Department for Environment Food & Rural Affairs

Air quality $PM_{2.5}$ targets

Detailed evidence report

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We would like to thank the following organisations who played key roles in either undertaking, supporting, steering or developing the evidence to inform $PM_{2.5}$ target setting under the Environment Act 2021.

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Statement of interests

Conflicts of Interest

All conflicts of interest were identified either through existing terms of reference for expert groups or through contractual arrangements. Where individuals or organisations took part in workshops or provided expert views, these are made clear in the appropriate output documentation.

Statement of transparency for statistical robustness

The evidence considered as part of the target setting process has been commissioned through internationally renowned modelling experts and sector leads/experts. AQEG and COMEAP, whilst not providing a formal steering group, were utilised as key expert groups to provide oversight and views on the existing evidence but also to guide much of the work that was undertaken. Discussions were held with these expert groups throughout the target evidence development and at key points in the evidence process. Relevant advice and guidance notes are published alongside this report and referenced herein.

As standard within government evidence development, this work has been reviewed by heads of profession and other government departments at key points in the process.

Changing status of evidence

This evidence has been developed over a two-to-three-year period and it is recognised that the evidence base is constantly evolving. Our regular engagement with AQEG and COMEAP has in part enabled this work to be mindful of the latest evidence and to enable some degree of future proofing outcomes. However, it is recognised that this work represents the analysis that could be undertaken with available resources and time, and that future work will be required in order to reflect emerging evidence over time. The Environmental Target Framework within the Environment Act 2021 sets out how targets will be evaluated and assessed as well as how they may evolve in the face of changing evidence.

Executive summary

This evidence report is designed to inform the public consultation[1] launched in March 2022 on the suite of environmental targets developed for England under the Environment Act 2021 (1) and relates to evidence regarding air quality targets. It should be read alongside the consultation document and air quality target impact assessment, which are published as separate documents on the consultation webpage. It provides a summary of the evidence used to develop the air quality targets as well as proposals for how the targets will be set. Other evidence reports are available for the targets related to other policy areas. This document enables respondents to the consultation to see the evidence underpinning the targets and consider this information in their response.

The report summarises: the results of new research and analysis commissioned specifically to inform the development of the new air quality targets; the independent expert advice received; and views from the stakeholders engaged as part of the target development process.

Target development process

The development of the new environmental targets under the Environment Act 2021 is a two-to-three-year process involving the following steps or stages: (1) establishing the targets' scope, (2) gathering evidence and carrying out analysis to inform the targets, (3) public consultation and (4) drafting the necessary legislation to put the targets into law. The first two of these steps are summarised in this report. Following step three, the public consultation, the targets will be refined in the light of the responses received and legislation drafted to be put before parliament by 31st October 2022 in line with the timelines set out in the Environment Act 2021.

Throughout the development of the target evidence base independent expert groups have provided advice and recommendations. Each target policy area has one or more expert groups consisting of specialists in relevant fields of work. In the case of air quality, the already established Air Quality Expert Group (AQEG) and Committee on the Medical Effects of Air Pollutants (COMEAP) provided advice on air quality modelling and monitoring, and the health impacts of air pollutants. This was in the form of written notes, discussions during regular meetings and bespoke workshops. Other experts also contributed through workshops, a call for evidence and bilateral discussions with officials.

The Environment Act targets were developed as a suite of targets, and the independencies between targets and other policy goals, such as reducing greenhouse gas emissions, were considered. The targets are part of wider environmental policy development and action and are not the only avenue open to instigate environmental improvement. They cannot be considered in isolation but are part of an overall environmental strategy as outlined in 'A Green Future: Our 25 Year Plan to Improve the

[1] https://consult.defra.gov.uk/natural-environment-policy/consultation-on-environmental-targets/

Environment' (2). This sets out Defra plans to improve the environment, within a generation and will be carried forward in future Environmental Improvement Plans (EIPs).

Proposed target scope and metrics

The air quality targets are focused on reducing concentrations of fine particulate matter ($PM_{2.5}$) as this is the air pollutant which causes the most harm to human health. The existing air quality standards for other air pollutants will remain and will not be substantively affected by the new targets. The targets relate to ambient concentrations in air as a surrogate of average population exposure. There are many factors that contribute to personal exposure such as the amount of time spent indoors, or within different environments, employment type and modes of transport used. Ambient concentrations do not account for all exposure, however they are shown to relate strongly to the health impacts across the general population and are therefore a key metric of harm and reducing ambient levels is a key factor in reducing population wide exposure.

Whilst it is likely that some components of $PM_{2.5}$ are more damaging than others, the expert advice has been that total $PM_{2.5}$ mass remains an effective indicator of health damage. $PM_{2.5}$ mass is generally more practical to measure routinely than its subcomponents. Therefore, $PM_{2.5}$ mass will be the basis of these targets. Defra will continue to review the scientific research in this area, and it may be that in the future, understanding of the health impact and measurement technology has advanced sufficiently to consider setting targets for $PM_{2.5}$ components.

The targets will be focused on long-term exposure with respect to ambient levels of $PM_{2.5}$ as it is the accumulative effect over many years which causes the most damage for the majority of people. Ambient concentrations are used here as a surrogate of true exposure. Exposure to short-term peaks remains important for susceptible people, but as the two are interconnected, action to reduce long-term exposure will also reduce short-term peaks. The Government’s response to the coroner’s Prevention of Future Deaths Report following the inquest into the death of Ella Adoo-Kissi-Debrah (3) outlined the immediate action that will be taken to improve public awareness about air pollution such as the commitment to undertake a comprehensive review of existing sources of information provided to the public. This will enable steps to be taken to mitigate and manage the impacts of short term and long-term exposure.

As proposed in the target policy paper published in August 2020 there will be two $PM_{2.5}$ targets; the annual mean concentration target (AMCT) which sets a maximum concentration to be reached by a future year, and a population exposure reduction target (PERT) which sets a reduction in average population exposure to be obtained by a future year compared to a base year. The two targets will work in tandem to drive action across the country, whilst ensuring improvements in the areas with the highest concentrations for which there is wide-spread support from experts and stakeholders.

Proposed target assessment approach

Targets will be assessed through long-term fixed monitoring, although modelling will still provide supporting information and indicators of progress. The current uncertainties that are associated with modelling a complex pollutant such as $PM_{2.5}$ meant that basing assessment on monitoring was a clear recommendation of experts. The existing national air quality monitoring network (the Automatic Urban and Rural Network - AURN) which (as of 1 January 2022) includes 63 $PM_{2.5}$ monitoring sites in England, will be used for assessment purposes.

The AMCT will be assessed using the concentrations measured at all individual sites operational in a calendar year. The target will be met if all sites are equal to or below the AMCT level by the set date. If any site exceeds the target by the set date, an assessment will be made of the concentrations recorded at each monitoring site over the previous four years. The target will be met if all monitoring sites did not exceed in three out of the previous four years. This is to account for transient events that may affect the assessment year, so that it does not represent the true trend.

The metric to inform the PERT will be calculated from the average of measurements made at monitoring sites across England that considered to be in locations representative of typical concentrations across a region. This is likely to comprise ‘urban background’ sites, which tend to align with population density, or ‘suburban’ sites, where that is more appropriate. The metric for the PERT will be based on a three-year average to reduce the impact of weather conditions in any particular year and ensure the target focuses on the underlying trend. The PERT will be met if the change in the measure of average concentration across the country (i.e., the population exposure reduction metric as measured by monitoring) between the target year and the base year, is greater than or equal to the target percentage reduction.

Existing requirements for monitoring equipment, site location and data capture will be retained to provide a consistent approach to evaluating trends over time. Some aspects of how instruments are calibrated and have their performance assessed will need to evolve over the coming years, to align with more challenging requirements to measure $PM_{2.5}$ at or around the new (lower) target concentrations. We also plan to expand the $PM_{2.5}$ monitoring network over the next three years to support the assessment and delivery of the new targets.

Proposed target level and date

The Environment Act 2021 requires that the Secretary of State is satisfied that the targets are achievable. Modelling and analysis was carried out to better understand what $PM_{2.5}$ concentrations are achievable by when, and the scale of action needed to achieve them.

Scenarios with different levels of emission reductions were modelled to ascertain what future $PM_{2.5}$ concentrations might be achieved under different scenarios. The scenarios represent possible future changes, not government policy or a prescribed pathway to target delivery. Air quality modelling based on these emissions was used to assess future $PM_{2.5}$ concentrations and ascertain what target levels could be reached at different points in time. The lowest target values can only be obtained under a ‘speculative’ scenario which includes large scale behaviour change and implementation of technology not yet available. The ‘medium’ and ‘high’ scenarios are more achievable, but depend on additional policy. The ‘baseline’ scenario illustrates the progress that is likely to be made through policies that are already committed to.

Influences on $PM_{2.5}$ concentrations such as weather conditions, variation in estimates of emissions from key sectors (such as domestic combustion) and modelling uncertainty were evaluated as part of the assessment. For example, modelled annual mean concentrations can vary by more than 1 µg m^{-3} under the same emission scenario for different weather conditions. These variations were taken into account when evaluating which targets are achievable.

Impact of proposed targets

The target ambition level set will have implications in terms of health benefits of achieving the target, but also in the cost of delivery and the scale of changes both businesses and individuals will need to make.

Some of the measures included in the scenarios are also necessary to meet the UK’s net zero greenhouse gas emission commitment, but others are additional, and are specifically to address $PM_{2.5}$. For example, although electric vehicles produce no tailpipe emissions, they still emit $PM_{2.5}$ from brakes and tyres, so new technology (not currently commercially available) is needed to reduce emissions from that source. Another key source of $PM_{2.5}$ is domestic combustion of solid fuel. Some level of reduction in emissions from road transport and domestic combustion are assumed in all the scenarios, meaning that progress in these sectors is central to meeting the wider targets. Further technological advancement in the abatement of emissions will determine the degree to which it is likely that some level of reduction in activity will be required particularly with regards to road traffic and domestic wood burning in large urban areas. The scenarios include a range of technological advancements, but in some sectors, the degree to which they can reduce emissions in future years is significantly uncertain. The scale of emissions reduction needed, and by extension the assumptions around new technology and subsequent need for restrictions or changes in behaviour, depends on the scenario. Action to reduce further emissions from road transport and solid fuel burning, along with other measures contained in the scenarios, could have a large impact on people’s lives, and may require financial investment by individuals, business, and government. The magnitude of $PM_{2.5}$ reduction and how quickly it is carried out will determine the scale of intervention required, as well as the costs of implementation and the health benefits forthcoming.

In addition to overall health benefits, the scenarios evaluated showed large improvements in health disparities. Currently the highest $PM_{2.5}$ concentrations are often found in the areas of higher deprivation. Under all scenarios the difference in the $PM_{2.5}$ concentrations that the most and least deprived areas are exposed to decreases. There are also other co-benefits of implementing the scenarios, such as reducing the harm air pollution exerts on biodiversity.

The health and other benefits have been monetised and compared to the cost of implementing the measures contained in the scenarios. This showed a net benefit in implementing measures that were similar to those included in the medium and high scenarios, but there needs to be a recognition that there is a high initial cost.

Proposed targets and rationale

Annual Mean Concentration target – 10 µg m^{-3} to be achieved by 2040

Population Exposure Reduction Target – 35% reduction by 2040

After considering all the evidence government proposes that the AMCT is set at a level of 10 µg m^{-3} and the PERT is a 35% reduction in the population exposure metric compared to a 2018 baseline, and both to be met by 2040. Five-yearly interim targets will be set to ensure suitable progress is made towards the targets over the coming years. The first interim targets and a pathway to meet these will be published in January 2023 in the Environmental Improvement Plan. The proposed targets best reflect the evidence and provide an appropriate balance between health benefits and restrictions on society. Going further or faster with respect to the target levels or dates would require much greater restrictions on society and increased costs, for an increasingly smaller benefit. A range of measures across different sectors will be needed in order to reach the targets and this will take time to implement, and each will require suitable engagement and consultation. Whilst challenging, the evidence demonstrates that with sufficient action the proposed targets are achievable.

In 2018 the average population exposure was 10 µg m^{-3} and the highest measured value was 16 µg m^{-3}. The proposed targets therefore represent a large improvement from current concentrations, with significant health benefits. A reduction in population exposure of 35% is equivalent to 214,000 fewer cases of cardiovascular disease, 56,570 fewer strokes, 70,000 fewer cases of asthma and 23,000 fewer cases of lung cancer over eighteen years (based on modelled impact data). The average gap between the lowest and highest deprivation will be halved.

Introduction

Purpose of this report

This Evidence report is aimed at anyone who is interested in the evidence that has been commissioned and used to inform the $PM_{2.5}$ targets set through the Environment Act 2021 (1).

It is complementary to the main consultation document, through which views are sought on the proposed targets, and the Impact Assessment which summarises the key economic analysis that has been undertaken. These can be found on the consultation webpage, along with a short summary of the evidence described in this report[2].

The purpose of this report is to draw together in one place, the process that has been followed to inform the setting of new $PM_{2.5}$ targets through the Environment Act 2021 and to detail how expert advice, evidence and analysis has been commissioned and used to inform key decisions regarding the setting of targets that we are now consulting on.

This report draws on a wide range of material; including recommendations through regular engagement with expert groups, advice and recommendations from technical target workshops, learning from workshops and interviews with sector specialists, key findings from a call for evidence, and on modelling assessments specifically commissioned for this purpose. It highlights where stakeholders and expert's views have informed the targets as well as how the evidence has been reviewed and quality assured.

The Environment Act 2021

The Environment Act 2021 sets a new domestic framework for environmental governance and includes commitments to secure improvement on air quality, biodiversity, water and resource efficiency. An important aspect of this Environment Act is the power to set long-term, legally binding environmental targets in England. Setting targets will provide a strong mechanism to deliver long-term environmental outcomes. This will build upon progress towards achieving the long-term vision of the 25 Year Environment Plan and help tackle some of the serious challenges that remain. Environment Act targets will help stimulate investments in green technology and innovative practices by providing long term certainty for business. They will help business to plan ahead, including how they rebuild from the Covid-19 crisis.

With respect to air quality, the Act delivers on key commitments first set out in the Clean Air Strategy 2019 (4) (CAS) – including the commitment to set new air quality targets to reduce the impact of exposure to fine particulate matter - $PM_{2.5}$ the pollutant that has the most significant impacts on public health. These targets are set for the purpose of meeting the requirements of the Environment Act 2021 and are not to be confused with "target values" that have a very specific meaning as defined within the Air Quality Standards

[2] https://consult.defra.gov.uk/natural-environment-policy/consultation-on-environmental-targets/

Regulations 2010 (5). Common to both AQSR and these targets are the setting of a standard to be achieved (a concentration recorded over a given time period), a level of compliance or exceedance that is allowable (if any) and a target date by which that standard must be achieved (objective).

$PM_{2.5}$ is not a single chemical, but any substance in the air which is not a gas and is less than 2.5 µm in size. It can be emitted directly (referred to as primary $PM_{2.5}$) or produced when other constituents (precursors) react in the atmosphere (to form secondary $PM_{2.5}$). Some $PM_{2.5}$ occurs naturally from sea salt, soil, pollen etc., but human activities such as combustion and abrasion greatly increase the amount of $PM_{2.5}$ in the air. There is strong evidence that exposure to $PM_{2.5}$ has a wide range of health impacts, and long-term exposure has been linked to respiratory and cardiovascular disease, cancer and dementia. Although it is not possible to eliminate $PM_{2.5}$ entirely, efforts to reduce concentrations and reduce the impact on health will be beneficial to health. Average annual mean concentrations have reduced since 2010 by 24% at urban background locations and by 30% at roadside monitoring stations (excluding 2020 and 2021 which were affected by the covid-19 pandemic) (6), however there is more to do.

The Environment Act 2021 aims to drive further reductions by establishing a duty to set a target specifically on $PM_{2.5}$ concentration, alongside a further long-term target for air quality. Long-term targets set through the Act will be supported by interim targets, which will set a five-year trajectory towards meeting the long-term targets. Whilst interim targets are not legally binding, they set a clear direction of travel and will enable an ongoing assessment of whether the government is on track to meet its longer-term target ambitions. The long-term targets need to be brought before parliament by 31 October 2022.

Context

The Clean Air Strategy 2019 (4) outlined a range of action that is needed to improve air quality. Much of this action is already underway – such as legislation to limit the use of wet wood and domestic coal to reduce emissions from domestic combustion. As we continue to deliver the Clean Air Strategy, these proposed targets will be a key tool in reducing $PM_{2.5}$. They will act alongside the emissions targets (7) that the UK are already committed to, as well as existing Air Quality Standards (AQSR 2010) enabling the delivery of significant public health benefits across the country. These targets will be set at national level and as air quality is a devolved area, apply to England only. There will be a role for Local Authorities to support meeting the targets and whilst this role will be fully explored through the Air Quality Strategy review during 2022, it is discussed in more detail later in this report.

The “Environment Bill - Environmental Targets Policy Paper” published in August 2020 (8) (hereafter referred to as the “Environmental Targets Policy Paper”) detailed the key principles and process for target setting. The paper outlined proposals for the long-term air quality target focussing on reducing population exposure to $PM_{2.5}$, which will act in tandem with the $PM_{2.5}$ annual mean concentration target (AMCT) specified in the Act. The AMCT will provide a maximum concentration limit, focusing attention on reducing concentrations where they are highest, whilst the population exposure reduction target (PERT) will drive continuous improvement across the country, providing a key driver to deliver public health benefit.

A dual target approach is important for tackling a “non-threshold” pollutant such as $PM_{2.5}$. It assures a balanced approach, drives action in locations that meet the concentration target and avoids disproportionate focus on hotspot locations. This means actions to reduce $PM_{2.5}$ can be more readily linked to public health benefit. Stakeholder engagement and discussions with the expert groups before and after the publication of the Environmental Targets Policy Paper established that there was strong support for both targets and this dual target approach to reducing $PM_{2.5}$ health harm.

Through the process of setting new air quality targets there has been significant interest from experts, stakeholders, parliamentarians, and the public. Much of this interest has been supportive of the commitment to act on $PM_{2.5}$ and more specifically to focus both on lowering the levels where the concentrations are currently highest – bringing equity and ensuring no one is exposed to excessive levels, as well as developing a target specifically on reducing population exposure - to deliver the most effective health benefit across the country.

