	Rural
	9	27.157	26.858	0.003	0.106	0.190	8.154	25.008	2.149
	10	14.795	14.729	0.003	0.025	0.038	7.827	14.262	0.533
	11	8.560	8.541	0.003	0.014	0.003	6.617	8.399	0.160
BAU2030	Conc.	National	England	Scotland	Northern_I	Wales	London	Urban	Rural
	9	8.475	8.447	0.003	0.014	0.011	6.324	8.309	0.166
	10	4.377	4.358	0.003	0.014	0.003	3.955	4.306	0.071
	11	1.460	1.450	0.003	0.005	0.003	1.337	1.439	0.021
Central	Conc.	National	England	Scotland	Northern_I	Wales	London	Urban	Rural
	9	4.714	4.697	0.003	0.010	0.005	4.303	4.627	0.087
	10	1.813	1.802	0.003	0.005	0.003	1.673	1.781	0.032
	11	0.370	0.365	0.003	0	0.003	0.287	0.357	0.013
High	Conc.	National	England	Scotland	Northern_I	Wales	London	Urban	Rural
	9	4.577	4.559	0.003	0.010	0.005	4.178	4.493	0.083
	10	1.615	1.604	0.003	0.005	0.003	1.491	1.583	0.032
	11	0.357	0.351	0.003	0	0.003	0.275	0.344	0.013
Central +	Conc.	National	England	Scotland	Northern_I	Wales	London	Urban	Rural
	9	4.293	4.278	0.003	0.010	0.003	3.959	4.215	0.079
	10	1.404	1.396	0.003	0.002	0.003	1.307	1.383	0.021
	11	0.318	0.313	0.003	0	0.003	0.247	0.305	0.013
MTFR	Conc.	National	England	Scotland	Northern_I	Wales	London	Urban	Rural
	9	3.525	3.510	0.003	0.010	0.003	3.326	3.466	0.059
	10	0.951	0.945	0.003	0	0.003	0.867	0.936	0.014
	11	0.197	0.191	0.003	0	0.003	0.129	0.184	0.012

Accumulated exceedance

The alternative way of quantifying improvement is by calculating accumulated exceedance as defined in section 3, summing the population times the exceedance of the standard over all grid cells where the concentration is above the standard. Exceedance is calculated in units of million people.µg/m^3, referred to as Mpu.

Figure 6.2 shows the graphs of accumulated exceedance for different threshold values for each scenario using the same colour scheme as in Figure 6.1. Table 6.2 again gives accumulated exceedance of 9 and 11 µg/m^3 as well as the WHO standard of 10 µg/m^3 as a sensitivity to model uncertainty, together with a regional break down.

The starting point in 2016 is an accumulated exceedance of 24.6 (13 to 45) Mpu, corresponding to an average of 0.37 µg/m^3 per person in the UK above the WHO standard. The purple graph shows the effect of removing wood-burning to illustrate its importance. There is very big improvement in the BAU2030 scenario to 4 (1.2 to 10) Mpu, a reduction already of 84%. The central and high scenarios aimed at compliance with the NECD give a further reduction to 1.3 (0.5 to 4.6) Mpu, equivalent to almost a 95% reduction relative to 2016. Beyond this the Central+ and MTFR scenarios give small further improvements to 0.77 (0.3 to 3) Mpu for the MTFR with the greatest reduction, equivalent to a 97% reduction.

Using accumulated exceedance also gives big improvements for London, since it reflects the reductions in concentration to this population with the highest exposure. For the baseline in 2016 the accumulated exceedance for London is 19 (12 to 27) Mpu, 77% of the total for the UK. In the BAU2030 scenario this reduces to 3.3 (0.6 to 8.5) Mpu, a reduction of 83% - similar to that for the UK population overall. For the central and high scenarios this reduces further to 0.8 to 0.9 (0.12 to 3.9) Mpu, corresponding again to a 95% improvement relative to 2016. For the extreme MTFR scenario the accumulated exceedance for London is down further to 0.4 (0.04 to 2.5) Mpu giving a 98% improvement relative to 2016, similar to that for the national accumulated exceedance.

The advantage of using accumulated exceedance to quantify improvement rather than the number of the population above the standard, is that it addresses overall exposure and reflects improvements for the most exposed people as well as those close to the threshold. Thus it is a better indicator of improvements in health. It also gives more consistent improvements for the national and most exposed populations; whereas the number of people above the standard can change substantially when large numbers just above the standard are reduced to just below it with modest changes in concentration, but remain stubbornly constant revealing no improvement for city populations well above the standard.

Figure 6.2. Accumulated exceedance for different concentration thresholds (Mpu)