While the targets have been under development there have been calls, parliamentary debates and amendments put forward to the Environment Act as it progressed through parliament, regarding the role of World Health Organization (WHO) air quality guidelines (2005) and proposals to align the concentration target to those guidelines. WHO air quality guidelines consider the weight of evidence regarding the impacts of air pollution on health and provide guidelines for consideration when setting targets to minimise such impacts. The WHO guidelines for $PM_{2.5}$ are based on concentrations at which health effects have been seen to occur, but these do not consider the feasibility or costs of achieving such concentrations, critical factors when setting targets. Assessment of feasibility and cost is a major focus of this report.

During this evidence gathering, the WHO updated its air quality guidelines, lowering the recommendation for the $PM_{2.5}$ annual mean concentration guideline from 10 µg m^{-3} to 5 µg m^{-3} (alongside changes to guidelines for a range of other pollutants) (9). The changes to guidelines for $PM_{2.5}$ further highlight the importance of air quality and demonstrates that there is evidence of health impacts at levels significantly lower than the existing legally binding limit value of 20 µg m^{-3} within the Air Quality Standards Regulations 2010. In addition, it emphasises that there is no evidence of a safe level that can be set to provide full protection from exposure to $PM_{2.5}$. $PM_{2.5}$ cannot be completely eliminated in the way that some pollutants may have been in the past, as it is formed from a whole range of human and natural sources. It is therefore important to focus on continuous improvement through the setting of a population exposure target to drive action and maximise health benefits, even if levels are below a legal concentration limit.

The Environment Act 2021 states that the Secretary of State must be satisfied that the targets are achievable, and that the actions taken to deliver them are proportionate. As the Clean Air Strategy 2019 highlighted, reducing $PM_{2.5}$ will require action from all aspects of society. Detailed policies to achieve the targets are not proposed at this stage but it is important for the public to understand the scale of interventions and the changes to everyday lives that will be required to achieve the proposed targets, and for views to be expressed through the consultation process. This report outlines what the evidence shows is likely to be possible in future years in terms of reducing concentrations of $PM_{2.5}$ and the scale of interventions that will be required. It also describes the evidence behind decisions on how the target metrics will be defined and measured. The separate Impact Assessment[3] lays out the details of the potential benefits and costs of implementing measures to meet the target, but the evidence behind the assessment approach taken is summarised herein. The evidence in this report informs both the AMCT and the PERT.

Target development process and timetable

The Environmental Targets Policy Paper identified four steps to enable the systematic development of evidence and meet the criteria and principles set out in the Environment Act in order to develop strong and meaningful targets. Input from experts, stakeholders, the public and Parliament has and will continue to play an important role in making sure we have robust targets that drive positive environmental outcomes. The policy paper outlined the key criteria for setting targets, such as long-term targets having a minimum duration of 15 years; they must have a clearly defined level or quality standard to be achieved, which can be objectively measured; they must identify a specific date for achieving each target; they should be ambitious but achievable; and that independent expert advice must be sought by government to inform the development of targets.

Similarly the Environmental Targets Policy Paper (8) outlines key principles that were established, such as the targets should help to meet the key goals and outcomes set out in the 25 Year Environment Plan (2) (or in future Environmental Improvement Plans) as well as wider government environmental policy ambitions; where possible, targets should be based on environmental outcomes; a system-based approach to the natural environment should be taken, as far as possible, so that we consider the targets collectively and understand their interdependencies with the wider environment; when we are developing targets, we will consider how they will contribute to meeting the significant improvement test, as set out in section 7(3) of the Environment Act 2021; and when developing targets, we will consider any relevant international best practice and commitments.

The steps are:

Step 1: Setting the scope of the targets

Step 1 provided the overall direction and focus for target setting. Part B of the Environmental Targets Policy Paper provides an overview of the government's proposed scope for targets. This is the starting point from which specific targets will be developed by government to meet the criteria and principles (as referenced above).

Step 2: Developing fully evidenced targets

Step 2 focused on developing the detail of the targets, for example an achievable level of improvement to the environment, over a given time period and how this will be measured. It involved detailed analysis of scientific evidence. Government and its statutory advisors

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[3] https://consult.defra.gov.uk/natural-environment-policy/consultation-on-environmental-targets/

(such as Environment Agency, Natural England and the Joint Nature Conservation Committee), as well as other evidence partners, provided evidence to inform target proposals.

During this step, the potential measures have been identified that could drive action and help achieve environmental outcomes. Socio-economic analysis will assess the costs, benefits and distributional impacts of any such measures on businesses and wider society. These considerations will help ensure that proposed targets are achievable and affordable whilst still driving the ambitious changes we need to the environment.

The principles in developing targets outlined in the Environmental Targets Policy Paper guided target development so that they are robust and meaningful, and supported wider environmental aims across government, such as reaching the net zero greenhouse gas budget target by 2050.

Target development was supported and scrutinised by independent experts. This included assessment of the evidence and scrutiny of Defra’s analysis on the deliverability and impacts of proposed targets. Experts were asked to publish their views at appropriate points during this step of the target development process and these publications are linked throughout this document.

By the end of this step we will have developed objectively measurable metrics as well as proposals for target standards, dates to be achieved and first interim milestones for targets (see essential criteria and principles in the section above).

Step 3: Public consultation on target proposals

Alongside iterative engagement with key umbrella organisations throughout the target setting process, and any wider engagement (such as through digital tools), we will consult stakeholders and ask for written responses on the proposed targets within each priority area. This will provide an opportunity to hear a range of views on the ambition, evidence and achievability of target proposals. An impact assessment will accompany the consultation and consider the environmental and socio-economic considerations associated with each target. This step will provide time for written contributions to be made.

Step 4: Drafting target legislation

Once the government has collated responses from the public consultation, responses will be considered and summarised in a published government response. Government will then decide the targets to be set. Statutory Instruments setting out the targets will be laid before Parliament and published in draft by 31 October 2022 and will come into force once approved by Parliament.

This report is part of Step 3 - the public consultation and describes the results of Steps 1 (scoping) and 2 (evidence development). Step 4: drafting of target legislation, will follow once the public consultation responses have been reviewed and considered.

The air quality target setting process has drawn on the expert input of a wide range of organisations to ensure that the best evidence was available; these included the Air

Quality Expert Group (AQEG)[4] and the Committee on the Medical Effects of Air Pollutants (COMEAP)[5] as well as experts in air quality modelling from Imperial College London and UK Centre for Ecology and Hydrology (UKCEH) and leading air quality consultants and academics. We also drew on the wider expertise of air quality community through a call for evidence to inform the expert advice to Defra. Defra have worked closely with the Environment Agency, particularly on key aspects such as the evolution of the monitoring regime, and this work is ongoing. We are working closely with the other policy teams setting targets under the Environment Act Targets Framework to ensure that the targets are coherent, and systems interactions are considered throughout.

Following consultation, the evidence will inform the development of the statutory instrument to set into legislation the target levels, dates and define the appropriate detail around the assessment programme.

Overall approach

Over the past two to three years Defra has been working with world renowned experts in air quality modelling, monitoring and health to:

- Define the target metrics and determine how they will be measured and calculated
- Understand what target values are achievable by when and what drives changes in $PM_{2.5}$ concentrations
- Quantify health benefits, economic cost and effects on exposure disparities.

Setting targets for $PM_{2.5}$ is a complex challenge as $PM_{2.5}$ is emitted from many sources, both manmade and natural, as well as being formed in the atmosphere from emissions of other pollutants. It is also a transboundary pollutant impacting areas large distances away from where it was released. This means a significant proportion of $PM_{2.5}$ in England (particularly Southern and Eastern England) originates from outside of the UK (AQEG estimated that historically it has been in the region of 21-30%). More information on $PM_{2.5}$ can be found in AQEG's *Fine Particulate Matter in the UK* report (10) and its report *Mitigation of United Kingdom $PM_{2.5}$ Concentrations* (11).

Air quality modelling has been used to predict how $PM_{2.5}$ concentrations may change in future years in response to both our best estimate of future conditions and emissions, as well as in response to additional measures and actions that can be taken to meet future targets. However, the complexity of $PM_{2.5}$ as a pollutant means that there are a great many uncertainties with predicting its concentration in future years. Key uncertainties include secondary formation in the atmosphere, the complexity of emissions sources and activities, the role of meteorology and transboundary pollution and the impact climate change may have on future attainment.

Air quality modelling provides a means to estimate how our best understanding of current emissions, sources and chemistry of $PM_{2.5}$ (including gases that form secondary $PM_{2.5}$)

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[4] https://uk-air.defra.gov.uk/research/aqeg/

[5] https://www.gov.uk/government/groups/committee-on-the-medical-effects-of-air-pollutants-comeap

result in the concentrations we have experienced in previous years. Such predictions can be compared to observations from monitoring that have taken place at specific locations and can provide a guide to concentrations where observations were not made.

When estimating how concentrations may change in future years, adjustments are made to the emissions inputs to replicate the future, based on our best estimate of the baseline and the effect of applying a range of additional measures to that. In predicting impacts the modelling must consider the dates that measures could viably be implemented, the degree to which they will be taken up and the degree to which they will impact emissions, either by affecting activity levels or the rate of emissions from those activities. Future policy direction across a range of areas will also affect air pollution in future years and these need to be accounted for but are also a source of significant uncertainty - such as policies to meet net zero.

Models will always be uncertain but can help provide information about how concentrations may respond to specific interventions and how, taken as a whole, concentrations could change under particular scenarios. Uncertainty must be considered when interpreting the data and some assessment of uncertainty through sensitivity analyses has been undertaken to support this analysis.

Whilst this work outlines the range and scale of interventions that may be required to reach different target levels by different target dates, it is not the intention at this stage to outline detailed policy pathways or action plans for delivering the targets. No work was carried out on developing individual policies beyond those already in train e.g., recent legislation restricting sales of domestic coal and wet wood, and many of the measures or interventions considered in the illustrative future scenarios for modelling purposes are not current government policy. It is important that differing levels of interventions were explored to assess the future achievability of target levels but to also understand what it would require in terms of the interventions or restrictions on our everyday lives to reach different target levels, before these targets are set.

Target scope

By setting targets aimed at reducing $PM_{2.5}$ concentrations we are focussing on the pollutant of most harm to human health. Whilst there is recognition that exposure to $PM_{2.5}$ is complex, these targets focus on concentrations in ambient air, so do not consider air pollution inside buildings or in very specific work-place environments or related to particular transport modes, for example. In part, this is because wider legislation is in place to account for work-place exposure but is also because the evidence shows that there is a strong association between health impacts and outdoor ambient concentrations. Whilst more wide-ranging targets may be desirable in the longer term, the evidence regarding ambient exposure demands that action is taken now, rather than risk making commitments that are not deliverable either due to the complexity of evidence or due to significant evidence gaps.

These targets build on existing ambient air quality legislation such as the Air Quality Standards Regulations 2010 (AQSR 2010) (5), in considering ambient concentrations at publicly accessible outdoor locations that are representative of general population exposure.

Whilst there is recognition of the associations between different size fractions, properties, and constituent chemical components of particulate matter, as well as the nature of secondary particulate matter, all evidence gathering relates primarily to total $PM_{2.5}$ mass. Associated pollutants or other definitions of particulate matter including PM_{10}, ultrafine particulates, particle number or constituents of $PM_{2.5}$ such as black carbon are not specifically considered but are referenced in various locations through this work. The current emphasis on $PM_{2.5}$ mass follows strong advice and guidance from expert groups including the AQEG who advised on monitoring, modelling and air quality science, and COMEAP who provided clear health advice through the process. The focus of the evidence gathering was primarily on understanding what future $PM_{2.5}$ concentrations are achievable under different ranges of interventions; how the targets could be measured, and progress tracked; and consideration of the costs of those interventions compared to the impact of achieving different target levels.

Target vision and policy objectives

Before targets are set it is important to convey a clear vision and outline the policy objectives to ensure that the end goal is kept to the fore when developing the targets. This also helps with communication of the targets, giving a framework to consider whether the targets have or are likely to meet the objectives, both in terms of the levels of ambition set, but also the balance between the two targets.

These $PM_{2.5}$ air quality targets aim to:

1. **Provide equity by driving action in the locations where highest levels of exposure occur thereby delivering a 'minimum' standard of air quality across the country**
   - we propose to do this by setting an AMCT.
   - this target will drive action that is most effective at reducing levels where the concentrations exceed the target level.
   - alone, this target will not necessarily drive wider action and would not be most effective at delivering public health benefits, however it helps to protect the more vulnerable members of society living in the areas with the highest exposure.

2. **Encourage actions that reduce concentrations of $PM_{2.5}$ in ways that deliver the greatest public health benefits (at all levels of government and sectors of society)**
   - we propose to do this by setting a PERT.
   - this target will drive action that is the most beneficial for public health across the whole population, wherever they live.

3. **Drive continuous improvement over the long-term, to encourage action to deliver air quality improvements beyond the ‘minimum’ standard of air quality - addressing the fact that there is no threshold below which exposure to $PM_{2.5}$ does not have an impact**

    - we propose to do this in part through the PERT
    - alongside a defined role for local authorities in supporting $PM_{2.5}$ reductions.

4. **Support action to reduce health disparities with regards to air pollution; and the most appropriate way to deliver benefits for those most at risk from adverse health effects of air pollution**

    - The AMCT will partly address exposure disparities by ensuring a ‘minimum’ standard across the country; and the PERT will benefit the whole population, including those who are most susceptible. An assessment was made of how the different emissions scenarios would address disparities in exposure and further analysis will be undertaken as policies and plans to meet the targets are developed.

5. **Form part of a comprehensive and integrated strategy to deliver cleaner air, and sit within a supporting target framework of measurement, regular review, and assurance**

    - We will work with the other target policy areas, other government departments and local government, so that independencies with other environmental policy aims such as net zero are captured and co-benefits are realised.
    - We will develop a robust system of measurement, regular review and assurance to support the targets.

In setting the targets to meet these objectives there are number of specific principles that they must meet that build on the Environment Targets principles.

The success of air quality targets will be judged not solely on whether they are ultimately met, but on how well they meet the key principles outlined as requirements for targets.

Key success criteria for the targets:

Clear and simple to understand- it is important that targets are simple and understandable so that there is a level of transparency in how they are going to be measured and assessed.

Lock in long term ambition – to set out a clear trajectory that brings certainty and enables long term investment in technologies to reduce $PM_{2.5}$ but also assurance that investment in measures will have a long-term future.

Be universally relevant– reducing $PM_{2.5}$ is a challenge to all of society, all aspects of society should be working to reduce their contribution to $PM_{2.5}$ pollution.

Promote continuous improvement - acknowledges that whilst $PM_{2.5}$ is unlikely to be a pollutant that we can eradicate, it is important to strive to continuously invest and support measures that reduce our exposure to a pollutant that is causing significant long-term harm.

Reduce public health harm – these targets will have very significant and long-term benefits for health. Whilst setting targets that are both ambitious but achievable, we can all play our part to the benefit of us all.

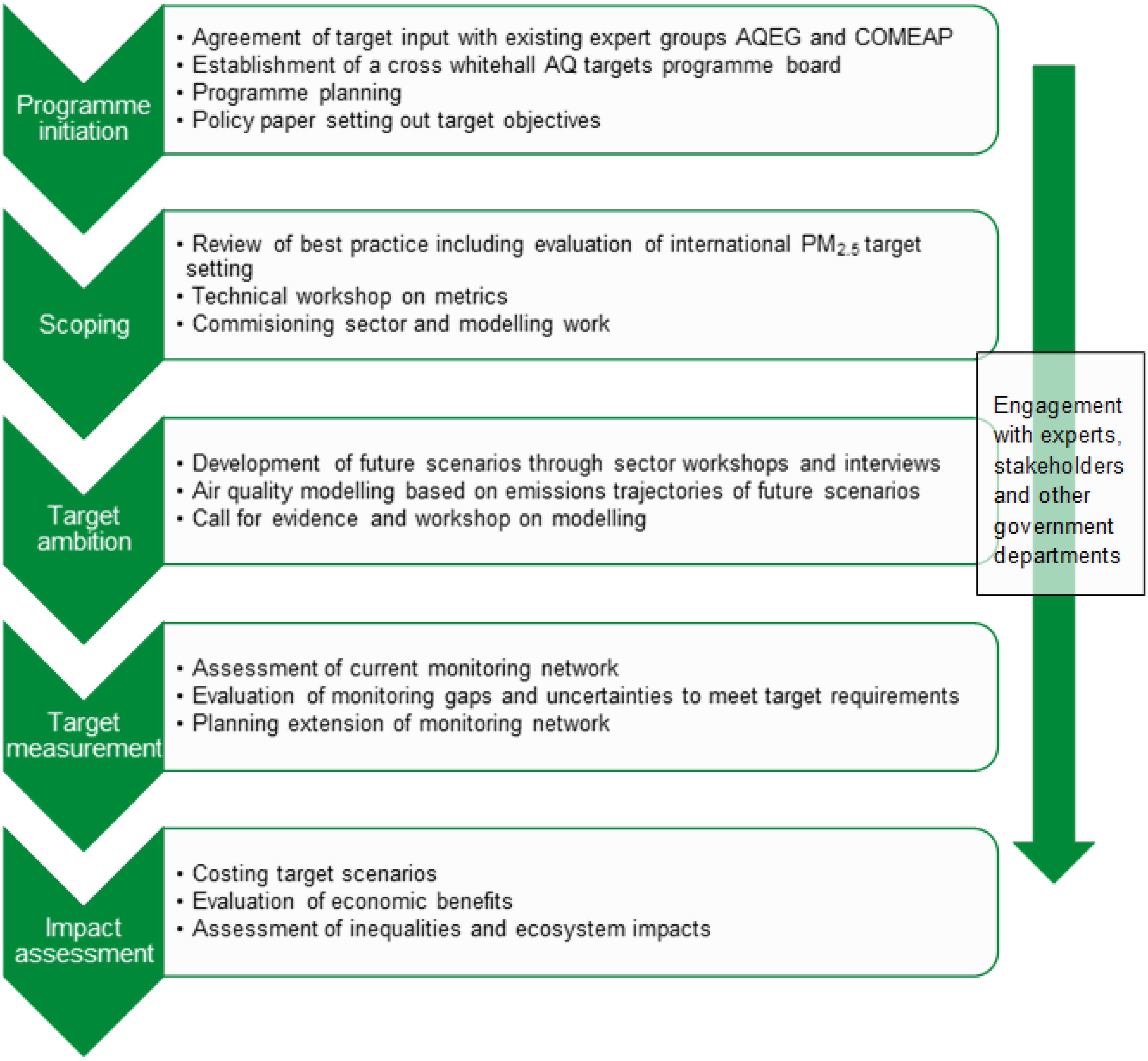
Protect the most vulnerable – it is important to remember that whilst $PM_{2.5}$ affects us all, it can be most impactful on those that are most vulnerable. Therefore, whilst targets will drive down exposure for all there is more to do to ensure information is accessible to enable people to be informed and take action to reduce exposure.