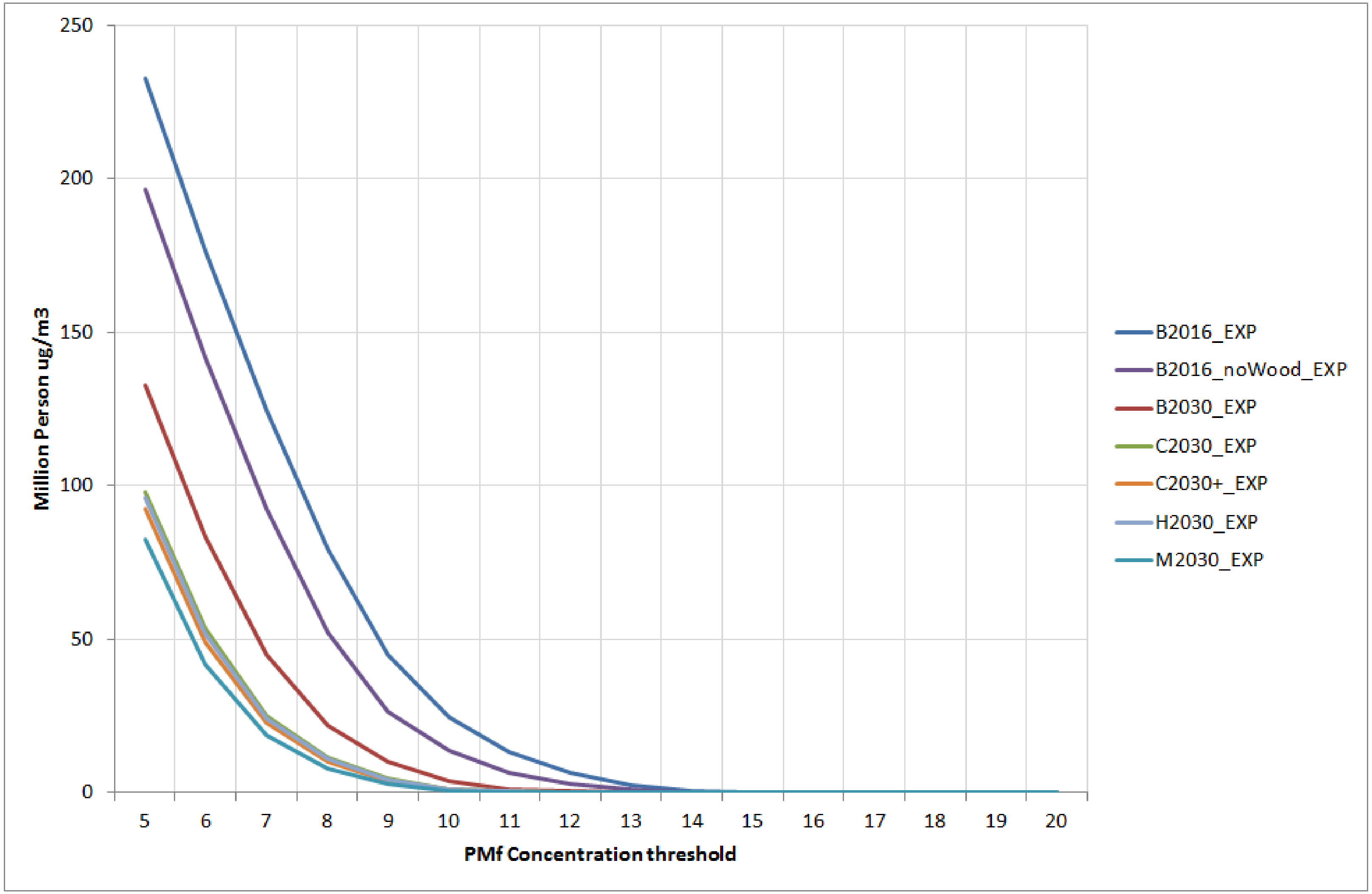


Table 6.2 Regional break down of accumulated exceedance (Mpu)

B 2016	Conc	National	England	Scotland	Northern_I	Wales	London	Urban	Rural
	9	45.161	44.936	0.009	0.080	0.136	27.007	43.485	1.676
	10	24.626	24.564	0.006	0.024	0.032	18.963	24.106	0.520
	11	13.327	13.295	0.004	0.009	0.019	11.635	13.107	0.220
BAU2030	Conc	National	England	Scotland	Northern_I	Wales	London	Urban	Rural
	9	10.332	10.272	0.010	0.024	0.027	8.462	10.102	0.230
	10	4.031	3.992	0.007	0.010	0.022	3.274	3.910	0.121
	11	1.166	1.142	0.004	0.001	0.019	0.643	1.089	0.077
Central	Conc	National	England	Scotland	Northern_I	Wales	London	Urban	Rural
	9	4.573	4.531	0.009	0.008	0.024	3.903	4.434	0.139
	10	1.341	1.314	0.006	0.001	0.021	0.902	1.258	0.083
	11	0.483	0.461	0.003	0	0.018	0.137	0.416	0.067
High	Conc	National	England	Scotland	Northern_I	Wales	London	Urban	Rural
	9	4.360	4.320	0.009	0.007494	0.024	3.707	4.226	0.134
	10	1.260	1.233	0.006	0.000346	0.021	0.826	1.179	0.081
	11	0.466	0.444	0.003	0	0.018	0.123	0.400	0.066
Central+	Conc	National	England	Scotland	Northern_I	Wales	London	Urban	Rural
	9	4.067	4.029	0.008	0.00722	0.022	3.473	3.938	0.128
	10	1.150	1.125	0.006	0.000214	0.019	0.749	1.071	0.079
	11	0.429	0.409	0.003	0	0.017	0.109	0.365	0.064
MTFR	Conc	National	England	Scotland	Northern_I	Wales	London	Urban	Rural
	9	2.954	2.922	0.006	0.005	0.021	2.475	2.849	0.105
	10	0.767	0.745	0.003	0	0.018	0.413	0.695	0.071
	11	0.328	0.312	0.001	0	0.016	0.045	0.269	0.058

7. The special case of London

The preceding sections have emphasized the special problems in eliminating the exceedance of the WHO standard of 10 µg/m^3 for $PM_{2.5}$ in London. In this section this is examined in more spatial detail. The maps in figure 7.1 show $PM_{2.5}$ concentrations for the base year of 2016, the business as usual BAU2030 scenario, the Central scenario and the MTFR scenario.

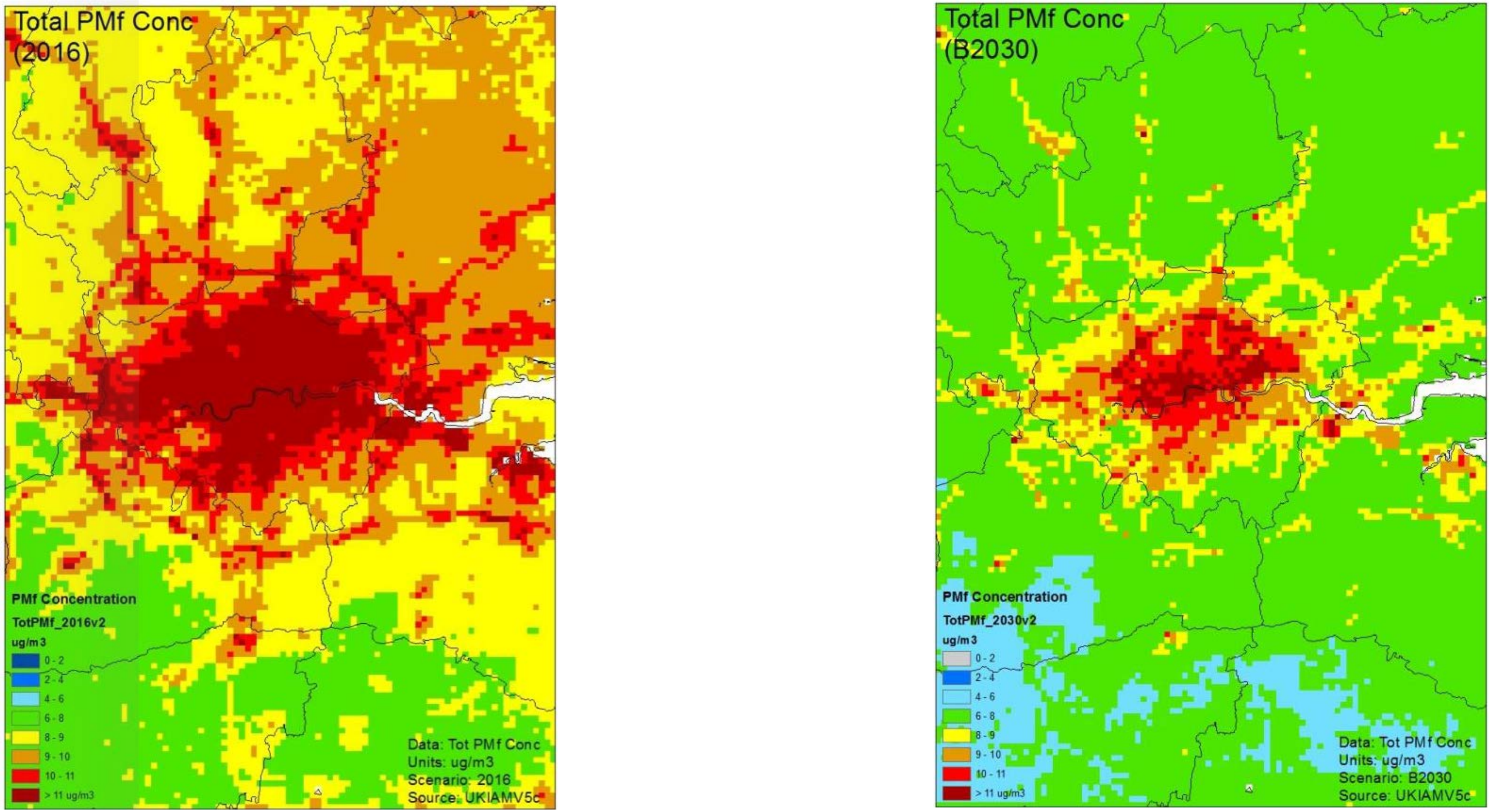
These reinforce the messages from preceding sessions that there is a massive improvement from 2016 to the BAU2030 scenario, even though the red contour in the latter still includes a large area exceeding 10 µg/m^3, and parts of inner and central London are still dark red as above 11 µg/m^3.