These principles are central to the viability and efficacy of the targets developed and are therefore considered and referenced throughout this report.

Key elements in developing $PM_{2.5}$ targets

The target development process needed to develop a robust and unambiguous approach to metric measurement and required an extensive programme of work with input from experts in a range of different disciplines. Figure 1 provides a schematic of the main aspects of air quality target development process. The details of each element are provided in the report sections which follow.

Figure 1: Target evidence development process



In setting new targets for $PM_{2.5}$ it is important that due consideration is given to defining the metric, including establishing how the metric will be measured and calculated, and developing an appropriate assessment approach. With respect to setting the level for the target it is important to take into consideration the health evidence, to develop an approach to modelling future scenarios to assess potential progress and a method to evaluate both the potential costs and benefits of achieving the target. Following sections take each element in turn to describe work undertaken, the advice given, and evidence sourced to inform decisions on each aspect of defining the targets.

Systems approach

The multi-component and multi-source nature of $PM_{2.5}$ means its generation is integrated into every aspect of our lives and so $PM_{2.5}$ concentration has independencies with multiple other policy objectives. The targets need to be considered as part of a system, rather than in isolation and this is clearly stated in the Environmental Targets Policy Paper as a key principle of the Environmental Targets in the Environment Act 2021. Work was undertaken to develop a systems map of $PM_{2.5}$ to inform the target development work. This did not aim to capture every $PM_{2.5}$ interdependency, however it did illustrate how wider socio-economic factors such as the economy, urban planning and population distribution affect $PM_{2.5}$ concentrations. The interdependencies can be very complex, for example, a robust economy is more likely to result in greater investment in developing and installing lower emission technology by government, industry, and individuals. However, it also tends to increase travel and consumption of goods and services which would increase these activities and potentially create more sources of emissions.

None of the interconnecting factors are likely to remain static in the future, and some of these changes will have positive impacts on $PM_{2.5}$ reduction and others negative. Key drivers for change are public awareness and agency on environmental and health matters, technical innovation and investment as well as government regulation. There are other policy areas with similar drivers for change, for example net zero. There is a great deal of alignment between actions to reduce $PM_{2.5}$ and greenhouse gas emissions, however there are also actions needed to reduce $PM_{2.5}$ which do not also contribute to net zero, for example, reducing road vehicle emissions, even if the vehicles have no zero tailpipe emissions, due to particulates from brake, tyre and road abrasion. There are also areas where there are potential conflicts, for example combustion of biomass may play a role in reducing carbon, but without appropriate mitigation will emit additional $PM_{2.5}$. For this reason, net zero is considered throughout this work and an illustrative net zero scenario is explored as a comparison in the modelling, with discrete assessments such as the impact of increased biomass burning considered as part of the sensitivity analysis. Note the net zero scenario used in this work is only illustrative, as it has been developed during a period of rapid evolution of government strategies to deliver net zero.

The map helped to inform the sector studies and sensitivity analysis, enabling the most important and uncertain sectors to be identified.

The air quality targets also interact with the other targets being developed to meet the requirements of the Environment Act 2021, for example agriculture improvements could be made that benefit both air and water quality, and air pollution affects biodiversity. The Environment Act 2021 targets have been developed as part of a portfolio, taking into account interdependencies as far as possible, and there has been engagement throughout the target development process between the policy areas. See the main consultation document for details[6].

Expert and stakeholder engagement

A range of experts and stakeholders have been integral to the target development work and involved throughout the process.

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[6] https://consult.defra.gov.uk/natural-environment-policy/consultation-on-environmental-targets/

Expert groups

Two long-standing independent groups were engaged early and throughout the development process, and their role to act as key advisors and interpreters of scientific information was agreed with group members. The Air Quality Expert Group (AQEG)[7] provided technical input in relation to metrics, modelling and monitoring. The Committee on the Medical Effects of Air Pollutants (COMEAP)[8] provided information on the health impacts of air pollution which fed into the metric definition, monitoring approach and impact assessment. Input was through participation in discussions in bespoke workshops, preparation of advice notes, holding a call for evidence on modelling and providing feedback on the planned approach at regular member meetings at each development stage. Further information on each group and a list of members is available on the relevant group websites. Advice provided by both groups is referenced throughout this report and linked through the $PM_{2.5}$ Targets section on our UK Air webpage[9].

Other experts, industry, government and NGOs

Additional experts from outside of these groups also contributed to the target development through attendance at workshops, bilateral discussions with Defra officials, responding to the call for evidence and as suppliers of specific pieces of commissioned research and analysis. These were mainly academics and consultants working on different aspects of air quality. Key departments such as the Department for Transport (DfT) and the Department for Business, Energy and Industrial Strategy (BEIS) were represented on the cross-government Air Quality Targets Board and so were able to provide feedback throughout. There was also engagement with representatives of local authorities through the Local Air Quality Advisory Group (LAQAG) and a workshop in relation to how the national targets could be reflected through the Local Air Quality Management regime. The Devolved Administrations (DAs) were involved through their representation on AQEG and bilateral meetings but as air quality is a devolved policy area, these targets are set for England only. Stakeholders such as non-governmental organisations (NGOs) were engaged at milestone points through roundtables with officials, often with the Chairs of the expert groups in attendance to provide additional technical detail.

Iterative engagement has taken place with key umbrella organisations throughout the target setting process. Engagement will continue until the targets are finalised and set in legislation, for example, discussions and workshops will continue with local authorities with respect to the role they will play in helping achieve the targets, as well as wider stakeholders in relation to the consultation.

The public and small businesses

In addition to the public consultation, throughout January through to April we undertook a public facing engagement exercise. The aim was to engage with a cross section of the

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[7] https://uk-air.defra.gov.uk/research/aqeg/

[8] Committee on the Medical Effects of Air Pollutants - GOV.UK (www.gov.uk)

[9] https://uk-air.defra.gov.uk/library/air-quality-targets

public and small businesses to gather qualitative evidence on views and attitudes towards the sorts of policies associated with differing levels of air quality and to understand the real-life impact that different policy scenarios are likely to have on individuals and small businesses.

Data was gathered through approximately 13 online discussion groups, engaging with around 80 individuals. Recruitment has been targeted at members of the general population who would be unlikely to engage with the formal consultation process, but likely to be impacted by prospective policy. For example, individuals who burn solid fuels at home, individuals with health conditions that make them more vulnerable to air pollution, and individuals with impaired mobility. We have also engaged with small businesses that are likely to be impacted by prospective air quality policy such as construction firms that may rely on the use of Non-Road Mobile Machinery (NRMM), mobile businesses/service providers that rely on a personal transport vehicle (e.g., plumbers, electricians, care professionals), and small catering firms/restaurants that use cooking appliances which create $PM_{2.5}$.

This project is intended to provide evidence on stakeholder attitudes to inform the target setting process. The findings of the focus groups will complement the responses to the formal consultation, broadening the type of people reached and enabling more in-depth discussions on these complex issues.

Learning from target setting by others

As part of the scoping stage of target development a review of international target setting for $PM_{2.5}$ was conducted. A number of countries with potentially useful experiences or approaches in setting $PM_{2.5}$ targets or standards were selected as case studies (Australia, Canada, Norway, US, New Zealand and the EU Air Quality Directive). Defra interviewed officials and consultants involved in setting the targets to identify any good practice or recommendations. This exercise was not a comprehensive review of international practices but aimed to capture relevant learning that could be incorporated as well to identify any innovative approaches that could be helpful in developing new targets. A brief summary of the key findings is provided here.

The majority of countries have some form of $PM_{2.5}$ air quality standard or target[10], with the annual mean concentration of $PM_{2.5}$ mass the most common metric employed, followed by a 24 hour mean concentration of $PM_{2.5}$ mass. Two examples of a population exposure metric were identified; the Average Exposure Index (AEI) in the EU Air Quality Directive and a standard still under development in Australia, but where reporting of the metric is required. There were no alternative metrics being used as standards or targets, although different indicators such as black carbon measurements may be used to add additional information.

[10] A standard applies currently, whereas a target or objective should be met by a certain date. Sometimes planned reductions in standards are published several years in advance so effectively become targets.

The annual mean concentration standards identified in the review varied from 40 µg m^{-3} (India) to 8 µg m^{-3} (Australia). Since the 2020 the EU's annual mean $PM_{2.5}$ concentration standard (and the UK's current standard) is 20 µg m^{-3}. Some countries adopted standards based on existing external guidance (e.g., following WHO guidelines, EU or US standards), others set standards based on expert and political judgement of what is acceptable/achievable, and a limited number of countries carried out evidence-based assessments. It is difficult to compare population exposure targets as in the EU the percentage reduction depends on the initial concentration and is over different time period time (the UK's target was 15% reduction between 2010 and 2020) and in Australia there is no current target only a reporting requirement.

The legal standing of air quality standards varies considerably, and often standards set are not met. The EU standards have legal consequences for exceedance, but many national standards rely on voluntary compliance. Examples of implications of exceedances include fines (EU only), requirement to produce action plans, additional planning restrictions in areas where air quality standards are not met (Australia) and financial consequences where access to funding is reduced for states which exceed standards (US). In most of the case studies it was the national government that set the standards and regulatory framework, but the state/province that was responsible for meeting it. However, this reflects the political structure of the countries.

The approach to developing standards seem broadly similar across the case study countries, with a national government lead from the environment and/or health ministry but with the involvement of experts and stakeholders. Some countries set targets based on agreement of a suitable level, of those carrying out bespoke analysis, the types of analysis include air quality modelling and impact assessments.

There were some differences in the application of the targets. The majority were assessed using monitoring, with regulations on the equipment type, location, data capture threshold etc. of those monitors. Only the EU allowed modelling to be used in assessment. Some countries excluded exceptional events when assessing compliance for example Australia excludes the impacts of bush fires on the 24-hour standard.

In conclusion, Defra's approach to target development is broadly consistent with other countries, and more evidence based than most. The most appropriate target or standard very much depends on the local situation, including its natural characteristics such as geography and events such as bush fires, its political climate and structure, monitoring and modelling capacity and the main sources of pollutants.

Defining the target metrics

Air quality targets require a standard or level to be achieved and a date when that level must be met. Appropriate definition of the metric, including how it will be measured and assessed is important to ensure that the target is both objectively measurable (a key criteria of the Environment Act 2021 Target Framework) but also that the outcome of achieving the target meets the policies objectives.

Whilst expert discussions often highlighted both emerging evidence as well as some areas where there are evidence gaps, there was consensus amongst experts that the existing evidence was suitably developed for the setting of targets that were robust with respect to the likely trajectory for evidence over the next 10-15 years, and that they will be able to meet the key principles for targets including being unambiguously defined and easily communicated. Many discussions considered complex options, but it was often the case that such options were rejected for not being suitably transparent or not being unambiguously definable or simple enough to communicate. Key aspects of how the targets will be defined are discussed in this section.

Pollutant type

The focus on $PM_{2.5}$ is primarily because evidence indicates that $PM_{2.5}$ is the pollutant of most harm. The Environmental Targets Policy Paper provided more information on the rationale for a focus on $PM_{2.5}$ and the scope of targets proposed to address the challenge of reducing health harm from exposure to $PM_{2.5}$. Existing standards for other air pollutants remain in place and are not affected by the new targets.

The UK is already committed to reducing the emissions of $PM_{2.5}$ and precursor gases to meet legally binding emission ceilings by 2030, but it is important to also have in place standards that protect directly against health harm. Existing Air Quality Standards Regulations 2010 set out legally binding standards for a range of pollutants including $PM_{2.5}$, yet despite those standards not being exceeded, ambient $PM_{2.5}$ generates a significant burden on the health of the country's population.

$PM_{2.5}$ (mass) measurements have been routinely made on a national scale since 2009 to report against existing legislation. There is therefore an established framework for measurement and historic data to provide a robust basis for trend analysis and a grounding for assessing progress against new targets.

Additional research-based measurements are also made that support understanding of particle composition and distribution across the country. With a view to future proofing the targets we asked for advice from COMEAP regarding whether there was sufficient evidence to set more refined targets based on components of $PM_{2.5}$ (e.g., metals, black carbon etc) or indeed smaller fractions of PM/alternative metrics (e.g., ultrafine particles/particle number). COMEAP (Annex H: COMEAP advice on health evidence relevant to setting PM2.5 targets) advised that although undoubtedly some components may prove more harmful than others, the evidence currently was clear that a focus on $PM_{2.5}$ mass (i.e., the total quantity of $PM_{2.5}$ in air) has the most robust associations to health harm. This and future targets based on specific emission reductions is an area that could be explored for future targets. Particle composition measurements will continue to be important to support understanding of the key sources of $PM_{2.5}$, as well as measures to control them. There was strong support for Defra to consider how any additional investment in monitoring could also consider improvements to compositional measurements, to track progress towards targets. Such measurements while not needed to fulfil the requirements for assessment of the target metrics will undoubtedly support the further development of evidence around the associations and mechanisms of harm. This is an important evidence gap in developing more specific component-based assessment or targets in future years. Such measurements are also required to support the tracking of policies and emission trends as part of regular assessment of progress towards meeting the targets.

COMEAP and AQEG advice also highlighted that it was important to retain existing PM_{10} legislation to ensure that there is suitable focus on the coarse fraction of particulate matter. This has impacts on health beyond that of $PM_{2.5}$ and measurement is needed for the purposes of assessing the sources of coarse particulates.

There were no further viable options proposed by experts for serious consideration beyond that of $PM_{2.5}$ (mass).

It is proposed that: Both targets will be based on $PM_{2.5}$ (mass) and these targets will complement existing PM_{10} standards.

Assessment method

It is recognised and experts agreed, that both long-term fixed monitoring and modelling are important tools in the assessment of targets. Key challenges raised on monitoring related to measurement uncertainty and differences between types of instruments, particularly as measurements will need to be made at increasingly lower concentrations that will push the boundaries on performance of existing methods deployed in the Defra Automatic Urban and Rural Network (AURN). With respect to modelling, it was felt that there were some significant and important uncertainties in relation to modelling a complex pollutant such as $PM_{2.5}$.

There was a strong view amongst experts from early in the target development process, that assessment of legally binding targets for $PM_{2.5}$ should be based on data from fixed monitoring alone. This recommendation was made because there is an established framework for how monitoring is carried out, the performance of instruments is regularly evaluated, and data is ultimately traceable to international metrological standards. With respect to models, it was felt that they are less transparent, less traceable and more subject to changes in inputs and user criteria. There was a clear view from experts that modelling is a vital tool in estimating concentrations at locations that are not monitored, and also for making associations between emissions to air and the concentrations we breathe. They remain critical as tools to help inform policy making as well as for health impact studies. However, the uncertainties associated with modelling mean it may not be as robust for demonstrating compliance with a legally binding target when compared to fixed monitoring, particularly as the assessment will need to consider concentrations at lower than current compliance assessment at 20 $\mu g\ m^{-3}$.

Practical decisions would have to be made to balance both cost and viability of operating a larger number of monitors but it is not possible to monitor at a sufficient geographic density to capture a level of resolution comparable to detailed modelling, so a monitoring-only assessment regime somewhat constrains metrics that are available to us.

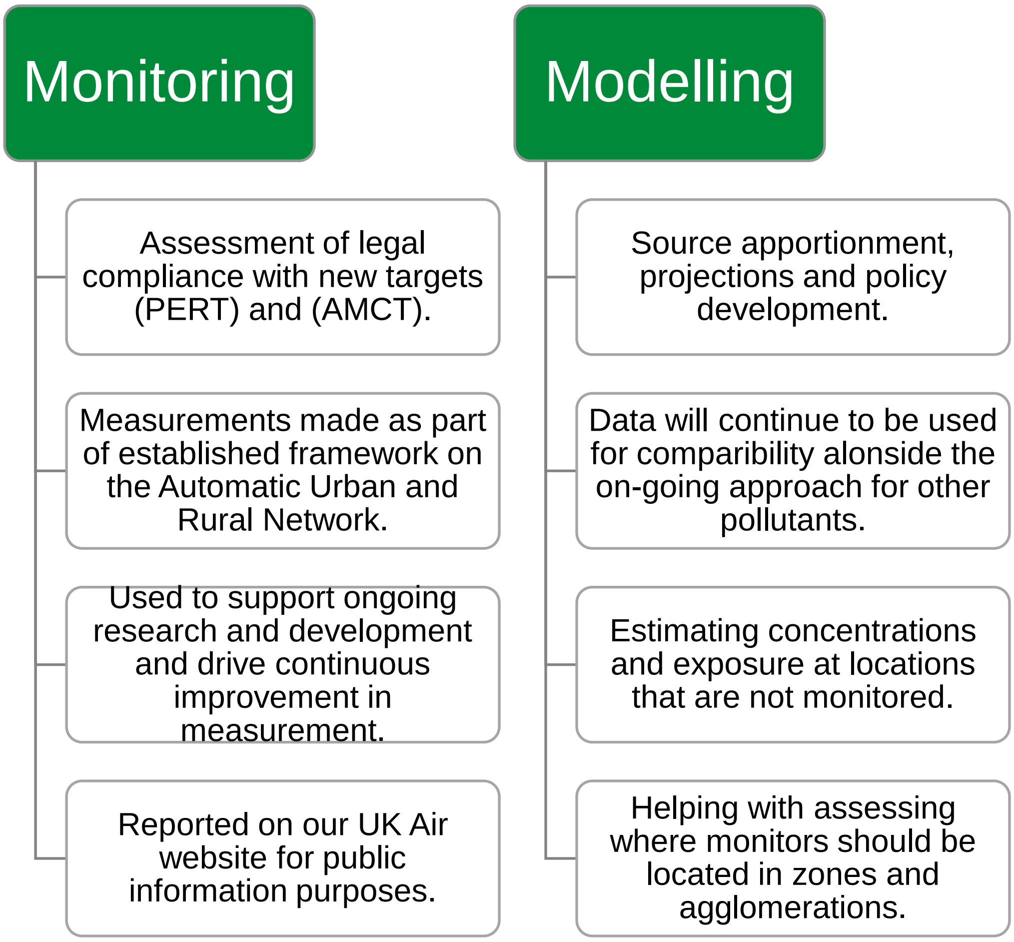
Particulate matter ($PM_{2.5}$ and PM_{10}) are somewhat unique compared to other air pollutants as they are pollutants that are defined by the measurement method used to monitor it, rather than being pure materials (such as NO_2) that may be referenced to absolute amounts of a specific chemical.

Routine measurements of $PM_{2.5}$ in the UK use only instruments that have been demonstrated to meet suitable performance characteristics relative to the gravimetric reference method BS EN 12341 (12) and this performance is certified by the Environment Agency's Monitoring Certification Scheme (MCERTS). In addition, ongoing assessment of performance is undertaken to ensure that instruments deployed on the network continue to meet performance specifications in real world conditions. Whilst indicative measurements by equipment such as sensors can be helpful, they do not currently meet the requirements of MCERTS and therefore will not form part of the compliance assessment process with the new targets. However, they may become more useful as indicative measurements over time or for assessing the efficacy of specific measures.

As part of this advice, it was clear that both monitoring and modelling are important, and that Defra should continue to support ongoing research and development to drive continuous improvement in measurement and modelling technologies to support the further development of assessment methods and reduce associated uncertainties. Figure 2 shows how both monitoring and modelling will inform this work in the future.

It is proposed that: Assessment will be based on fixed monitoring using standard methods deployed at site locations on the Defra's Automatic Urban and Rural Network (AURN)

Figure 2: Schematic on how monitoring and modelling will aid development of assessment methods



Long and short-term exposure

$PM_{2.5}$ concentrations vary across the country, due to proximity to key sources of pollution and due to the differential weather across the country. $PM_{2.5}$ also varies temporally (by time of day or by season) due to how sources of emissions vary (i.e., how much fuel is used to heat our homes in a period of time, for example) or with respect to how those emissions behave in the atmosphere (i.e., temperature, wind direction, wind speed and rainfall etc).

Health harm is related to the exposure we experience, and the exposure depends on the concentrations we encounter through our daily lives. Measurements of pollutants in ambient air are largely averaged over time periods that are associated to health harm (e.g., hourly, daily, yearly for example, depending on the pollutant). For example, it is not possible to assess how short-term fluctuations in a pollutant might be associated to short term health impacts if we only know how concentrations vary year to year. For $PM_{2.5}$, 24 hours is a useful time averaging associated to short term health impacts, whereas other pollutants such as SO_2, for example, periods as short as 1-hour are used. Annual averaging (the average concentration over a calendar year) is a commonly used and useful metric for assessing trends in long term exposure.

Long-term exposure to $PM_{2.5}$ has the largest impact on human health, as it is linked to multiple health impacts for the general population such as cardiovascular disease, respiratory illness and cancer. However, for those who are vulnerable due to age or due to the presence of pre-existing conditions, fluctuations in short term exposure (i.e., changes over 24 hours) are also associated to impacts such as onset of asthma, for example.

In setting these targets we sought expert advice from COMEAP (Annex B: COMEAP engagement meeting on the PM2.5 target setting process) and it was clear that whilst short- and long-term exposure are both important, and inherently linked, focussing targets on reducing the impacts of long-term exposure is likely to drive the most significant health benefits. Advice indicated that there was no need for a separate short-term target, as frequency distributions of daily average concentrations are fairly stable, suggesting that policies to reduce long-term exposure would also be sufficient to protect against short-term exposure. It was also considered that short-term harm is better addressed through the provision of information and public awareness, rather than through targets.

Advice identified that whilst there was not a strong case for short term targets for $PM_{2.5}$, it was important to have some form of PM standard associated to short term exposure and recommendations were to retain existing PM_{10} standards for this purpose. However, it is important to make clear that whilst recommendations for the targets to be based on annual mean concentrations, measurements of $PM_{2.5}$ generally allow for near real time reporting of information, so fluctuations in $PM_{2.5}$ are and will continue to be reported on our UK Air website for the purposes of informing the public about air pollution, particularly when concentrations are elevated during short term episodic conditions. Provision of such data will be included in the review that is being undertaken to improve provision of information to the public.

Practical considerations are also important. Modelling daily variance is significantly more demanding than it is for annual mean concentrations, requiring more detailed information for inputs, such as temporal and seasonal emissions and weather – limiting the number of scenarios that can be assessed.

Some countries have approached $PM_{2.5}$ targets differently, Australia for example, have adopted both a 24 hour and an annual average target, but this decision was in part due to the impact of sporadic bush fires, which is not an issue in England.

It is proposed that:

- **The targets will be based on annual mean concentrations (calendar year) to align to trends in long-term exposure.**
- **Near real time data will continue to be made accessible to provide information around short term exposure to $PM_{2.5}$ (and other pollutants).**

Metrics

There are additional factors that must be considered, beyond the scientific evidence, when developing and defining metrics for targets.

Key considerations include:

- **Communication** – whilst there is some inherent technical complexity as regards air quality measurement and assessment, where possible, the targets need to be easy to understand and explain. This ensures a common understanding of what they are for, how they are assessed and what progress is being made towards achieving them. This is important for both transparency and credibility.
- **Definable in law** – these are legally binding targets and therefore the definition must be clear and not open to misinterpretation.
- **Comparison with others** – it is important to base targets on existing knowledge and understanding and where possible be consistent with how information is presented to allow for comparisons with other targets and pollutants.

A monitoring-only approach (as discussed later) cannot replicate the resolution models can provide but is a means of assessment of compliance that is based on real world assessment. This places a greater demand on monitoring undertaken and the resilience of such measurements; steps will be taken to develop the current network such that it is suitably representative of both the highest concentrations across the country and representative of average population exposure (the principles for how these will be established are discussed further later). Monitoring data is easily communicated, the measurement regime (such as instrument performance characteristics) can be appropriately defined and measurements are not subject to changes in methodology.

Modelling allows for a greater diversity of metrics to be calculated and these can be helpful in both assessing progress as well as assessing the impacts on health. The following metrics do not constitute an exhaustive list but provide some illustration of the types of metrics that have been considered in discussions with expert groups and have been used to some degree in the evidence evaluation. These are largely useful metrics from modelling-based assessments and can, to varying degrees, be useful as measures of progress, but will not form part of the assessment of compliance.

Population (number of people) living in locations above a threshold

This was used in the Clean Air Strategy (4) commitment to reduce the number of people living in locations above the WHO guidelines by half, by 2025. Whilst this is a relatively simple metric to understand and communicate, it is reliant on modelling and dependent on the model used. It is therefore not a suitable metric for a legally binding target. This is due to its binary nature – whereby it is reliant on “counting people” above or below a threshold. Once concentrations get close to that threshold, the metric can be very sensitive to small changes in the model or its inputs. It also has issues with respect to changes in populations over time.

Area above a threshold

Similar to the above, and whilst it is somewhat attractive to be able to say what proportion of the country is above or below the target, this metric only considers the area and doesn't consider where people live. Again, this metric is reliant on the model used and is binary in nature so suffers from similar limitations to the population metric.

Accumulative exceedance

This considers populations that exceed the target level and calculates for each person, the level of exceedance. These exceedances are totalled up for the whole population and subsequently, as concentrations reduce, the accumulative exceedance would also reduce. This is a better measure of progress than the binary nature of people exceeding or area exceeding, as it also considers by how much they exceed. Again though, it is dependent on the model used and when close to the target will be sensitive to small changes in assumptions, inputs or model performance.

Population weighted mean concentration (PWMC)

This metric is useful for calculating the average concentration based on residential population across a region (either nationally or regionally) and is directly related to the calculations required for health impacts. It is calculated by multiplying each modelled concentration by the resident population (to weight the value by the representative population that is exposed to that level), summing all the values and dividing by the total population (of the region or country – depending on the calculation). This metric requires modelling in order to calculate it but monitoring in locations representative of population density can provide an approximation of this metric as discussed later.

Population weighted mean exceedance (PWME)

This is similar to the PWMC in that it requires modelled data and utilises the concentration and population in each location. It differs in that it simply considers the locations that exceed a specific level and calculates a population weighted average – i.e., an average of how much the population exceeds the threshold. This is a useful metric for calculating progress towards a target and has been used in our interpretation.

As well as the technical limitations listed, more complex metrics can also be too complicated to be communicated readily and therefore less effective at driving action. Therefore, it is felt that the absolute concentration is the most important and most commonly understood metric and allows for direct comparison between measurements made across the country with the target – meeting our three key principles of being communicable, legally definable and comparable.

The population exposure reduction target is more challenging to define by monitoring alone and more detail is provided below. However, the key principle with regards to the metric is that it will be based on the average of a representative distribution of monitors across the country, and the metric will be an average of the annual mean levels from those locations – to provide an indicator of average exposure for the country.

It is proposed that:

- **The metric for the concentration target will be an annual mean concentration in µg m^{-3} assessed at individual monitoring sites.**
- **The metric used for the population exposure reduction target (PERT) will be based on the annual mean averaged across a representative population of monitors across the country to provide an indicator of average population exposure.**

Location

The location where targets are assessed is key to how meaningful the targets are. With an assessment regime based on measurements, assessment can only take place where monitoring takes place and therefore the locations of monitoring sites need to be suitably representative. The existing AURN comprises a network of $PM_{2.5}$ monitors (as well as monitors for other pollutants), and that network will be expanded to support the assessment of these targets. Modelling will be used as part of the process to determine suitable locations before such expansion takes place.

Air quality assessment currently takes place at different location types across the country, and these are described with site terminology such as rural, urban, background, industrial or roadside[11]. Where the assessment takes place will in part determine how difficult it is to reach the targets, as although $PM_{2.5}$ shows smaller spatial gradients across sites compared to other pollutants such as NO_2, the highest concentrations will often be measured at near source locations. Engagement with experts raised several challenges with regards to assessment of $PM_{2.5}$ at near source locations including whether these are representative of population exposure and whether measurements can be reliably made at such locations.

Annual Mean Concentration Target (AMCT)

The purpose of the concentration target is to reduce $PM_{2.5}$ concentrations where they are highest, to reduce exposure disparities and ensure that no one is exposed to excessive levels. Advice was mixed on the types of site location that should be used to assess this target. Some experts were of the view that near source measurements were often very specific to the sources contributing and often only representative of very small geographic areas or portions of a road (for example) and therefore should not be included. In addition, whilst some locations may have public access, it may be unlikely that those locations are representative of long-term exposure at that location, i.e., across a calendar year, unless it is a residential street. However, others felt that exclusion of near-source sites could allow for excessive exposure at such locations. The counter argument, that setting a (higher concentration) target that was achievable in near source locations may mean that the target would be too easy to achieve in locations away from local sources of pollution.

[11] https://uk-air.defra.gov.uk/networks/site-types

On balance, it was felt that as the concentration target is focussed on reducing concentrations at hot spot locations, some near source locations should be considered for inclusion as part of the assessment against the concentration target, provided they are suitably representative of adjacent exposure levels, are located where there is public access and are where people are likely to spend a suitable proportion of their time. The PERT will ensure that any concerns that areas below the target level will not take action or may worsen should be avoided.

Near source locations present some challenges for modelling future concentrations and whilst this introduces some risk that concentrations could remain higher in future years than models indicate, some provision has been made to include a margin of tolerance when assessing the likely concentrations at near source locations compared to levels assessed using lower resolution modelling.

It is proposed that:

- **The concentration target should apply at all locations that are currently assessed under Air Quality Standards Regulations 2010, including near source locations.**
- **Monitoring cannot take place at all hotspots, so there will be a minimum requirement for a number of representative measurements to be made at near-source locations across the country.**
- **Concentrations modelled to be exceeding the target will inform progress and policy development as well as informing the evolution of the monitoring network, but will not be considered an exceedance of the target.**

Population Exposure Reduction Target (PERT)

There was a clear consensus through discussions with experts that near source locations were not representative of wider population exposure, and whilst a small proportion of the population could be described as living in such locations, near source locations should not be included as a measure of wider population exposure. As the PERT will be based on a representative number of monitoring sites across the country to allow for an average exposure metric to be calculated, the number of monitors needed in near source locations would not have a significant influence on the PERT calculation. Advice given by AQEG was that the PERT should largely be based on monitors located predominantly at urban background locations and be indirectly population weighted by locating monitors in urban monitoring locations that are representative of significant proportions of the population (more detail is given in later).

It is proposed that:

- **Measurements for the PERT should be based predominantly on urban background monitoring and will not include near source locations.**

Spatial resolution

A monitoring only assessment regime is limited to the scope of the monitoring network. Whilst this is an inherent challenge and cannot aim to replicate the spatial resolution possible with modelling, plans to increase the number of monitors operational in England on the AURN will improve its representivity. Details are provided about the principles that will apply when we look to expand the network. However, the assessment principles for the two targets are as follows:

It is proposed that:

- **Both targets will require a minimum number of monitoring sites and details will be set out in the statutory instrument which sets the targets in law.**
- **An assessment will be made of existing monitoring and the need for new monitoring will be balanced against the need to maintain long term trends from existing monitoring.**
- **Any requirement for new sites will consider viable locations that are representative of higher concentrations in the zone, where there is public access, meeting the appropriate siting criteria for monitoring sites and where there is a viable location for a fixed monitor.**

Calculation method

There are a number of considerations regarding how the metrics are calculated and much of this is dependent on the fact that the targets will be based on data from the monitoring network. More detail is provided on different aspects of this in the monitoring section of this report, but the key principles are discussed here. In addition, some aspects will continue to evolve as statutory instruments are developed.

Air quality monitoring is already widely undertaken. Existing regimes are in place to ensure high levels of data capture and high-quality data so that there is confidence in the targets and how they are assessed.

Many of the key principles with respect to calculating the metrics are related to the operational processes associated to real time monitoring of air pollutants and will be maintained from existing frameworks and guidance. Factors including how the annual mean is calculated from hourly data captured at each monitoring site, what data capture limits to apply and what procedures to use for rounding etc will be explored and more detail provided when targets are set.

There was a strong recommendation to base the PERT metric on multi-year averaging, to smooth inevitable year-to-year variability arising as a result of weather conditions. Previous analysis (13) considered the applicability of multi-year rounding and this approach was generally supported, based on a three-year calendar mean. Multi-year calculations place greater emphasis on high levels of long-term data capture as monitors that fall below the threshold may not be used in the calculation.

In addition, there is a significant challenge with how to calculate change for the PERT over time if the monitoring network is to be expanded – as the averaging from year-to-year will not be comparable. This is discussed further later.

An additional area where expert advice was sought was around regionality and this is discussed in the next section. Detailed discussions with experts also focussed on matters such as how to address the handling of exceptional events.

It is proposed that:

- **Targets will be based on annual (calendar) arithmetic means derived from hourly data.**
- **The concentration target will apply at each measurement location, whereas the PERT will be calculated as an arithmetic mean of a population of monitors across the country (to be defined).**
- **It is advised that data capture limits will apply, as there was little support for backfilling missing data with modelling or statistical techniques.**
- **Information with regards to details such as rounding etc will follow as part of the statutory instrument.**

Regional targets

When setting appropriate levels for a target it is important to consider the heterogeneity of $PM_{2.5}$ concentrations observed across the country and the reasons for such differences. For example, setting a target at a level that is achievable in the most challenging regions of the country, could mean that no action is taken elsewhere.

Fundamental to addressing this issue is the fact that we are setting two targets. The concentration target will cap concentrations across the country, such that the target level is not exceeded and driving action in the locations where concentrations are highest; whereas the population exposure reduction target will drive action in locations that would otherwise not be required to meet the concentration target alone, but where there are reducible emissions. Such reductions will contribute to reducing exposure in such locations by lowering local levels (beyond the concentration target) but also helping to reduce regional contributions.

Some consideration was given to whether there was scope for regional based targets either for the concentration target or for the population exposure reduction target.

With respect to the concentration target, advice was clear, that differential levels in different locations should not be considered. Essentially, allowing certain areas of the country to have higher levels than other areas is simply not a fair or viable approach. Therefore, in considering a viable target level for the concentration target, it is important to consider the achievability at locations where it is most challenging to reach. When assessment is made against the concentration target, regionality will still be considered as existing English zones and agglomerations[12] will be maintained.

With respect to the population exposure reduction target, the advice was less clear cut. For this target it was important to make a distinction between setting a different level to be achieved (i.e., taking into consideration the reduction potential in a region and setting different requirements/targets for different areas) or alternatively, having a national target that can be assessed on a regional basis (to establish the contribution made at a regional level). There was little support for the former, as it was felt that setting a bespoke level for a region was not viable, as pollution in different zones could differ significantly; but for the latter there was a more interest from experts. However, the key to whether regional assessment was viable, ultimately rests on the constraints with regards to the number of monitors required to establish a measurement with an appropriate level of uncertainty. As there is an associated uncertainty with respect to any measurement made, there would need to be enough measurements in each region when calculating the population exposure metric to ensure that the change was robust quantified. Clearly, each region will contribute measurements, but there will be a much higher level of uncertainty associated to the changes over time for individual measurements made compared to the average exposure calculated from all representative sites. Despite plans to expand the monitoring network, the density of monitoring required to assess progress on a regional basis means regional assessment is therefore not possible.

More generally, it was felt that regional assessment and/or regional targets could in some ways be counter-productive, as they may promote challenge with respect to transboundary and regional pollution (blaming neighbouring regions for not meeting targets) and the inherent issues with respect to modelling contributions and sources would mean that these assessments would not be objectively measurable.

It is proposed that:

- **Regional targets should not be pursued, but strong links will be built to the Local Authority Quality Management regime through the review of the Air Quality Strategy.**
- **Targets will be national and will be assessed across the country and consideration will be given to spatial representativeness when expanding the monitoring network.**

Transboundary and natural components

Key to setting targets is to consider the measures available to us to control $PM_{2.5}$ such that levels set can be achieved by the target year. However, a substantial proportion of $PM_{2.5}$ concentrations in England are from sources not within UK control either because they are generated from natural sources or because they originate from sources outside the UK e.g., other countries or international shipping. International cooperation to reduce transboundary pollution will play an important role in reducing $PM_{2.5}$ and achieving the

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[12] https://uk-air.defra.gov.uk/air-pollution/

targets, but it is also a key uncertainty and creates a risk should transboundary impacts not reduce in line with expectations. Similarly, natural components are largely not controllable and factors such as climate change may mean such contributions could change in future years.