Large areas of outer London are now green (<8 µg/m^3) and at low risk even in extreme years.

Proceeding to the Central scenario there is further improvement, with the major roads become more apparent, reflecting the role of non-exhaust emissions (which are now enhanced with the new modelling to reflect more braking in congested urban areas and less on faster roads). The MTFR shows a little further improvement with larger areas of green, but still showing some red areas with a few dark-red grid squares above 11 µg/m^3. It should be noted that no allowance has been made for special measures within London including policies to induce behavioural change and moves to reduce road transport; or for future strengthening of the ULEZ (although by 2030 older vehicles in the fleet will have been removed). A greater proportion of electric vehicles in London may help NO_x, but will be less effective in reducing the important non-exhaust emissions except where helped by regenerative braking. More work on special measures in London is clearly required, but additional changes would need to be made to eliminate the worst hot-spots associated with concentrated traffic.

Another factor to consider is the irreducible natural background contribution, which is substantial and also uncertain. As a final experiment this has been removed for the MTFR scenarios to see if the remaining $PM_{2.5}$ due to anthropogenic emissions alone exceeds the WHO standard. The resulting map is shown in figure 7.2 indicating only around 3 grid squares above 8 µg/m^3, all coinciding with high traffic concentrations identified in previous work on NO_x.

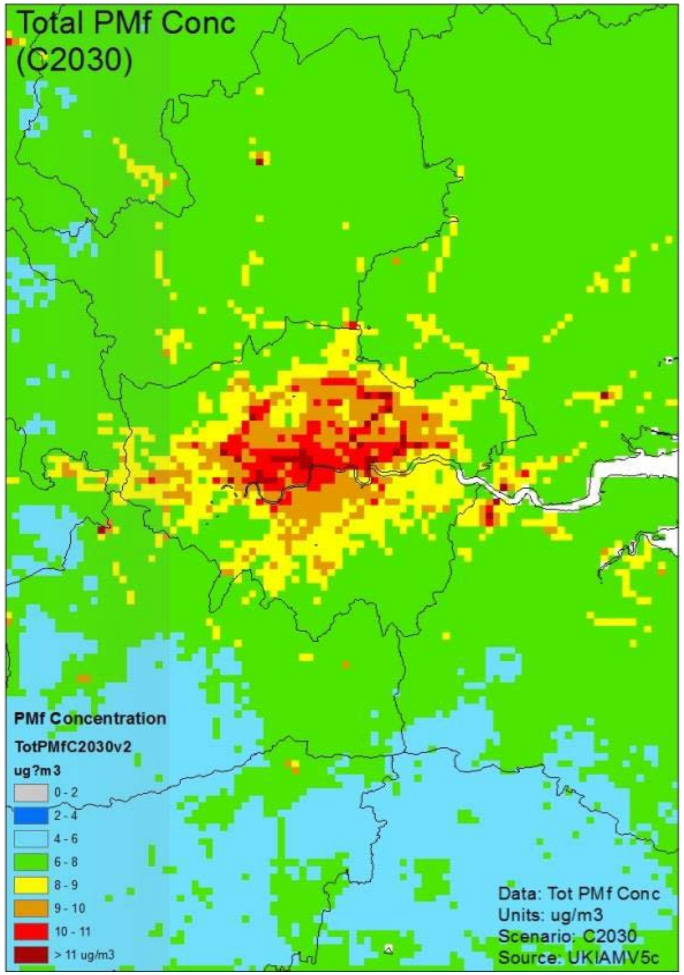
Figure 7.1 Maps of $PM_{2.5}$ over London for selected scenarios