Experts were asked whether appropriate methodologies could be envisaged that would allow for targets to be set that could take account of these uncertainties – as is the case with current $PM_{2.5}$ and PM_{10} standards where the contribution attributable to sea salt can be subtracted when assessing compliance.

Whilst there is obvious appeal to being able to align targets more closely with the national actions that are subsequently planned to achieve them, it must be recognised that evidence indicates that it is the total mass of $PM_{2.5}$ that is the most clearly linked metric of health harm. Although it is likely that natural components are less harmful, currently there is no means to determine or quantify components of $PM_{2.5}$ that are either more or less harmful. Accepting that key point, it was also felt that whilst modelling can help to assess the different sources of $PM_{2.5}$ and will support assessment of progress made, there is currently not a feasible approach to subtract either natural or transboundary contributions that would be appropriate for assessment of legally binding targets.

Therefore, the expert discussions focussed on how targets can be set despite these uncertainties and considerations, such that target levels and dates account for both expected progress but also any unexpected deviations from expectations. As explained in the modelling section, key sensitivity analysis was carried out that looked at what levels were achievable under different assumptions with regards to non-UK sources of emissions and these were used as part of the evidence to inform target levels. In addition, information was submitted to the call for evidence that looked at the impact of climate change on $PM_{2.5}$ where it was clear that changes in atmospheric circulation, for example, may have a significant impact on future $PM_{2.5}$. AQEG advised that whilst this is a significant uncertainty, such effects were extremely complex and it was not something that could be taken account of in the air quality modelling.

However, whilst the complexities of subtracting specific components was recognised as challenging for transboundary pollutants and natural sources, there was recognition that there is an established protocol for subtraction of sea salt that could be retained.

Some countries include a provision to exclude exceptional events from the legal assessment, for example a fire next to a monitoring site. However, it was considered that these were more impactful for short-term exposure targets and so provision for these were not included.

It is proposed that:

- **Targets will be set for total $PM_{2.5}$.**
- **Further consideration will be given to whether existing allowances for the subtraction of sea salt (from total $PM_{2.5}$ mass) will be maintained.**
- **No provision will be made for handling contributions due to exceptional events, transboundary pollution or other natural sources of $PM_{2.5}$.**

Target assessment

This section is focussed on how evidence and expert advice has been used to form views on how the targets will be assessed. It is important that the targets are objectively measurable but also that there is transparency around how the targets will be assessed and legally defined.

Assessment overview

Assessment of levels of $PM_{2.5}$ with respect to a legally binding target will be based on monitored concentrations at representative fixed monitoring locations around the country. When asked for views, expert groups recommended that assessment of the target and legal compliance should be based on monitored concentrations at representative locations across the country.

Key pieces of advice were provided as part of the AQEG technical workshop held on 2 September 2020 (Annex C: Technical workshop on target metrics). This included advice on:

- Defining and calculating the metrics
- How to measure against the new targets
- How to use the metrics in practice

In addition, information was provided on how to develop the $PM_{2.5}$ targets when compared to the existing target methodologies. The following sections provide further information on the proposals to monitor against the new targets.

Site classification

Air quality is currently assessed through the deployment of fixed monitoring at a range of location types across the country alongside modelling. Stations are classified according to the dominant emission source impacting the monitoring station location. These classifications provide useful descriptive information for understanding the nature of the physical and pollution environment surrounding the station. There are three types of station: industrial, traffic and background, which are combined with a description of the area type: urban, suburban, or rural to form an overall station classification. These classifications are required for air pollution assessment for all pollutant types under the Air Quality Standards Regulations 2010 and are described on the UK Air website[13].

Whilst locations can be described by key characteristics, it is impossible to define environment types in suitable detail such that different parts of the country have entirely comparable monitoring siting – for example a site in London will have different characteristics to those of a site in Manchester, despite them having similar basic

[13] https://uk-air.defra.gov.uk/networks/site-types

requirements such as both being defined as sited at urban background locations (for example). However, categorisations remain important to enable comparisons and assess legal compliance. To continue to compare with previous datasets and assess on-going long-term trends, it is intended that the current system that defines siting locations will be maintained. This will also ensure that the monitoring of $PM_{2.5}$ is categorised in the same manner as other air quality pollutants such as PM_{10}, nitrogen dioxide (NO_2), sulphur dioxide (SO_2) etc.

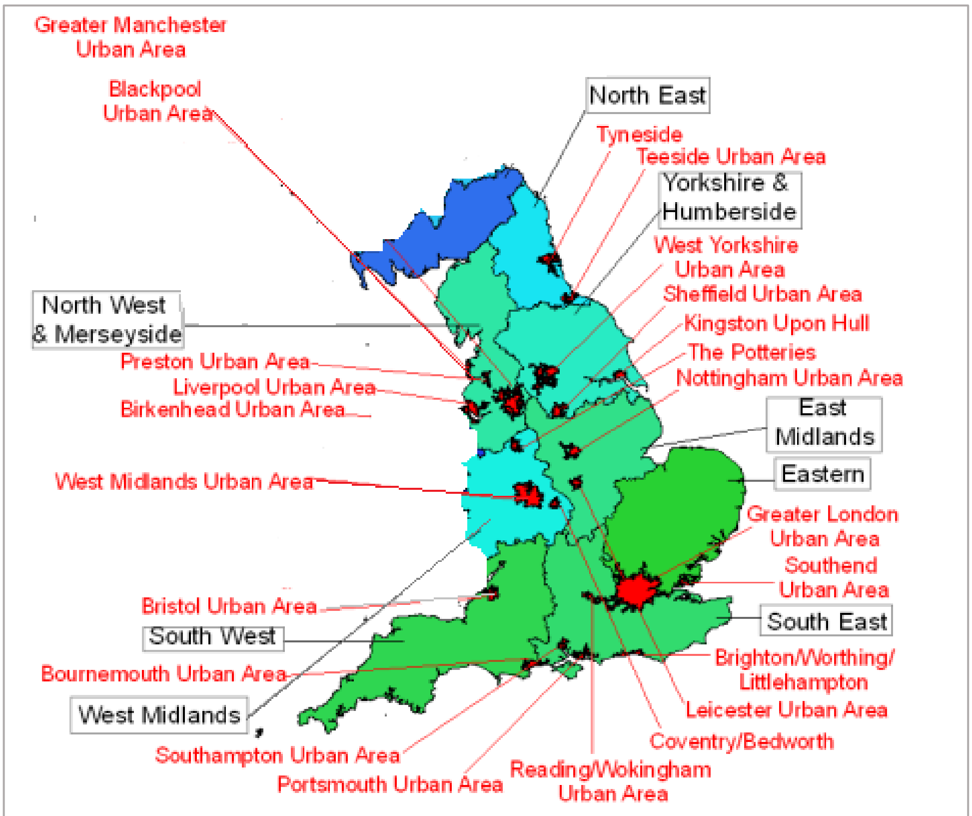
It is proposed that:

- **The site categorisation for monitoring sites will remain unchanged.**

Reporting

For the purposes of air quality assessment, England (along with the rest of the UK) has been divided into zones and agglomerations for the purposes of air pollution monitoring reporting since 2001, according to the requirements of the air quality legislation at that time.

Figure 3: Map of reporting zones and agglomerations



Agglomeration zones (red). Non-agglomeration zones (blue/green).

The eight zones are based on former Government Office boundaries within England from 2001. In addition, there are 23 agglomerations that have been designated as urban areas which are greater than 250,000 population in size. These designations are useful as they allow distinct areas to be assessed separately, recognising the impact of local sources and environmental conditions. When views were sought, expert groups recommended that the assessment of the new targets and legal compliance should continue to be reported using this system to ensure consistent trend analysis and comparability with previous datasets. There was a consensus view that there was no benefit in changing this system particularly for $PM_{2.5}$ when this is the current reporting mechanism for all other UK pollutant assessment.

It is proposed that:

- **Assessment including establishing an appropriate level of monitoring will utilise existing zones and agglomerations for England (as set out in**
- **Table** 1**).**

Table 1 illustrates how populations in 2019 differed for each zone and agglomeration across England, illustrating how markedly the populations in each differ.

Table 1. English Zones and Agglomerations

Name of Zone /Agglomeration	Zone/Agglomeration Population in 2019
Greater London Urban Area	9,756,479
South East	7,126,547
Eastern	5,720,058
South West	4,673,818
East Midlands	3,740,367
North West & Merseyside	3,604,852
Yorkshire & Humberside	3,231,914
West Midlands	2,845,914
West Midlands Urban Area	2,429,869
Greater Manchester Urban Area	2,214,358
North East	1,556,945
West Yorkshire Urban Area	1,381,404
Tyneside	795,383

Liverpool Urban Area	784,009
Nottingham Urban Area	638,653
Sheffield Urban Area	612,086
Bristol Urban Area	579,910
Leicester Urban Area	457,557
Brighton/Worthing/Littlehampton	442,595
Portsmouth Urban Area	416184
Bournemouth Urban Area	394,510
Coventry/Bedworth	359,328
Reading/Wokingham Urban Area	319,562
Teesside Urban Area	318,275
Southampton Urban Area	317,338
The Potteries	294,685
Birkenhead Urban Area	290,910
Kingston upon Hull	279,388
Southend Urban Area	256,199
Blackpool Urban Area	230,498
Preston Urban Area	218,750

Air quality information for zones and agglomerations and individual monitoring sites is made available through the web page UK Air Information Resource (UK AIR) [14] with real-time data being accessible every hour. Statistics and comparisons to the legislative standards and objectives is made available through an annual report Air Pollution in the UK which is published on UK AIR[15]. Both requirements are currently enshrined within the Air Quality Standards Regulations 2010 and will be continued. AQEG were supportive that there should be the same level of public access to data and information for these new

[14] UK AIR

[15] https://uk-air.defra.gov.uk/library/annualreport/

targets e.g., *'for the sake of public transparency, the new sites should be capable of reporting 'live' hourly data'.*

It is proposed that:

- **Assessment of the two new targets will be included as part of this long-running series of annual reports which summarise the measurements from the national air pollution monitoring networks and will maintain access to real-time data and statistics through UK AIR.**

Monitoring equipment

As explained above, $PM_{2.5}$ is defined in legislation according to how it is measured and is described as:

> *The mass of particulate matter per unit volume of air passing a size-selective inlet with a 50% cut point efficiency[16] at 2.5 µm particle aerodynamic diameter.* (5)

$PM_{2.5}$ is somewhat unique compared to other pollutants in that it is defined by the methods by which it is measured (in line with international best practice) and there are a number of different analytical methods that have been developed for this purpose. (10)

Equivalence Framework

A range of $PM_{2.5}$ air quality monitoring instruments are currently deployed on the UK network. In order to ensure that measurements made are reliable and comparable the instruments deployed on the national network must meet performance criteria defined within the AQSR 2010 and the CEN standard method for monitoring ambient particulate matter concentrations EN16450. The Environment Agency (EA) operate a standardisation programme known as "MCERTs for Particulate Matter"[17] that establishes whether an instrument type is capable of performing on the network to the appropriate standard. Once deployed on the network, the EA operate a programme to demonstrate the ongoing performance of such instruments in the real world - known as "*demonstration of ongoing equivalence*" with respect to the reference method. Such systems ensure that monitors deployed on the network perform to a standard that is consistent, regardless of the technology behind its operation.

The current requirements are set out in the AQSR 2010 and the reference method for the sampling and measurement of $PM_{2,5}$ is that described in EN12341:2014 'Ambient Air — standard gravimetric measurement method for the determination of the PM_{10} or $PM_{2,5}$ mass concentration of suspended particulate matter' (12). The gravimetric method, whilst termed the reference method, has limitations in terms of being operationally

[16] As defined in the reference method for the sampling and measurement of $PM_{2.5}$.

[17] Certification - MCERTS for UK Particulate Matter - Defra, UK

intensive but also as it cannot provide near real time data that is so important for public information about air pollution concentrations.

As highlighted, experts identified the need to undertake robust assessments of uncertainty with respect to different measurements made on the network with different instruments. AQEG advised that further research is needed and changes to uncertainty boundaries may be required, as it is expected that it will be more challenging for instruments to meet the current performance requirements at lower concentrations. This arises as techniques approach their limits of detection and changes in the composition of $PM_{2.5}$ over time may also occur (Annex G: AQEG advice note on Measurement Uncertainty for PM2.5 in the Context of the UK National Network).

Work is already underway to explore this and will inform the development of an appropriately updated equivalence programme. In the first instance, a one-year research project will be instigated to supplement current equivalence assessment at London Teddington and Manchester Piccadilly. This will be based on the collocation of a reference method at three urban background locations (using three University 'Supersites'), three urban traffic locations and a rural background site. This will provide additional information on instrument performance to inform evolution of the equivalence programme.

Whilst it is intended to continue with the current approach to establishing a standardisation regime that allows for deployment of different monitors across the network, there is a need to factor in suitable flexibility for an updated equivalence programme to be put in place.

It is proposed that:

- **The equivalence framework will continue but will be reviewed in the future so that the programme can be adapted to reflect the performance of the instruments and expanded uncertainty once assessed with respect to the new target levels.**

Data Objectives

In the past there has been a focus on two primary data objectives to be achieved by instruments deployed for $PM_{2.5}$ monitoring. These are:

- Data capture of at least 90% (but if maintenance time is taken into account this can be lowered to at least 85%).
    - This means that the instrument must be operational for 90% of the period over which the concentration is being assessed (i.e. 90% of the year for an annual mean)[18].

- Expanded uncertainty (Wcm%) of 25% to be achieved within each compliance year where (Wcm%) is calculated at the limit value.

[18] Commission Implementing Decision laying down rules for Directives 2004/107/EC and 2008/50/EC of the European Parliament and of the Council as regards the reciprocal exchange of information and reporting on ambient air 2013

- This means that there is a level of uncertainty allowed which accommodates the natural measurement fluctuations that can occur when monitoring. This is ± 25% for $PM_{2.5}$ measurements [19].

Data capture criteria

It is important to make sure that the dataset being used to assess target compliance is not under-representing the $PM_{2.5}$ at a location through missing records. Experts' consensus was for keeping things simple in respect of the management of missing data from monitoring stations and avoiding complicated data manipulation (such as statistical gap filling) so that trust in what was reported was not diminished. Compliance with the data capture objectives for each pollutant at each site, is currently reported in the series of reports entitled "AURN Annual Technical Report", available via the Library pages of UK AIR[20]. Therefore, the current approach of assessing this will be maintained in line with its use for the other pollutants.

Previously European guidance (14) has been in place that sets out the implementing requirements with regards the reciprocal exchange of information and reporting on ambient air (Decision 2011/850/EU). This sets out the requirements of data reporting including use of standardised reporting of time and significant numbers and rounding and where appropriate these will be maintained and defined when these targets are set.

It is proposed that:

- **Data objective requirements for data capture, standardised reporting and rounding will continue to be applied where appropriate and detailed when these targets are set.**

Monitoring locations

Current network monitoring

The AURN is the largest automatic monitoring network in the UK and provides the majority of the England's statutory compliance monitoring evidence base (as well as those of the devolved administrations). The network monitors a range of pollutants for the purpose of assessment against ambient air quality standards and provides data for public information purposes in near real time. As of the 1 January 2022, there were 63 sites that monitor $PM_{2.5}$ which are located across England (with additional sites across the UK as a whole)[21]. Table 2 lists how many sites are part of each site classification within England.

[19] These have been defined under the Air Quality Standards Regulations 2010, through the European Commission (EC) Guidance to Demonstration of Equivalence 2010 and also the CEN Standard EN16450:2017.

[20] http://uk-air.defra.gov.uk/library/

[21] London Marylebone has been included as a single site although has additional $PM_{2.5}$ capacity.

Table 2. $PM_{2.5}$ AURN Monitoring Sites according to site classification

Urban Background	Urban Traffic	Suburban Background	Urban Industrial	Rural Background
37	18	2	4	2

Types of monitoring equipment

The monitors that have been approved by Defra as equivalent for use in the UK and are part of the AURN are listed on UK AIR[22].

As of the 1 January 2022, the network is mainly served by Met-One BAM1020 and Palas Fidas 200 monitoring equipment following an update in the network instrument types between 2017 to 2021. The Met-one BAM1020 is located predominantly in urban traffic locations and Palas Fidas 200 in urban background locations.

Table 3. $PM_{2.5}$ AURN Monitoring Sites according to siting criteria and instrument type (1 January 2022)

Instrument	Urban Traffic	Urban background	Rural Background	Suburban Background	Urban Industrial	Total
Palas Fidas 200	3	27	2	2	1	35
Met-one BAM1020	15	10	0	0	3	28
Total	**18**	**37**	**2**	**2**	**4**	**63**

[22] Certification - MCERTS for UK Particulate Matter - Defra, UK

Minimum requirements for assessing the targets

To assess the targets in a consistent manner across the country it is important to utilise a robust approach to monitoring.

With respect to the siting of instruments to assess the concentration target, the key challenge will be to monitor at locations where concentrations would be expected to be elevated and where there is relevant public exposure. Whilst monitoring cannot take place everywhere, a minimum requirement for monitoring will be required and will be defined in legislation.

Expert advice has recommended that the PERT should be based on a population of monitors across the country sited at locations that provide appropriate estimates of levels of $PM_{2.5}$ that are representative of average concentrations that the population, as a whole, will be exposed to in that area. This means a focus on urban background monitoring and suburban background monitoring together with information on rural background measurements (although this won't be part of the PERT metric). Future work will consider how the network can be effectively expanded in line with these recommendations.

The calculation of metrics and assessment of the AMCT and the PERT will be undertaken to at least the same standards as referred to by the AQSR 2010, taking account of any subsequent changes to guidance or developments in best practice.

Current Air Quality legislation also describes the minimum requirements for PM ($PM_{2.5}$ and PM_{10}) monitoring in each zone and agglomeration. It establishes the minimum number of sampling points as a joint total for PM_{10} and $PM_{2.5}$ for each air quality zone/ agglomeration depending on the population numbers in each zone and the previous recorded levels of particulate matter relative to a defined 'assessment threshold'. The number of sampling points required is determined by the AQSR 2010 which refers to Annex V of Directive 2008/50/EC (15) and also includes the following:

- the ratio of PM_{10} to $PM_{2.5}$ monitoring differs by no more than a factor of two.
- zones/agglomerations above an upper assessment threshold concentration of $PM_{2.5}$ have at least one urban background station and one traffic-oriented station where this would not increase the required number of sampling points (i.e., the zone would otherwise only require a single sampling point)
- the network-wide urban background sampling points and traffic-oriented sampling points differs by no more than a factor of two.