2016

BAU2030

CENTRAL



MTFR

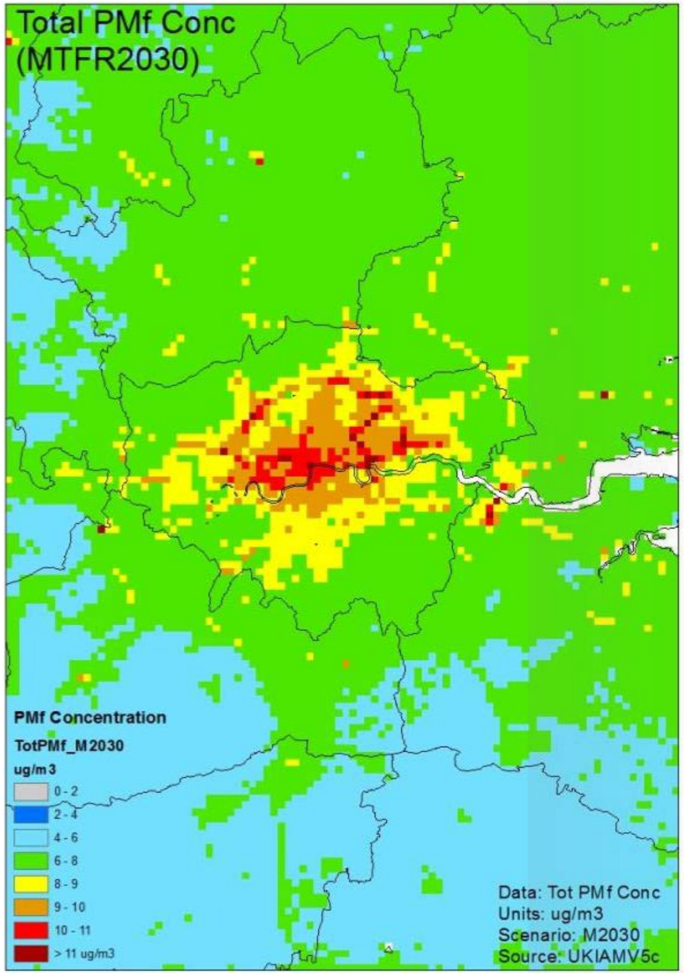
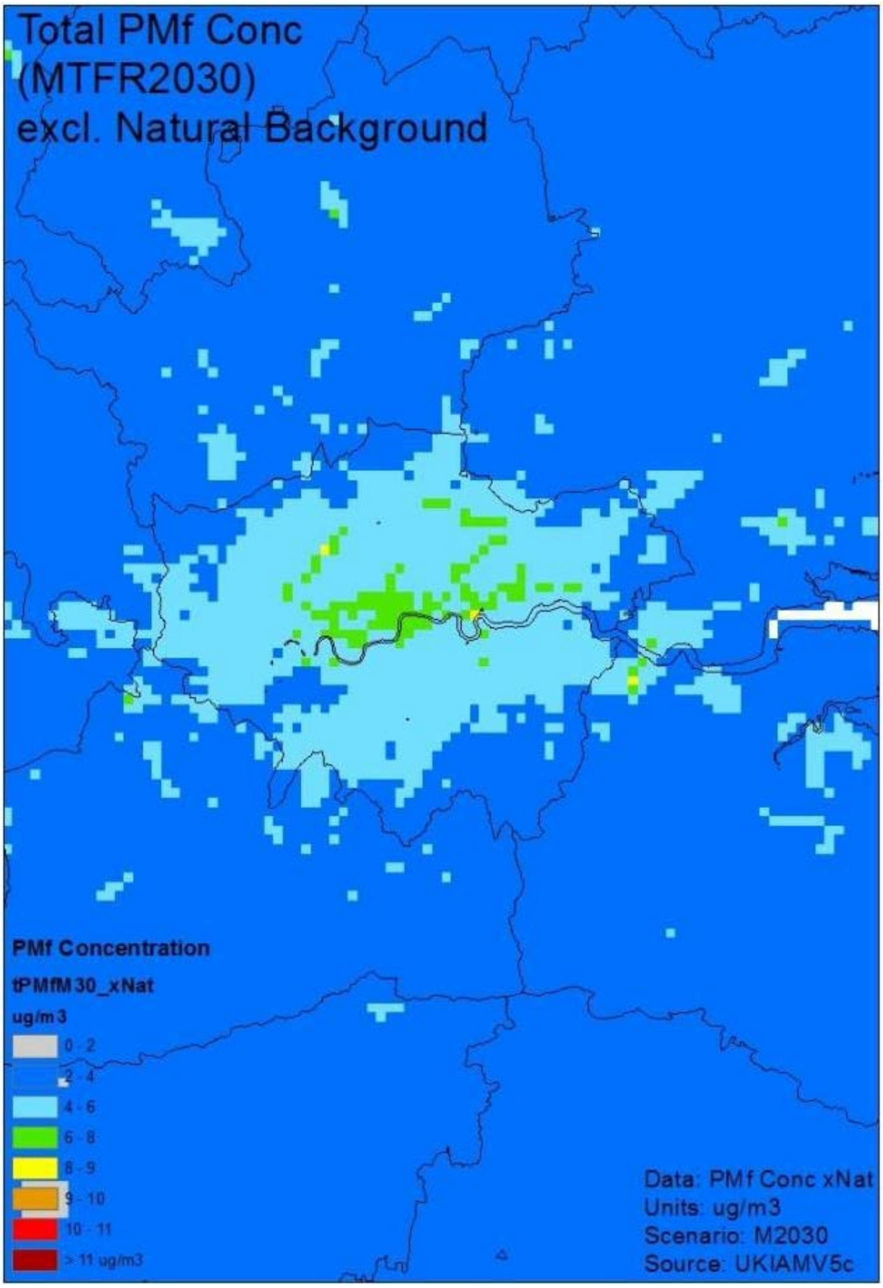


Figure 7.2 Map of $PM_{2.5}$ due to anthropogenic sources.



8. Summary and discussion

This report has described exploration of a number of abatement scenarios with increasingly strong emission reductions beyond the Business as Usual emission projections for 2030. The aim has been to explore reducing exceedance of the WHO standard of 10 μg/m^3 for $PM_{2.5}$ concentrations, taking 2016 as a starting point. The scenarios, and emission reductions relative to 2016 are summarised in table 8.1.

Table 8.1 Scenarios and % emission reductions relative to 2016

Scenario	NH3	SO2	NOx	PM2.5
BAU 2030	0.82%	54.51%	42.96%	16.20%
C2030 Central	20.23%	54.82%	50.16%	48.07%
H2030 High	22.25%	57.16%	51.66%	48.96%
C2030+ Central+	20.23%	74.10%	54.83%	50.41%
MTFR	22.25%	79.05%	63.00%	55.85%

These scenarios, together with $PM_{2.5}$ concentrations in 2016, have been modelled with the UK Integrated Assessment Model, UKIAM (version 5c), and illustrated by maps and a break down of contributions from different sources including the background from natural and irreducible sources, and imported from other countries and shipping. For UK emissions the contribution to secondary inorganic aerosol, SIA, is distinguished from the contribution of primary PM sources to primary $PM_{2.5}$ concentrations.

Already in 2016 it is clear that exceedance of 10 μg/m^3 is mainly confined to England. The maps show a very large improvement from 2016 to the BAU2030 scenario due to the combination of emission reductions in other countries to comply with the NECD, and to projected reductions in the UK. The population weighted mean concentration over the UK reduces by 1.44 μg/m^3 to 6.27 μg/m^3. Using a monetised health benefit of £50 per reduction of 1 μg/m^3 per person which matches the recently revised Defra damage costs, this equates to an economic benefit of £4.8 billion per year. There are also significant co-benefits in reduction of NO_2 exposure. It is noted that despite the reduction in the imported contribution from other countries, there is an important contribution from international shipping which reduces little by 2030 as growth in shipping counteracts abatement in the emission control areas. Already in the BAU2030 scenario it is clear that exceedance of the WHO standard is particularly focused in urban areas.

The two scenarios designed to achieve the further reductions needed for UK compliance with the NECD in 2030 are the central and high scenarios. They have similar emissions, and produce similar results despite the different distribution of abatement across UK sources. They give further improvement in population weighted mean concentration of 0.6 and 0.63 μg/m^3, equivalent to additional monetised health benefits for the UK of ~£2 billion per year. Most of the country is now below 8 µg/m^3, but still leaves London with major exceedance. Some small areas in other major cities such as Birmingham and Manchester also show exceedance, and several urban areas are above 8 µg/m^3 and could have hot-spots especially in extreme meteorological years.

Beyond this the Central+ scenario achieves only a small improvement of approximately 0.1 µg/m^3, despite deploying the full set of measures in the MPMD- indicating little benefit from going beyond the Central scenario. The MTFR achieves slightly more benefit with an improvement in population weighted mean concentration relative to the central scenario of 0.26 µg/m^3: but still leaves a problem of some lingering exceedance in London.

Exceedance of the WHO standard has been quantified in two ways. In the first the distribution of population exposed to different concentrations across the UK has been used to plot the number of the population exceeding different thresholds of concentration, and derive the number of people exceeding 10 µg/m^3. The number exceeding 9 and 11 µg/m^3 as thresholds plus or minus 1 µg/m^3 have been used to define a range as a sensitivity to model uncertainty. The graphs for each scenario are shown in figure 6.1, and reflect the comments on the maps above. Table 8.2 gives a summary of the resulting population in millions with exceedance, both for the UK as a whole, and for London as the area with the highest concentrations. The numbers in italics are the % improvements relative to 2016.

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It can be seen that the large improvement for the UK of a 70% reduction in the UK population above the WHO standard from 2016 to the BAU2030 scenario, is increased to 88 to 89% for the central and high scenarios aimed at compliance with the NECD. There is then a further improvement beyond this to 94% for the extreme MTFR scenario. But for London this indicator of population above the standard shows smaller improvements of 50% by the BAU2030 scenario, and ~79% for the central scenario; although thereafter there is more improvement with the increased abatement in the central+ and MTFR scenarios. But there is also a very large sensitivity to model uncertainty, where a difference of +/- 1 µg/m^3 results in the extreme difference from a 22% improvement to an 80% improvement for London in the MTFR scenario.

The second way in which exceedance has been quantified is in terms of accumulated exceedance, in which the magnitude of exceedance is also taken into account and credit is given for reducing the highest concentrations as well as to those already close to the threshold. A corresponding table of accumulated exceedance (in units of Million people.µg/m^3, or Mpu) is shown as table 8.3; again with % improvements relative to 2016 in italics and the same sensitivity study to +/- 1 µg/m^3 to model uncertainties. Here the % improvements are larger, with a reduction in accumulated exceedance for the UK population of 84% for the BAU2030 scenario, increasing to 95% for the central and high scenarios. Beyond this the MTFR achieves a 97% reduction. There is less sensitivity to model uncertainty than for the number of people above the standard in table 8.2.

But the biggest advantage of using the accumulated exceedance approach shows up in the figures for London. Here credit is given for improving the concentrations even when they are not reduced below the WHO standard. Thus relative to 2016 the BAU2030 scenario gives an 83% improvement, and for the Central scenario this increases to 95%. These improvements reflect the reduction in the population weighted mean concentration in London from 10.6 μg/m^3 in 2016 to 8.6 in the BAU 2030 scenario, and to 7.8 μg/m^3 in the central scenario. In the MTFR scenario, for which the population weighted mean concentration for London reduces to 7.5 μg/m^3, there is a 98% reduction in accumulated exceedance. These numbers for accumulated exceedance are very consistent with the national figures, and also much less sensitive to model uncertainties.

An alternative way of quantifying exceedance in an area is to divide accumulated exceedance by the number of people in millions in the area to which it applies (i.e. in the whole country or sub-region) to give the average exceedance for people in that area in units of μg/m^3. This would have the same advantages for setting targets to reduce to zero to achieve meeting the WHO standard.

Table 8.2 Population in millions above WHO threshold concentration for the UK and London

NB The figures in red italics are the % reductions relative to 2016

		National			**London**	
Scenario	model+1 μg/m^3	**central estimate**	model-1 μg/m^3	model+1 μg/m^3	**central estimate**	model-1 μg/m^3
B 2016	27.157	**14.795**	8.56	8.154	**7.827**	6.617
BAU 2030	8.475	**4.377**	1.46	6.324	**3.955**	1.337
	68.8%	***70.4%***	*82.9%*	*22.4%*	***49.5%***	*79.8%*
Central	4.714	**1.813**	0.370	4.303	**1.673**	0.287
	82.6%	***87.7%***	*95.7%*	*47.2%*	***78.6%***	*95.7%*
High	4.577	**1.615**	0.357	4.178	**1.491**	0.275
	83.1%	***89.1%***	*95.8%*	*48.8%*	***81.0%***	*95.8%*
Central +	4.293	**1.404**	0.318	3.959	**1.307**	0.247
	84.2%	***90.5%***	*96.3%*	*51.4%*	***83.3%***	*96.3%*
MTFR	3.525	**0.951**	0.197	3.326	**0.867**	0.129
	87.0%	***93.6%***	*97.7%*	*59.2%*	***88.9%***	*98.1%*

Table 8.3 Accumulated exceedance above WHO threshold concentration for the UK and London (Units are millions of person.µg/m^3 or Mpu)

NB The figures in red italics are the % reductions relative to 2016

		National			**London**	
Scenario	model+1 µg/m^3	**central estimate**	model-1 µg/m^3	model+1 µg/m^3	**central estimate**	model-1 µg/m^3
B 2016	45.161	**24.626**	13.327	27.007	**18.963**	11.635
BAU 2030	10.332	**4.031**	1.166	8.462	**3.274**	0.643
	77.1%	***83.6%***	*91.3%*	*68.7%*	***82.7%***	*94.5%*
Central	4.573	**1.341**	0.483	3.903	**0.902**	0.137
	89.9%	***94.6%***	*96.4%*	*85.5%*	***95.2%***	*98.8%*
High	4.36	**1.26**	0.466	3.707	**0.826**	0.123
	90.3%	***94.9%***	*96.5%*	*86.3%*	***95.6%***	*98.9%*
Central +	4.067	**1.15**	0.429	3.473	**0.749**	0.109
	91.0%	***95.3%***	*96.8%*	*87.1%*	***96.1%***	*99.1%*
MTFR	2.954	**0.767**	0.328	2.475	**0.413**	0.045
	93.5%	***96.9%***	*97.5%*	*90.8%*	***97.8%***	*99.6%*

It has been shown that London presents special problems, and that even with the MTFR scenario there is still some remaining exceedance of the WHO standard. More detailed mapping has been produced for London to illustrate this - see figure 7.1. These illustrate the improvements in population exposure in London, despite the difficulty in attaining the standard completely. Thus the improvement in London's population weighted mean concentration of 2 µg/m^3 in the BAU2030 scenario corresponds to a monetised health benefit of around £880 million per year, and the additional improvement of 0.8 µg/m^3 in the central scenario to another £350 million per year. This is without taking account of any special measures in London over and above national measures. Note that removing the irreducible natural component of PM2.5, which is very uncertain, shows that the anthropogenic contribution to concentrations in London is reduced to below 8 µg/m^3 for the MTFR scenario except for a very few grid-squares with extreme traffic (see figure 7.2).

In this report some sources have been singled out for particular attention. These include non-exhaust emissions, where revised modelling has been undertaken to represent larger emissions in urban areas due to more braking and acceleration and to add road abrasion. This has emphasized the importance of this source in city areas, with an average contribution of over 1 µg/m^3 to $PM_{2.5}$ concentrations in inner and central London. There are also likely to be local hot-spots with higher concentrations where there is heavy and congested traffic. Unfortunately measures such as the introduction of electric vehicles are not as effective at reducing these non-exhaust emissions as they are in reducing NO_x and NO_2; although there may be some benefits of regenerative braking. This, and other potential ways of reducing emissions from brakes, tyres and road abrasion, need further research.