The new targets for $PM_{2.5}$ will require an appropriate increase in $PM_{2.5}$ monitoring across the country to better assess exposure reduction and potential elevated levels. Therefore, the minimum requirements for $PM_{2.5}$ monitoring which are already in legislation will still be relevant but will be built upon such that an increased number of monitors for England can be accommodated. This expanded network will be more representative of populations and where 'hotspots' of $PM_{2.5}$ are identified.

In the future, it is therefore proposed to proportionally increase the numbers of $PM_{2.5}$ monitoring stations relative to PM_{10} monitoring sites. Expert advice has strongly supported this change to enable an appropriate refocusing of resources onto the needs to improve $PM_{2.5}$ monitoring across the country. This advice has also been clear on the importance of maintaining the existing daily limit value for PM_{10} and a continued network for assessment, to ensure that PM_{10} is appropriately measured and controlled. Therefore, minimum requirements will still protect the current focus on PM_{10} monitoring whilst enabling the future expansion of the monitoring network to assess $PM_{2.5}$ against the new targets.

Consideration will be given to the future proportionality of urban background to urban traffic sites and this will be detailed in the subsequent statutory instrument. This will continue to enable flexibility to respond to the requirements of both the PERT (to better assess exposure reduction) and any future elevated levels identified against the AMCT. The approach for expanding the network is described further in the next section.

Measuring the Annual Mean Concentration Target (AMCT)

Currently the $PM_{2.5}$ network comprises 63 monitors and over the next three years (2022/23/24) the network will expand further.

Expert advice highlighted potential concerns with regards to including near-source locations as part of a concentration target, as it would focus policy and action toward hot-spot locations possibly at the expense of the wider population; while excluding them would potentially allow an increase in exposure at such hot-spots in the future. Therefore, the future expanded $PM_{2.5}$ network will:

- increase the number of locations where the new concentration target will be monitored to provide a greater spatial distribution.
- include additional monitors in hotspots (identified through modelling), predominantly at urban traffic/near source locations, but ensuring that monitoring follows a degree of proportionality with respect to the populations within each zone.
- ensure all $PM_{2.5}$ monitoring at all site location classifications are compared to the new AMCT.

Initial work undertaken to assess the performance of monitors currently deployed on the network has indicated the need for further comparative performance assessment, specifically at locations close to sources of pollution, such as busy roads. This work needs to be undertaken before decisions can be made on further expansion of the monitoring network - this work will begin during 2022.

It is proposed that:

- **The concentration target will have a minimum requirement for representative measurement and will require any new monitoring to be sited at appropriate locations where concentrations are likely to be highest and where there is appropriate public exposure. This will include all monitoring classifications.**

Calculating the Annual Mean Concentration Target (AMCT)

Based on expert advice, the concentration target will be assessed on a single year annual mean at each monitoring location (the average level over the calendar year from hourly readings).

- The AMCT will be met if all $PM_{2.5}$ AURN monitoring sites do not **exceed 10 µg m^{-3} in 2040.**[23]
- Only monitoring sites with a valid data capture (>85%[24] of hourly readings over the calendar year) will be assessed against the target.
- In 2040 all sites must meet the target of 10 µg m^{-3}. If any site registers an exceedance of the target (AMCT will be met if all $PM_{2.5}$ AURN monitoring sites do not **exceed 10 µg m^{-3} in 2040)**, an assessment must be undertaken as to levels recorded at each monitoring site over the previous four years. The target will be considered to have been met if all monitoring sites did not exceed 10 µg m^{-3} in three out of the previous four years. Therefore, each monitoring site is considered separately and assessed as to whether it has met the 10 µg m^{-3} target in three of the four previous years.

This is to respond to the potential impacts of meteorology and to allow for localised and transient sources impacting on $PM_{2.5}$ at individual monitoring sites. These may be specific to a particular year e.g., Sahara dust episodes, volcanic eruptions. This target allowance will also aid in the management, future policy development and regulation of key sources of pollutants for future years. The proposed AMCT metric is described in Table 4.

[23] The rounding rules would apply as set out by Commission Implementing Decision laying down rules for Directives 2004/107/EC and 2008/50/EC of the European Parliament and of the Council as regards the reciprocal exchange of information and reporting on ambient air (Decision 2011/850/EU

[24] This Data capture of at least 90% (but if maintenance time is taken into account this can be lowered to at least 85%).

Table 4. Assessment of Annual Mean Concentration Target

Assessment	Year	Period to be considered
Assessment of Annual Mean Concentration Target	2040	2040 – single year The target will have been met if all monitoring sites have not exceeded 10 µg m^{-3}.
If individual sites exceed the annual average >10 µg m^{-3} in 2040 then previous four years of data are assessed for each site.	2040	2036, 2037, 2038, 2039 The target will have been met if all sites do not exceed 10 µg m^{-3} in three out of the four assessment years.
Assessment of Annual Mean Concentration Target	2041	2041 – single year The target will have been met if all monitoring sites have not exceeded 10 µg m^{-3}.
If individual sites exceed the annual average >10 µg m^{-3} in 2041 then previous four years of data are assessed for each site.	2041	2037, 2038, 2039, 2040 The target will have been met if all sites do not exceed 10 µg m^{-3} in three out of the four assessment years.
Assessment of Annual Mean Concentration Target	2042	2042 – single year The target will have been met if all monitoring sites have not exceeded 10 µg m^{-3}.
If individual sites exceed the annual average >10 µg m^{-3} in 2042 then previous four years of data are assessed for each site.	2042*	2038, 2039, 2040, 2041 The target will have been met if all sites do not exceed 10 µg m^{-3} in three out of the four assessment years.

*Following this date, subsequent years will be assessed in the same way.

It is proposed that:

- **The AMCT will be assessed based on concentrations at specific locations and will require that no annual average exceeds the 10 µg m^{-3} target at an individual site, during and following the target achievement date (2040).**
- **The AMCT will also be met if all individual sites have an annual average equal to or less than the target on more than three occasions over the previous four years should the target be exceeded at that location in the assessment year.**

To ensure the robustness of this metric, it is important that only monitoring sites that have a valid data capture (>85% of hourly readings over the calendar year) will be compared to the new target. This will avoid monitoring sites that may only have a limited number of data points in the calculation of an annual average being assessed as compliant.

If the target is not met in 2040 (or subsequent years) the metric will allow the consideration of data from the previous four years annual average data e.g., 2040 would consider the annual averages from 2036 – 2039. This dataset would then require all four years data to be available and have a valid data capture (>85%) for each monitoring site to be included in this metric**.**

It is proposed that:

- **All monitoring sites will be required to have a valid data capture (>85%) over the previous four-year period should compliance be assessed to be deemed compliant, following an exceedance in the assessment year. They will not be assessed against the target if any years' data has less than 85% data capture in any of the previous four-year period.**

Monitoring the PERT

There were a wide range of views on how a measurement network could be defined for assessing the population exposure reduction target (PERT). There was however acceptance by experts that there was no single 'right way' to do this and that some degree of simplification was required in order to make the regime appropriately representative but also economically viable.

Key pieces of advice were as follows:

- Consideration should be given to the minimum number of monitors contributing to the PERT average to account for the inherent uncertainty in the instrument performance. This is to ensure that the measurement system is able to measure the expected change in the population exposure metric over time.
- Defra explored the potential minimum number of monitoring stations required to detect a specified level of change in the PERT over a given time interval. AQEG advised that 'It is not possible to determine in advance by how much uncertainty would be reduced though increasing the number of monitoring locations that contribute to the PERT. However, a law of diminishing returns surely applies'. Whilst more monitors will reduce the uncertainty in the PERT measurement and would also result in greater spatial representativeness, there may be diminishing

returns from having a PERT network that is the order of 100 monitors and above. Further work will be required to understand this further.

- Focus should be on measurements at locations that are representative of population exposure; this will require a significant focus on urban background monitoring and suburban monitoring if more representative of the zone or agglomeration population. This is to be representative of where people live and work. AQEG indicated that 'it is the totality of network that is representative of exposure, not any individual node within it'.
- That we should exclude near source environments such as roadside locations from the PERT calculation as they are not representative of exposure for large proportions of the population.
- Only monitoring sites with a valid data capture (>85%) [25] of hourly readings over the calendar year) will be assessed against the target.

It is proposed that:

- **The PERT will focus largely on the use of data from a representative network of monitors predominantly at urban background and suburban locations.**

The Air Quality Standards Regulations 2010 sets out the requirements for the minimum number of urban background stations for the purposes of assessing UK wide population exposure. Representative measurements of $PM_{2.5}$ at urban background locations were defined as requiring one sampling point per million inhabitants, summed over agglomerations and additional urban areas in excess of 100 000 inhabitants. This is met by at least 44 UK urban background and suburban sites across the UK (currently 39 being located within England). The minimum requirements for $PM_{2.5}$ monitoring which are already in legislation will still be relevant but will be built upon such that an increased number of monitors for England can be accommodated.

Funding is already available to implement expansion in urban background monitoring during 2022/2023. The focus by the end of 2023 will be to:

- Allocate those new sites to utilise (where possible) existing monitoring locations to ensure benefits of co-location (running costs, evidential value). This will also aid in the comparison of $PM_{2.5}$ to other pollutants monitored in the same location.
- Ensure that all zones and agglomerations to have at least one monitor that contributes to the PERT assessment metric.
- Allocate additional monitoring to zones and agglomerations where there are proportionately larger populations.

It is proposed that:

- **During 2022 and 2023 the network of urban background and suburban monitors will be expanded using the above principles. This will initially**

[25] This data capture of at least 90% (but if maintenance time is taken into account this can be lowered to at least 85%).

expand the current urban background/ suburban network in England from 39 monitors to approx. 57 monitors.

Future funding for the assessment of the PERT will be prioritised by allocating additional monitoring with the following key principles:

- Ensuring each zone and agglomeration has a minimum number of measurements.
- Ensuring monitoring in zones and agglomerations follows a degree of proportionality with respect to the populations but have a cap on the number of monitors needed for the largest population areas.
- Ensuring that within each zone and agglomeration, any new monitoring favours locations where there is an established monitoring location (where applicable), but that new sites consider representative measurements to be sited where higher proportions of the population live.
- Consideration is given to locating a proportion of monitoring in areas of deprivation.
- Allocations of new monitoring will also consider the distribution of existing monitoring within a zone/agglomeration and across adjacent zones/agglomerations in order to provide a degree of equity to the network locations (i.e., it will not solely be based on quantifiable criteria such as population).
- Ensuring that each zone and agglomeration is assessed such that dispersed populations in smaller villages/rural areas that collectively have a larger population compared to other urban centres and an elevated exposure are considered to ensure that they are adequately represented.

The aim to increase the number of monitoring sites across the country to enable a larger network for calculating the PERT has the potential to provide a much-improved dataset, enabling each zone and agglomeration to be represented and for geographical/spatial gaps to be filled. There will be greater spatial coverage and this will result in measurements being included that are more representative of a greater proportion of the population. All new monitors will also provide near real time data to the public.

It is proposed that:

- **The network of urban background and suburban monitors will be expanded after 2023 using the above principles subject to funding in future years.**

Calculating the PERT

The population exposure reduction target will report the change in the average exposure across the country over time. To ensure that this is a robust metric, experts advised that it should be based on a three-year calendar mean.

- AQEG recommended that the PERT assessment should be based on ‘a three-year running mean to reduce the impact of changing meteorology. However, the same reasoning applies to establishing the base period which is currently proposed to be a single year (2018). A three-year time-base would be more defensible.’

Such an approach has been used in previous exposure calculations (e.g. the AQSR 2010 ‘average exposure index’) and allows for a more stable assessment period to track changes to $PM_{2.5}$ population exposure. The new metric will be an ‘Enhanced Average Exposure Indicator Metric’ using an expanded network of urban background and (if more representative in specific locations) suburban sites.

It is proposed that:

- **The PERT will be based on an average of representative measurements across the country using a minimum number of urban background and suburban monitoring locations in each zone and agglomeration. The arithmetic mean $PM_{2.5}$ concentration at these sites will be calculated for three consecutive calendar years with valid data capture and the mean of these sites calculated as the PERT.**
- **The PERT will be based on a three-calendar year mean (the average of three consecutive calendar years). This will be compared to a baseline year (also calculated as an average of three calendar years).**

In order for the PERT to be a robust measure of changes to the levels of $PM_{2.5}$ population exposure, the metric should not be unduly influenced by the proposed monitoring network changes. However, restricting the PERT metric calculation to just existing monitoring sites would mean that any new sites deployed over the coming years to provide greater spatial representivity, would then not be included in the assessment.

An increased number of monitoring stations by 2040 will mean that the target assessment in future will be based on a different set of monitoring sites than those operational in the original base year. Experts advised that consideration should be given to any changes to the $PM_{2.5}$ monitoring network over the target period to either ensure that either the same monitor cohort is used when assessing against the PERT or that suitable provision is made to the metric to recognise a dataset evolving over time.

The following proposal is based on an approach (16) and adapted to enable the phased introduction of additional monitors onto the network and for the gradual inclusion into the PERT calculation in a statistically sound manner. The principle of this approach is to only compare changes in population exposure for sites that were open and operating in successive assessment years. By comparing the concentrations measured in the first assessment year and comparing the measurements for the same sites in the second assessment year, a calculation of population exposure reduction between the two years can occur. As each assessment year requires data for three consecutive years, this approach requires that monitors are operational for the full three-year period of the first year and the full three-year period required to calculate the next year. This means that sites are included if they have been ‘open/operational’ for a full four-year period. The cumulative change from one year to the next is summed across the period before comparison to the base year of 2018 (2016/2017/2018).

Whilst this is inherently more complex than simply including new sites as they come online, it avoids the exposure changes being due to the inclusion of new sites, that may be biased higher or lower than the existing network, rather than arising from a fundamental change in exposure. The baseline would be calculated as in

Table 5 and the PERT calculation is detailed in Table 6.

Table 5. Calculation of the PERT baseline year

PERT Baseline Year	Calculation	Number of open sites
2018	• Annual average calculated for each urban background/suburban site from each hourly reading. • Mean calculated for 2018 from annual average of existing urban background/suburban sites*. • Mean calculated over the previous three years annual average data period e.g., 2016, 2017, 2018).	39

*subject to minimum data capture requirements.

- For each compliance year an assessment is made as to how many sites were operating and met the data capture requirements. To ensure consistency of the approach, it is important that the calculation of the difference between two compliance years is only assessed at those sites that were operational over both periods. Otherwise, a different monitoring instrument cohort is being compared to each other.
- For each assessment year, a mean is calculated from the annual average data over a three year period (the previous three years data) e.g. for 2022 this would be annual average data for 2020, 2021 and 2022. Sites would only be included that met minimum data capture requirements. Therefore, only those sites that were operational during a full four-year period (covering both compliance years and their complete three-year data set meeting data capture requirements) are included for determining the year-on-year reduction (in µg m^{-3}).
- Assessment is then made for 2023 compliance year (2021, 2022 and 2023) using the sites that were operational/open for both the 2022 and 2023 assessment periods. The calculation for 2023 is then compared to 2022 for those operational/open sites to calculate the population exposure reduction between the two years.
- For 2024, you would need to understand the sites that were ‘open’ in all the years used to calculate both the average in 2023 (2021, 2022 and 2023) and 2024 (2022, 2023 and 2024). Only sites that were operational for all four years (2021 to 2024) are used in the calculation of a comparison of an annual average for 2024 with 2023 to calculate the population exposure reduction between the two years.
- The difference in assessment years is recorded and summed.
- The total percentage reduction would be calculated by summing up the population exposure reductions between years and comparing this against the 2018 baseline.

Table 6. Table illustration how the PERT will be calculated

Compliance Year	Annual Average Data Assessment Period	Difference in compliance years	Difference recorded
2018	Baseline Year 2016, 2017, 2018		
2019	2017, 2018, 2019	Initial reduction calculated in µg m^{-3} from comparing compliance year 2019	Initial reduction compared to baseline +/- µg m^{-3}
2020	2018, 2019, 2020	Year 2020 compared to 2019	+/- µg m^{-3}
2021	2019, 2020, 2021	Year 2021 compared to 2020	+/- µg m^{-3}
2022	2020, 2021, 2022	Year 2022 compared to 2021	+/- µg m^{-3}
2023	2021, 2022, 2023	Year 2023 compared to 2022	+/- µg m^{-3}

Measuring $PM_{2.5}$ as part of the Rural Network

Rural background $PM_{2.5}$ concentrations are currently monitored at only two sites in England as part of the AURN. Measurements at such rural locations contribute to assessment against the concentration target and are important for understanding the regional nature of $PM_{2.5}$. They are not however required for representative measurements of population exposure. Current sites are listed in

Table **7**.

Table 7. Current rural monitoring sites in England

Site	Location
UK-AIR ID: UKA00614 **Chilbolton Observatory**	The monitoring station is located approximately 200m SE from the outskirts of Chilbolton Village, in arable farmland.
UK-AIR ID: UKA00251 **Rochester Stoke**	The monitoring station is located on the western boundary of a rural primary school. The nearest main road is approximately 80 metres to the east of

	the location. The area is generally open and rural.

In addition to these rural measurements, there are separate monitoring networks that record other pollutant levels at rural background locations including some PM components/composition measurements (Table 8).

Table 8. Monitoring of PM components

Network
Particle Numbers and Concentrations Network Analysis of PM components, comparative analysis between secondary particles, the $PM_{2.5}$ fraction and particle sizes and numbers.
Acid Gas and Aerosol Network (AGANet) The network provides a long-term dataset of monthly speciated measurements of acid gases and aerosols that are used to provide temporal and spatial patterns and trends and compared with results from dispersion models.
AURN – Ozone monitoring. Providing high resolution hourly information.

Background concentrations can make a considerable contribution to the overall mass of $PM_{2.5}$ in urban areas, accounting for around 60 to 80% of the background concentrations in the major urban areas of southern England. In addition, elevated $PM_{2.5}$ concentrations are frequently associated with air transported into the UK from continental Europe.

Previously, the Air Quality Expert Group (AQEG) (10) recommended that '*The $PM_{2.5}$ monitoring network should be expanded to allow a better quantification of the rural background'.* This was on the basis that there are currently limited measurements to quantify sources and $PM_{2.5}$ composition in different types of location and in different areas of the UK. The expansion of the English network would aid in the verification of modelled background concentrations and also confirm the modelled spatial pattern of rural background concentrations. However, it was also advised that the rural background monitoring sites should not form part of the PERT metric as they are not representative of significant population exposure. Instead, increased monitoring at rural locations would be beneficial to understand the background concentrations across the country and aid evaluation of what is driving any overall change. Wherever possible, in expanding the network, it would be beneficial to use existing sites that have already been established through the rural ozone and AGANet network to benefit from co-location of measurements but also operationally with regards to maintenance and upkeep of the monitors.

It is proposed that:

- **The rural background monitoring capability will be increased but will not form part of the PERT metric.**

To increase our understanding of the rural background concentrations of $PM_{2.5}$ it is proposed that there is an iterative evolution of the existing network of monitors. Funding is already available to implement this step change in rural background monitoring for 2022/2023. The focus in the first phase by end 2023 will be to address the following:

- Ensure all zones (i.e. non-agglomerations) have at least one monitor that quantifies rural background concentrations.
- Allocation of new sites will utilise (where possible) existing monitoring locations to ensure benefits of co-location (running costs, evidential value). This will also aid in the comparison of $PM_{2.5}$ to other pollutants monitored in the same location.
- The network of rural background monitors will be expanded after 2022 using the above principles subject to funding in future years.

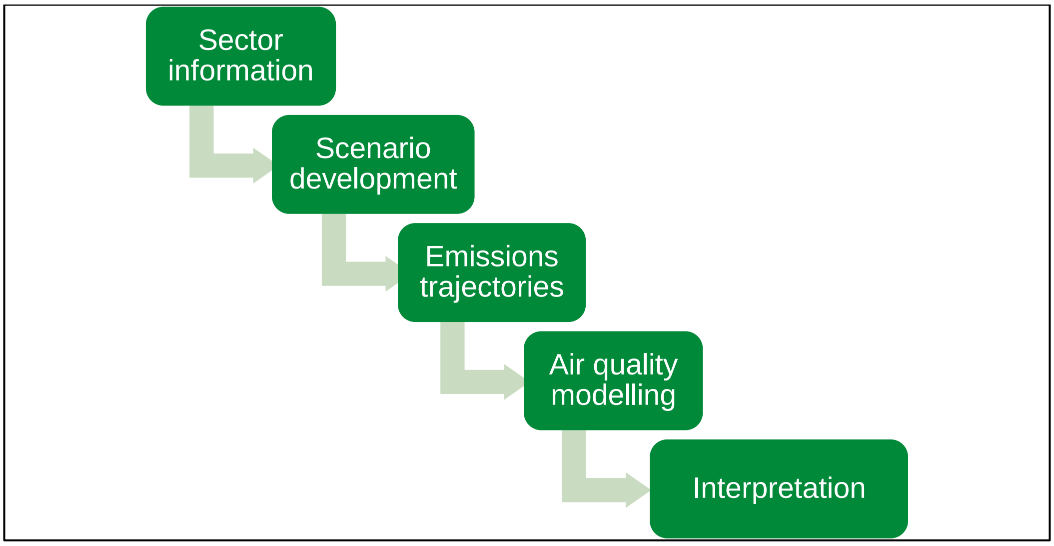
Achievable metric values and timeframe

This section describes the analysis and modelling carried out to better understand the achievability of different target values and dates. Air quality modelling is a useful tool in understanding the impact of emissions reductions on pollutant concentrations, however there are multiple sources of uncertainty both inherent in the modelling of complex chemical interactions and in the modelling inputs. The results are only indicative of potential future scenarios, and any single model run should not be taken as absolute prediction. However, by modelling a range of scenarios it is possible to gain insight into future reduction potential. In addition to informing target achievability the modelling outputs are also used in the impact assessment as described later.

Figure 4 the main steps of the analysis undertaken to explore what levels of $PM_{2.5}$ reduction are feasible in future years. While this report refers to “modelling” in a general sense, the schematic represents a framework for assessment, drawing on the input of a wide range of expertise, datasets and tools - all of which have complex interactions and challenges.

At each step there was engagement with relevant experts and stakeholders, and AQEG was consulted throughout.

Figure 4: Steps in modelling future PM2.5 concentrations



Sector information and scenario development

Future pollutant emissions will be determined by multiple factors, including technological innovations, changes in industry practices, public behaviour, socioeconomics, and external factors (for example, the covid pandemic significantly changed behaviours and subsequently change emissions from key sources such as road transport), all of which are impossible to predict with any certainty. However, some indication of what future emissions can be obtained by examining potential changes within different sectors of society and determining the likely impact on emissions. Defra commissioned a consultancy to review individual sectors, identifying possible changes which could affect emissions of $PM_{2.5}$ and precursors. Precursors are pollutants such as nitrogen oxides (NOx), ammonia (NH_3) and sulphur dioxide (SO_2) which can react in the atmosphere to form secondary $PM_{2.5}$ so are also important factors when looking to control $PM_{2.5}$ concentrations.

The consultants reviewed literature, such as sector roadmaps, horizon scanning reports and academic papers that provided information on technology and practices that may change in the future. From this they produced a list of what is referred to as “measures”. These are a mix of technologies, policy interventions, behaviour changes and trends. These measures do not necessarily directly correspond with a particular potential government policy, and the scenarios developed should not be considered policy pathways. They are possible futures for the purposes of mapping out which targets are feasible and only provide an indication of the types of action and scale of intervention that would be needed to achieve different concentrations by different dates in the future.

The measures identified in the literature review were discussed with industry experts and stakeholders through a series of one-to-one interviews and sector workshops.

Table 9 lists the sectors and engagement activities for each.

Table 9. Sector information

Sectors	Literature Sources	Interviews	Workshop Attendees
Agriculture	22	8	29
Aviation	16	6	17
Construction and Non Road Mobile Machinery (NRMM)	31	7	23
Industry and manufacturing	48	20	42
Domestic and commercial Combustion	46	10	15
Rail	13	7	See note
Road Traffic Technology	53	23	24
Shipping	29	4	17
Urban Mobility	58	20	16
Grand Total	**316**	**105**	**183**

Note: There was no rail workshop held, as interviews with key stakeholders were considered sufficient due to the high degree of centralisation within the industry with DfT, Network Rail, RSSB, RIAGB and RDG representing industry consensus

Interviewees and workshop participants were a mixture of academics and consultants working in a particular sector, industry practitioners or trade organisations and other government department analysts. The validity of individual measures, timeframe for implementation, supporting actions required, barriers, costs and co-benefits were discussed, along with any additional measures that might have been missed. The list of measures was then revised to reflect the discussions.

Participants were also requested to provide views on what constituted different levels of ambition and/or optimism in terms of implementation time and expected uptake. This information was used to assign the measures to three scenarios, referred to as medium, high and speculative. Measures included within the medium scenario tended to be proven technologies with fewer barriers to implementation or more modest changes in behaviour. The uptake and implementation times assigned to these were those considered more achievable. In the high scenario additional measures were added and uptake and implementation times more optimistic. The measures and uptakes within the speculative scenario were at the boundary of what stakeholders felt was plausible, including technologies still in development and significant changes in public behaviour. The scenarios created by these packages of measures were discussed with different teams within Defra and across other government departments before being finalised. This work formed the basis for the scenario measures, although with some modifications made by the modellers to enable the measures to be modelled and updates to reflect later advice.

Emission trajectories

The measures identified in the sector review were uploaded into bespoke software developed for Defra called the Scenario Modelling Tool (SMT). The SMT enables the impact of measures on future emissions to be modelled. The tool works by applying selected measures to baseline emissions, modifying the relevant pollutant emissions factors or activity levels by a percentage which can be varied over time.

The baseline emissions used for the target scenarios were the projections produced as part of the National Atmospheric Emissions Inventory (NAEI) 2018 (17). These are official statistics produced on behalf the Department for Business, Energy and Industrial Strategy (BEIS), Department for Environment, Food and Rural Affairs (Defra), the Scottish Government, the Welsh Government and the Northern Ireland Department of Agriculture, Environment and Rural Affairs using agreed international methodologies for the purposes of determining compliance with international agreements on emissions reductions (more information on the NAEI website[26]). The emissions projections are based on data such as projected energy use, traffic, GDP, population growth and takes account of the impact of legislation already in place, but not yet implemented. These projections were slightly amended to include the impact of more recent legislation that has yet to be incorporated into the NAEI projections, such as the regulations on domestic coal and wet wood, and data updates such as the amended emissions factors for diesel cars as a result of Euro 6 real world emissions testing (see Box 1). The NAEI 2018 adjustments are described in more detail in the Impact Assessment[27].

Box 1: NAEI 2018 adjustments

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

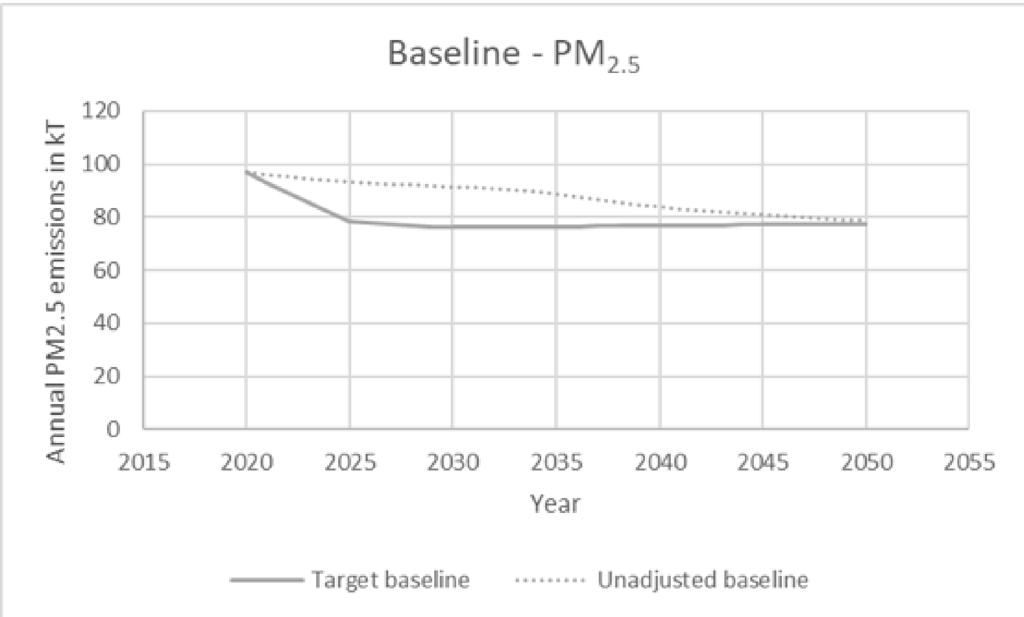
[26] https://naei.beis.gov.uk/

[27] https://consult.defra.gov.uk/natural-environment-policy/consultation-on-environmental-targets/

Emissions projections up to 2030 are made routinely as part of the NAEI programme, whereas the SMT allows for trajectories up to 2050. In setting long term targets it is important to be able to consider projections beyond 2030, therefore, our NAEI contractor was commissioned to extend NAEI projections up to 2050 for this work. In developing a methodology for this it was clear that data post-2030 was available for some sectors (transport and energy), but not for other sectors. Where there was not available data, emissions were conservatively maintained at the 2030 level. A short report on the approach taken, including an evaluation of the robustness of this approach is linked to in Annex D: Note on the extension of NAEI 2018 baseline projections.

Figure 5 compares the primary $PM_{2.5}$ emissions for the target baseline with the unadjusted NAEI 2018 projections, the short-term reduction due to recently introduced legislation can be seen particularly in the gradient of the target baseline up to 2025. The baseline adjustments also affect other pollutants such as NO_X, although to a lesser extent. As described in Annex D: Note on the extension of NAEI 2018 baseline projections it is likely that after 2030 emissions from some sectors will decrease and others increase, but due to limited information on future emissions after 2030 the baseline flattens from this point onwards. It is likely this is a cautious approach as it would be expected that drivers other than the new targets are likely to reduce emissions, for example actions related to net zero, future UK BAT and National Emissions Ceilings Regulations 2018 (NECR). The impact of net zero and NECR are explored through additional scenarios as described.

Figure 5: Comparison of unadjusted NAEI 2018 primary PM2.5 emissions trajectory and adjusted target baseline



The three target scenarios (medium, high and speculative) were modelled in the SMT by selecting the measures and setting the implementation start date, maximum uptake, date at which this was reached and uptake profile in line with the scenario being modelled. The measures were applied to all the UK[28], with some measures applicable to certain locations or types of location e.g. only urban traffic, certain types of industry or ports. Although not all interactions between measures and specifics of measure application can be modelled, the SMT is sophisticated enough to enable some interaction between measures, for example maintaining total energy needs when switching fuels. As the baseline is based on the NAEI, only sectors included in the NAEI are modelled, for example cooking emissions are not included but a separate sensitivity analysis has been undertaken on these.

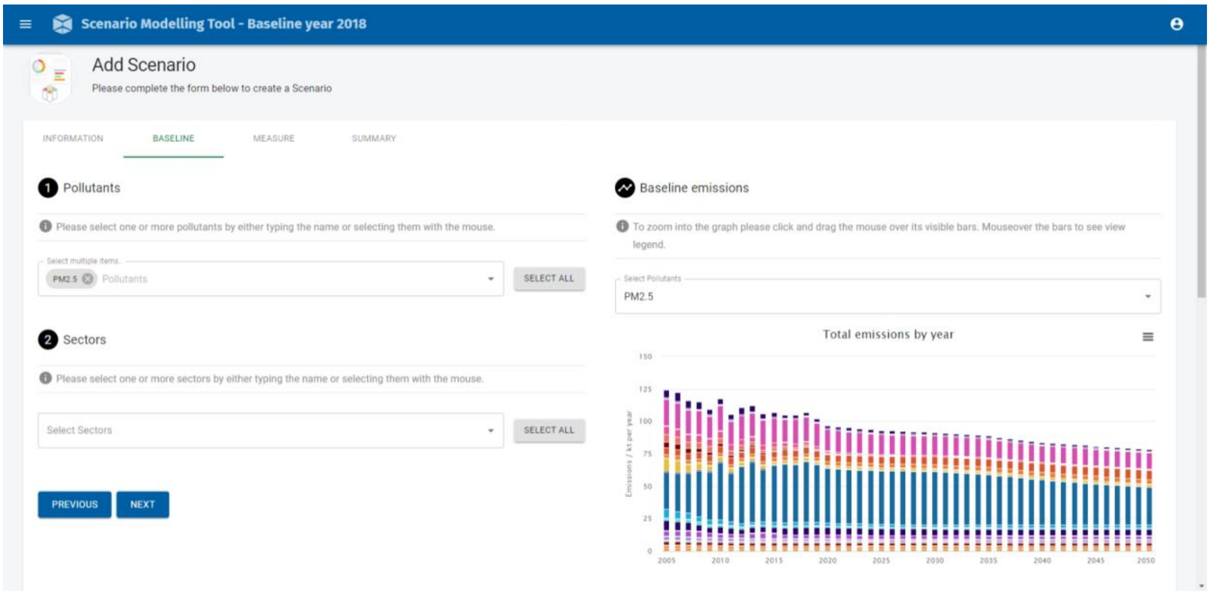
Based on the measures and parameters set for each scenario the SMT produces UK emissions trajectories for key air pollutants and GHGs for every year up to 2050. The tool also produced a summary of the accumulated costs of implementing the measures in the scenario based on estimated unit costs developed in the scenario development expert engagement work. This cost data was used in the Impact Assessment. Figure 6 summarises the target scenarios modelled and Figure 7 an illustrative screenshot of the SMT.

[28] In practice some measures may vary due to different policies within devolved administrations or local areas.