Another source of primary $PM_{2.5}$ whose importance has been emphasized is domestic wood-burning which again contributes around 1 µg/m^3 to concentrations in London. The effect of this source on exceedance of the WHO standard has been illustrated in figures 3.5 and 3.6. This is a source specifically addressed in the Clean Air Strategy with emphasis on using dry wood that has been properly produced and stored. This is one of the measures contributing to improvements in the scenarios modelled in this report.

Another source requiring further investigation is shipping, including international shipping. In this report new modelling data from FRAME has been used with revised shipping emission data from Ricardo. These indicate a much lower imported contribution to $PM_{2.5}$ concentrations in the UK than previous estimates. But this is still substantial, with a contribution to UK population weighted mean concentration of $PM_{2.5}$ in 2016 of 0.336 µg/m^3, and little improvement (0.02 µg/m^3) by 2030 due to growth in shipping counteracting stricter controls in the ECA areas. The corresponding monetised health costs for the UK are over £1 billion per year. Also there are special problems in modelling atmospheric transport over the sea from these emissions, and reasons for which these new modelling estimates may underestimate the contribution from shipping. The role of shipping requires further investigation.

Uncertainties in the modelling also need to be recognised, including limitations of the simplified modelling of source footprints in UKIAM. In some of the scenarios modelled, the large emission reductions made involve changes in atmospheric chemistry that challenge the linear scaling of sources in UKIAM. In addition to sensitivity studies undertaken with FRAME on this topic, we recommended complementary modelling with a full chemical model to check the concentrations of secondary inorganic aerosol, SIA. This is currently being undertaken with the CMAQ model by Kings College London, and we will welcome comparison.

It is also noted that there are missing sources of primary $PM_{2.5}$ in the NAEI inventory, for example from cooking; and account will need to be taken of further improvements in the NAEI. There may be additional contributions to $PM_{2.5}$ from IVOCs but these are still a subject for research. Other uncertainties arise because the BAU emission projections depend on underlying energy, transport and agricultural projections, which are subject to change. It is also assumed that other countries will meet their NECD ceilings.

Looking beyond 2030 a brief note has been prepared for Defra on synergies with climate policy based on previous work for the Committee on Climate Change (see Appendix C). This indicated that most measures to reduce greenhouse gas emissions would be beneficial except for increased use of biomass, and also the use of emergency generators in specific periods requiring supplementary energy. There are also possible problems with new forms of fuel. Further work could explore alternative energy, transport and agricultural scenarios; and include effects of behavioural change.

References:

ApSimon H and Oxley T (2018) PM2.5 from domestic combustion and the contribution from wood- burning. SNAPS contract report to Defra February 2018

EEA (2016) Emissions Inventory Guidebook 2016: road vehicle tyre and brake wear and road surface wear.

Kings College London and NPL (March 2017) Airborne particles from wood-burning in UK cities

Oxley T,Dore A, ApSimon H, Hall J & Kryza M (2013) Modelling future impacts of air pollution using the multi-scale UK Integrated Assessment Model (UKIAM) Environment International,61, pp17-35

Oxley T, Valiantis M, Elshaki A & ApSimon H (2009) Background,Road and Urban Transport Modelling of Air quality Limit values (the BRUTAL model) Environmental Modelling and Software,24,pp1036- 1050

O'Driscoll R, ApSimon H, Oxley T, Molden N, Stettler M& Thiyagarajah A(2016) A portable emissions measurement system(PEMS) study of NOx and primary NO2 emissions from Euro 6 diesel passenger cars, and comparison with COPERT (2016) Atmospheric Environment 145, pp81-91

O'Driscoll R, Stettler M, Molden N, Oxley T& ApSimon H (2018) Real-world CO2 and NOx emissions from 145 Euro 5 and Euro 6 diesel, gasoline and hybrid passenger cars. Science of the Total Environment 621, pp282-290.

Oxley T, ApSimon H, & de Nazelle A (2015) Investigating potential health benefits of focused PM2.5 emission abatement strategies in London. Environmental modelling and software 74, pp268-283

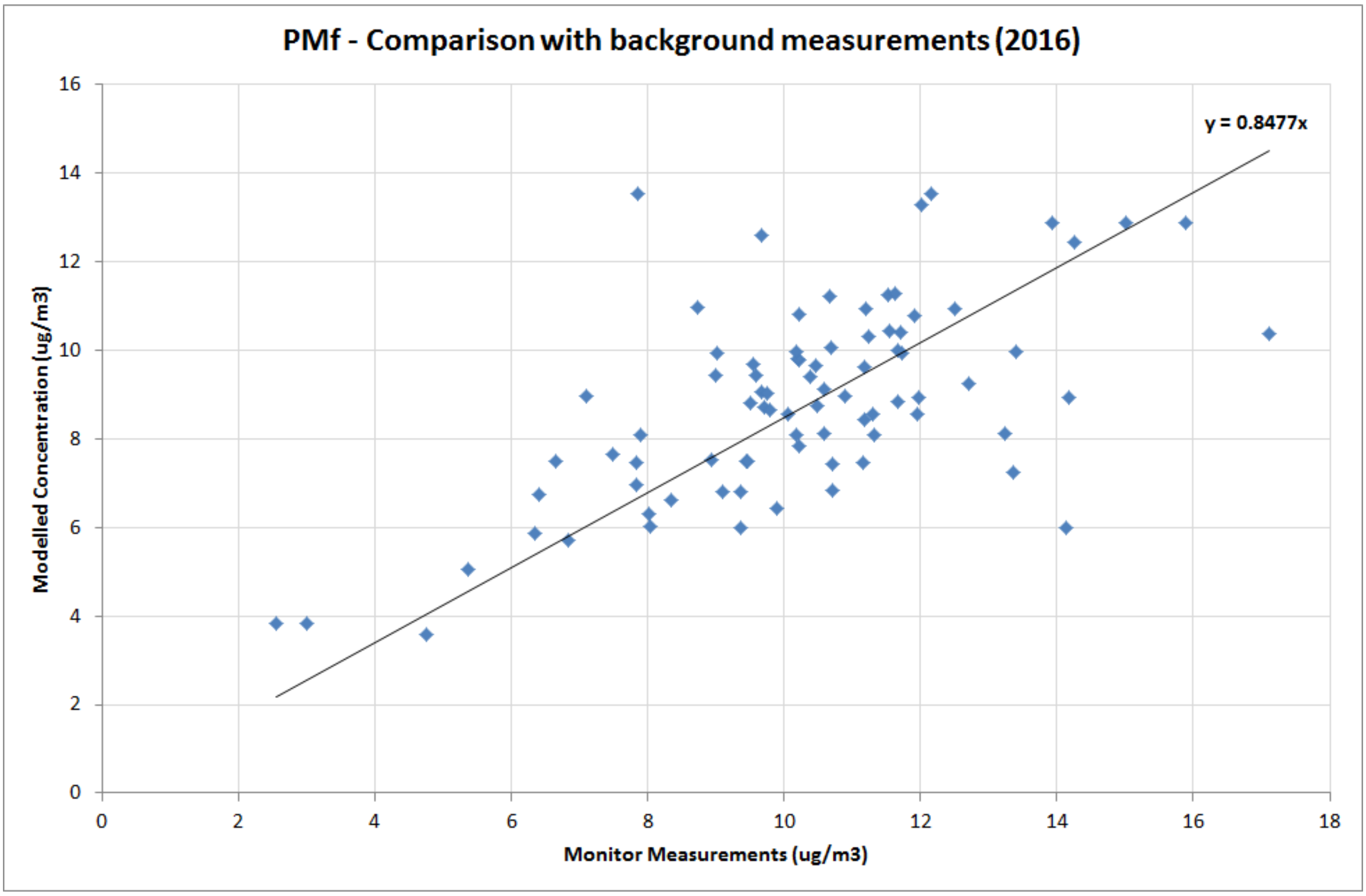
Oxley T and ApSimon H (2018) PM2.5 from domestic combustion and the contribution from wood- burning. SNAPS contract research report

Oxley T & ApSimon H, (2017) MPMD Ammonia scenarios (2015-2030). SNAPS contract research note.

Ricardo 2017. A review of the NAEI shipping emissions methodology. Report for BEIS

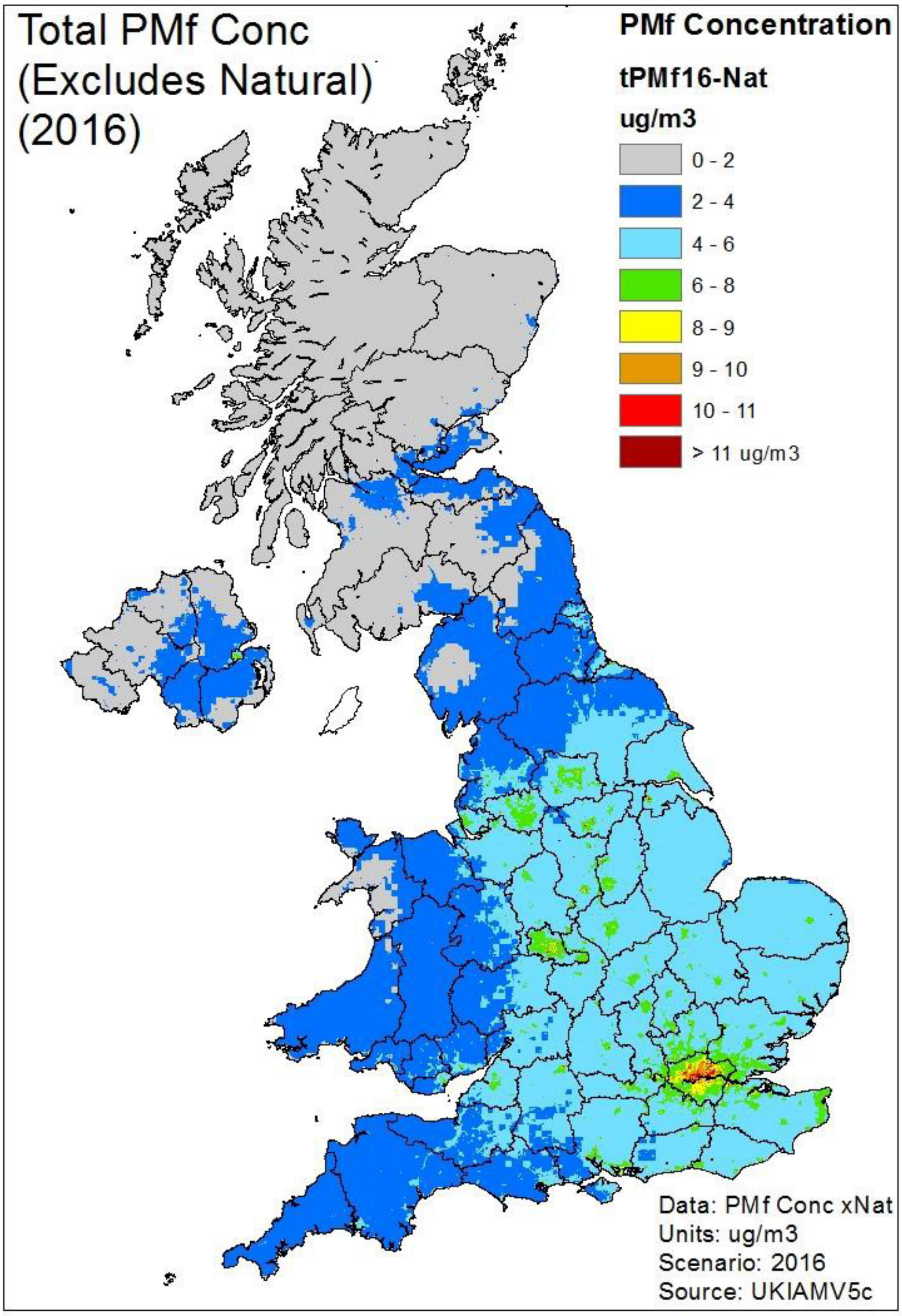
APPENDIX A: Comparison of model results and measurements

The scatter plot below gives a comparison between modelled concentrations in 2016 as plotted in figure 3.1 in the report, and measurements of $PM_{2.5}$ from the monitoring network. Some of the outliers coincide with significant differences across grid square boundaries. Overall there is a tendency to underestimate, partly driven by the highest measured values which may be affected by local sources as compared with grid-average concentrations. In making this comparison of measurements and modelling it should also be recognised that the modelling is based on annual average meterology, and there is significant interannual variability, although 2016 was not considered to be an extreme year.



APPENDIX B: Contribution of natural components

In the report some contributions to $PM_{2.5}$ were considered to be predominantly natural, and hence irreducible and independent of anthropogenic emissions and their control. The subject of what is truly a natural contribution is debatable, and there are also large uncertainties in such components as wind- blown dust, SOA, and how water content changes with the SIA concentrations. Nevertheless the natural irreducible portion makes a significant difference to total $PM_{2.5}$ concentrations. This is illustrated in the map below which corresponds to the total $PM_{2.5}$ concentrations in 2016 as shown in figure 3.1 with the natural/irreducible emissions removed.



APPENDIX C: Looking ahead beyond 2030

This appendix is a slightly extended version of a research note submitted to Defra

Looking ahead beyond 2030

Recent analysis to explore future scenarios to support development of the Clean Air Strategy has looked forward as far as the year 2030, when the UK is committed to achieving emission ceilings for SO_2, NO_x, NH_3, $PM_{2.5}$ and VOCs. These scenarios have taken as a starting point NAEI emission projections based on UK energy projections, transport projections and agricultural projections; and superimposed technical abatement measures. This note considers how the environmental improvements are expected to continue beyond 2030, in particular to reflect commitments to reduce greenhouse gas emissions up to 2050 and climate policy. Climate measures tend to complement air quality measures by changing the underlying activity levels as opposed to addressing emission factors.

Although various energy models have been used to look at future energy scenarios up to 2050, there are large uncertainties reflecting different assumptions. The 4th and 5th carbon budgets of the Committee on Climate Change, CCC, underpin government climate policy, but they also do not look ahead beyond 2030 and 2032 respectively. However, it is likely that similar measures would be used more extensively beyond 2030. In 2013 a study was undertaken for the CCC to investigate the air quality benefits of measures to reduce GHG emissions in the 4th carbon budget based on UKIAM, and published as an appendix to the CCC report (ApSimon and Oxley, 2013:Analysis of the air quality impacts of potential CCC scenarios). This compared three energy scenarios-a business as usual, BAU,scenario; a “dash for gas” scenario, and a “with measures”scenario aimed at reducing greenhouse gas emissions. It was clear that the greatest air quality benefits overall came from the “with measures” scenario. Below we summarise the individual measures in this energy scenario for each sector. The report showed that almost all measures were beneficial in reducing emissions of air quality pollutants except for increased domestic use of biomass.

Table of energy measures to reduce GHG emissions in CCC scenarios

Measures	Comments
Power sector: Phase out coal unless with CCS Increase use of biomass Reduce use of gas CCGT,except with CCS Energy efficiency measures including for electricity demand in other sectors Increased energy from renewables and nuclear	Total electricity needed reflects measures in other sectors- e.g. more electric cars Latest IPCC reports indicate that to reach a stricter target of 1.5 degrees increase in temperature, such measures as biomass+CCS will be required to give net negative emissions of CO2 It was noted that some post combustion capture amine CCS plant may potentially give emissions of NH3, but this can be avoided with more recent chemical processes. Similarly generating more biomass might require increased fertiliser applications with NH3 emissions- e.g as at present with surface slurry applications for some maize biomass crops, and use of NRMM for harvesting plus transport. Assumed that emissions from biomass combustion in power plants strictly

Measures	Comments
Heat generation: Fossil fuel use reduced by heat pumps and solar energy **Increased use of biomass** Biogas	These 2 measures had large opposing impacts with the first being beneficial for AQ but the increased use of biomass with potential adverse effects- as has arisen with domestic wood stoves and PM2.5 emissions. This stood out as the worst CCC measure for air quality

Transport measures Electric cars and vans Hydrogen buses HGV logistics to reduce mileage Smart choices to reduce car use	These measures were all beneficial for AQ with smart choices (behavioural change) giving the most benefit. But the assumed electrification of the fleet was far more modest (<10% switch from petrol/diesel by2030) than the Roads to Zero measures which have a substantial effect on NOx but do not reduce non-exhaust PM. NB No focus on improved efficiency of engines, and compliance with CO2 emission legislation: or transfer from road to rail for freight etc. Overall modest reductions in NOx and PM.
Efficiency measures for residential, industrial and non-residential energy use	The corresponding savings in fossil fuel use were less than half of those for the heat sector, with the biggest saving from reduced domestic use of gas NB There can be conflicts between energy efficient buildings and indoor air quality. These were not considered in the CCC report, but recent work has shown there is potential for optimisation of air intake to improve indoor AQ relative to outdoor, and hence reduce exposure to pollution. Such measures could be low cost and effective but have not yet been considered by Defra.

The agricultural sector and dietary change

The second part of the report for the CCC looked at some hypothetical agricultural scenarios reducing animal products and human diets with corresponding reductions in GHG emissions of CH4 and N2O. These scenarios had been developed by Cranfield with accompanying changes in plant products to maintain protein and calorific balances, and were as follows:

1) A 50% reduction in animal products involving a 40% reduction in consumption of dairy products and eggs, and a 64% reduction in meat consumption
2) A switch from red to white meat consumption involving a 75% reduction in beef and lamb, and a 45% increase in pig and poultry meat
3) A 50% reduction in white meat (pig and poultry)

Scenario 1 had the greatest effect on NH3 emissions with a reduction of 100kt, as compared with a far more modest reduction of ~20kt for scenario 3. As might be expected scenario 1 made a significant difference both to ecosystem protection and reduction of secondary PM. (These scenarios could be remodelled with updated modelling of the agricultural sector).

Energy storage and alternative fuels

Although biofuels were included in the CCC scenarios, there are also other possible alternative fuels to reduce GHG emissions which were not considered. Thus using excess wind or solar energy to produce hydrogen is effectively a way of storing energy for later use. Whereas hydrogen is not a problem for air quality, alternative production of ammonia, NH3, does raise potential problems. The NH3 can be liquefied, and used for example by ships towards meeting the IMO objective of halving GHG emissions from shipping by 2050. This would involve more extensive use of the Haber Bosch process (or equivalent) to convert atmospheric nitrogen gas to NH3, contributing to increases in the amount of reactive nitrogen and changes in the N cycle. The NH3 produced would generate NOx emissions or NH3 slip according to the way the NH3 was used and controlled, potentially leading to adverse effects on air quality.

Intermittency and generation capacity

Another consideration is the intermittency issue, whereby additional energy generation capacity is required for short periods when renewable energy output is reduced and energy demand can not be met. An example of this was the Capacity Markets study (ApSimon and Oxley,2016) where we showed the potential problems of diesel generators under this scheme. The main concern here was NOx, but there is also the potential for PM2.5 emissions from emergency diesel generators, especially if inappropriately located. This has been a concern raised by local authorities.

Discussion and suggestions

Above we have used work for the CCC to review likely climate policy measures and their effect on AQ emissions and impacts, picking up the domestic biomass issue as the potentially adverse measure. There could also be co-benefits from agricultural measures. This is consistent with other studies indicating the co-benefits of climate policies and air quality (e.g. ApSimon H et al 2009; Williams M et al 2018).

A possible way forward is to develop some scenarios for analysis with UKIAM which combine changes in activity levels and behavioural change with those involving technical abatement measures as in the MPMD. An interesting trial study could be to simulate the agricultural scenarios outlined above to explore the potential effects of dietary change.

References:

ApSimon H and Oxley T 2013. Analysis of the air quality impacts of potential CCC scenarios.Published on the CCC web-site: https://www.theccc.org.uk/publication/analysis-of-the-air-quality-impacts-of-potential-ccc-scenarios-by-imperial/

ApSimon H and Oxley T 2016 Capacity markets modelling: diesel generators study. Report for Defra under SNAPS contract.

ApSimon H, Amann M, Astrom T, Oxley T 2009. Synergies in addressing air quality and climate change. Climate Policy 2009, p 669-680