Figure 6: Summary of target scenarios

Target baseline	• Based on existing interventions and policies • Natural technology turnover • NAEI 2018 projections with some adjustments to account for recent legislation and updated data
Medium	• Based on measures/activity identified by the sector review • Implementation of proven technology and limited behaviour change, typical timescales and uptakes
High	• Based on measures/activity identified by the sector review • Technology considered likely to be implementable in the future by stakeholders, increased behaviour change and more rapid timescales
Speculative	• Based on measures/activity identified by the sector review • All feasible measures including emerging technology and significant behaviour change, optimistic timescales and uptakes

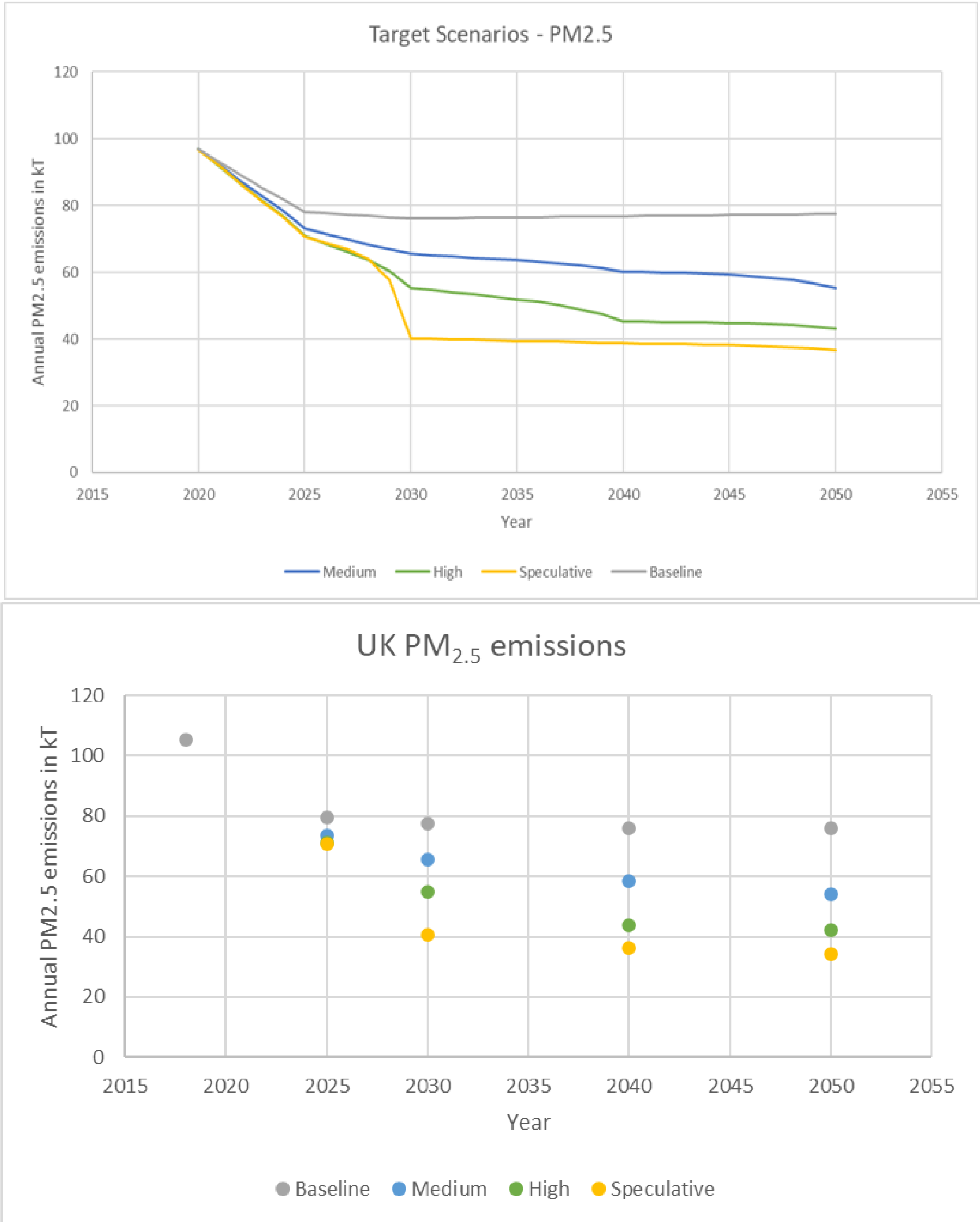
Figure 7: Screenshot of the scenario modelling tool (illustrative)



The baseline and speculative scenarios set the boundaries of what is considered likely future emissions. The baseline provides the conservative view, with emissions unlikely to be above this and the speculative the optimistic view with emissions unlikely to be below this. Medium and high provide markers within this boundary, showing the impact of various types of future changes. The trajectories for primary $PM_{2.5}$ emissions produced by the

SMT are shown in Figure 8(a). Trajectories for the precursor pollutants were also produced.

Figure 8: Primary PM2.5 emissions trajectories for target scenarios (a) as produced in the SMT, and (b) as modelled.



Note. The SMT trajectory does not include agriculture measures which affect mainly ammonia and were modelled separately and the emissions as modelled do not include domestic shipping. These sectors are small primary $PM_{2.5}$ emitters so do not materially affect the trajectories.

All scenarios produce significant reductions in $PM_{2.5}$ emissions compared to the baseline, with the difference between the three becoming greater from 2025 – 2030 onwards. This is because many of the measures included need a lead time for implementation. The shape of the curve is determined by the implementation date and uptake profiles for the measures, for example the step change in the speculative trajectory in 2030 relates to restrictions of one or more activities coming into force. Agriculture measures, mainly affecting ammonia, were run in a separate version of the SMT which enabled more detailed modelling to be undertaken, e.g., consideration of measures by type of livestock.

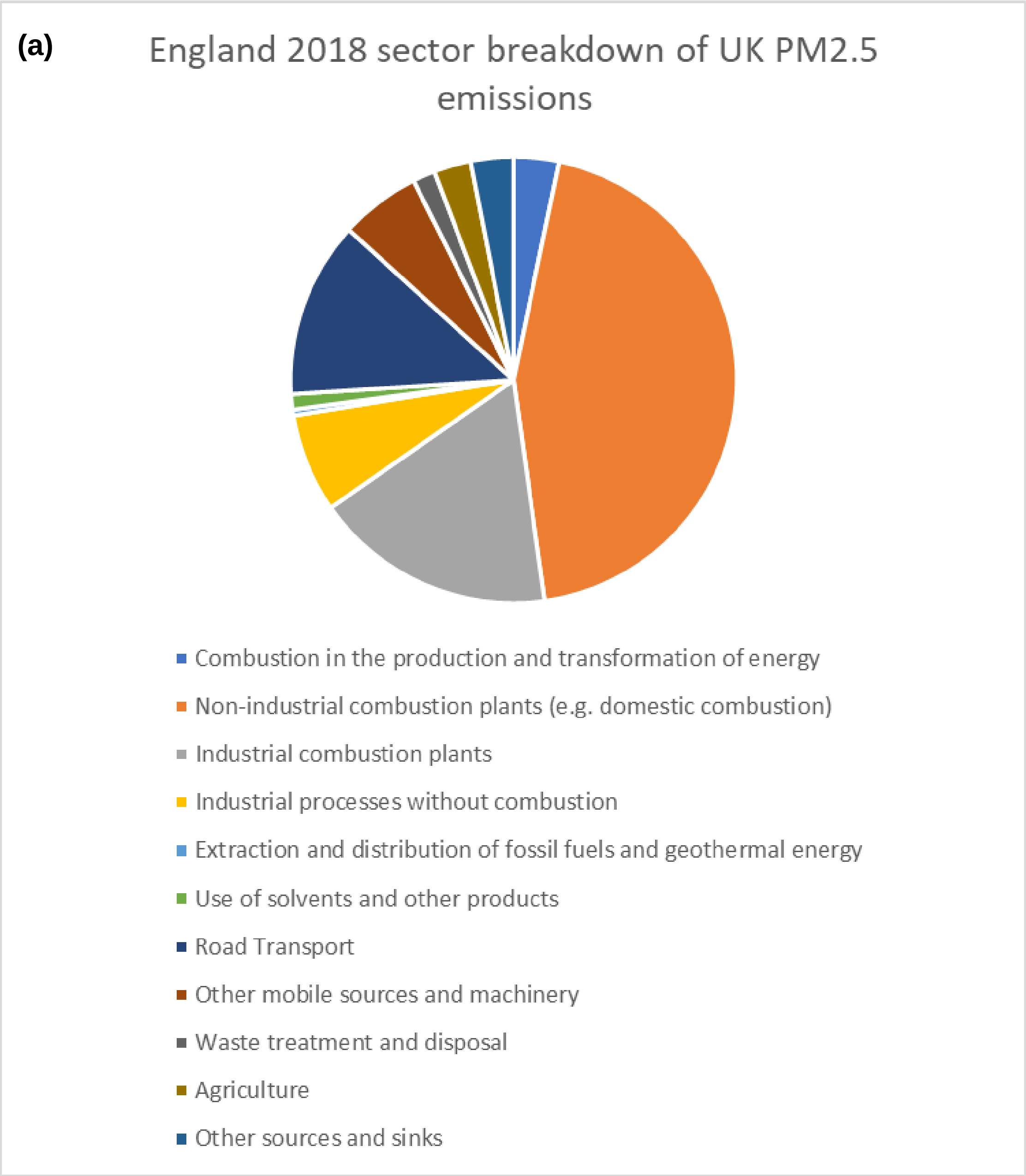
The most important emissions trajectories in terms of calculating $PM_{2.5}$ concentrations are those for $PM_{2.5}$, NOx, NH_3 and SO_2 and these are outputs of the SMT alongside greenhouse gas emissions (GHG). Changes in the emissions of GHGs were used when calculating the co-benefits of the scenarios.

In addition to the total amount of a pollutant released, where emissions take place is very important for air quality modelling. Emissions from ground sources close to where people live and work have a greater impact on population exposure close to the emissions source than emissions away from residential areas and at height (for example, industrial emissions may be via a 30-metre chimney/stack). This means for example road vehicle tailpipe emissions have a greater effect on $PM_{2.5}$ concentrations in urban areas than the same amount of pollution emitted from the stack of a power station outside of town. The modelling undertaken takes the location of the emissions, the emissions characteristics, as well as the emissions total into account.

The proportion of emissions from each source differ by location as well as pollutant, with key differences between urban and rural locations. For example, most of the ammonia across England is produced by agriculture, but in urban areas ammonia is released predominantly from waste treatment and disposal. Figure 9 shows the average mix of sources of $PM_{2.5}$ for England and the mix for London, illustrating the differences for a large urban area. Notable differences are the proportion of $PM_{2.5}$ produced by industrial combustion (5% in London compared to 18% for England), road transport (25% for London compared to 13% for England) and domestic combustion (53% in London compared to 45% in England). Note that emissions are taken from NAEI 2018, and there are uncertainties in estimates in historic emissions, as well as future emissions. As discussed later, emissions from some sectors such as domestic combustion are more uncertain than others, and for this reason specific sensitivity analysis has been carried out on these sectors. Work to improve the accuracy of national emissions estimates is an ongoing part of Defra's remit, and methodologies and estimates are continually revised to incorporate new information. For example, Defra commissioned a report on domestic burning (18) which suggested less burning is taking place than is included in NAEI 2018, and there is ongoing work (19) on developing improved emission factors (the amount of emissions released by unit of activity) for different types of domestic fuel including wet wood which produces greater emissions. Estimates of wood emissions may therefore differ in future NAEI updates, which may change the proportions from different sectors.

Emissions from the NAEI 2018 (Figure 9), the most up to date official estimates at the time of modelling, shows that the largest sources of $PM_{2.5}$ emissions are domestic combustion and road transport. In 2018 these two sectors combined are estimated to produce 58% of England's $PM_{2.5}$ emissions and 78% of London's emissions. Figure 10 shows how the sources of the England emissions differ in the 2040 scenarios. The proportion of emissions from different sources as well as the overall amounts differ by scenario and year, depending on the measures applied. All the scenarios include measures which tackle every sector, but as the largest contributing sectors road transport and domestic combustion emissions have the most reduction. Under the scenarios the proportion of emissions from road transport and domestic combustion decrease, for example in the high 2040 scenario the sectors produce 44% of England's emissions and 64% of London's emissions. However, they still remain the largest contributing sectors. As above future emissions projections, even as part of the baseline, are subject to a degree of uncertainty. It is also worth stating that estimates of London emissions differ in the NAEI compared to London's own inventory (the London Atmospheric Emissions Inventory or LAEI). Sensitivity analysis was undertaken in part to reflect such differences, particularly around domestic wood burning but also for sources like cooking that are in the LAEI but not currently in the NAEI.

Figure 9: Breakdown of 2018 PM2.5 emissions (a) for England and (b) for London (based on NAEI 2018)



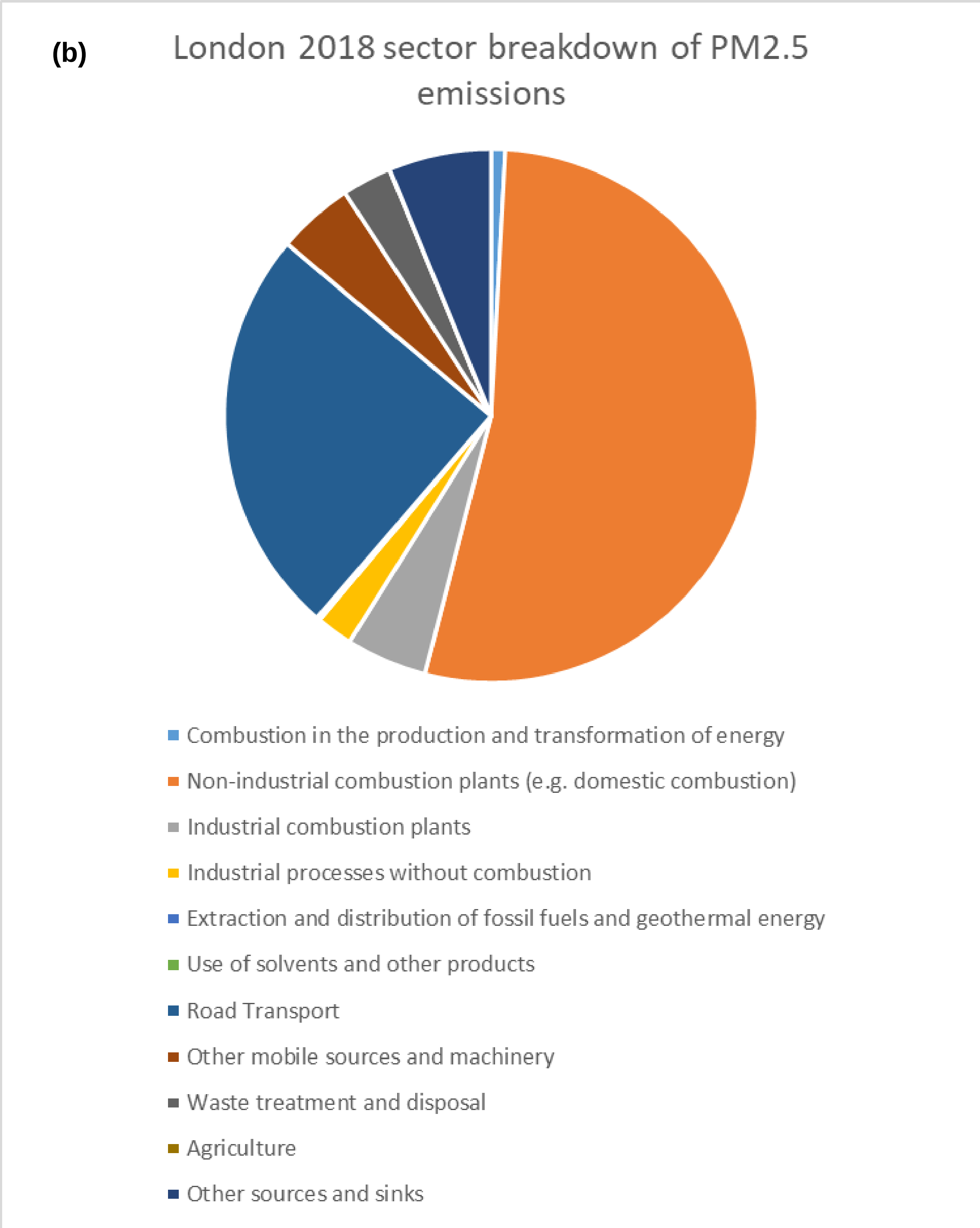
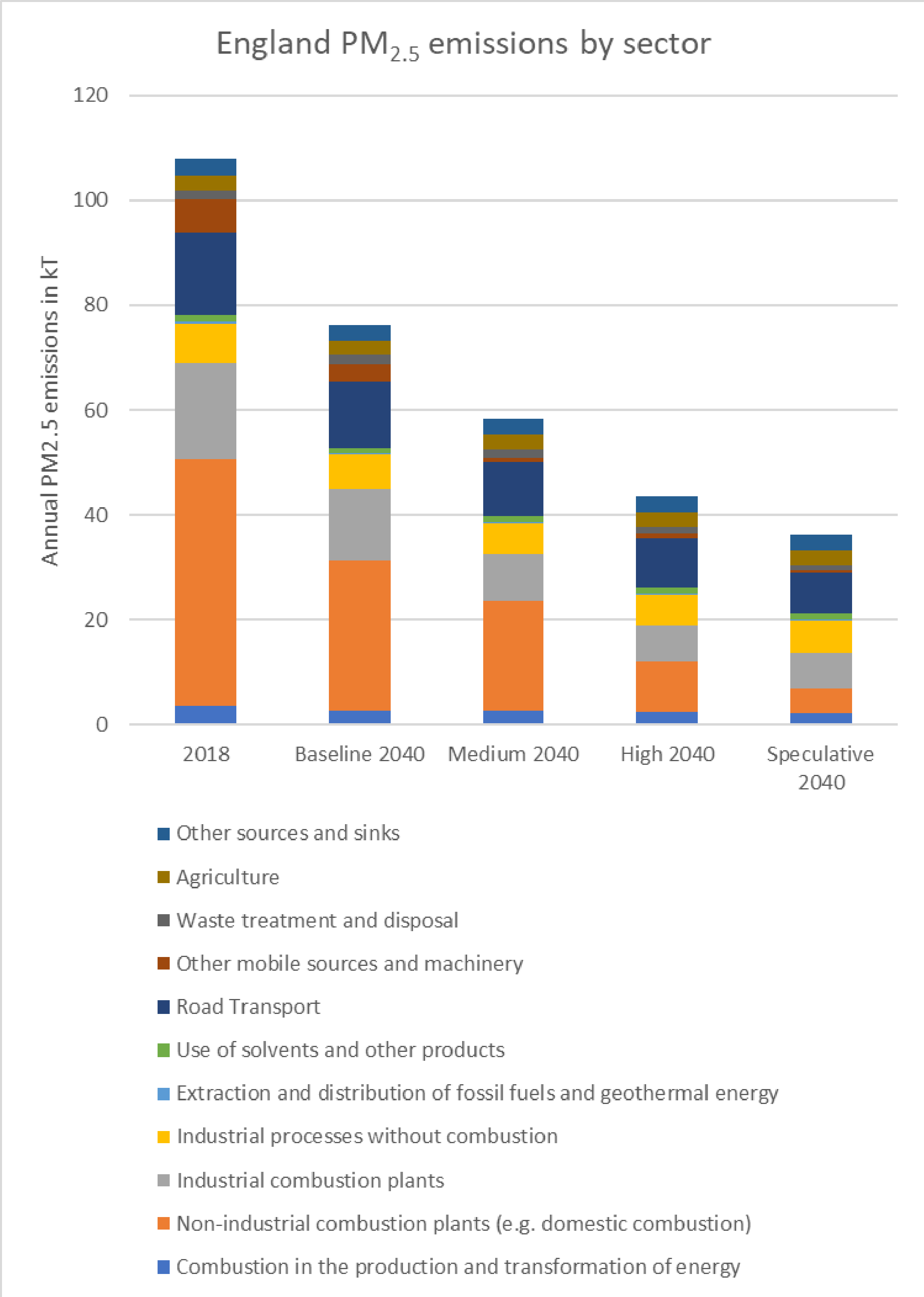

(b)
London 2018 sector breakdown of PM2.5 emissions
Combustion in the production and transformation of energy
Non-industrial combustion plants (e.g. domestic combustion)
Industrial combustion plants
Industrial processes without combustion
Extraction and distribution of fossil fuels and geothermal energy
Use of solvents and other products
Road Transport
Other mobile sources and machinery
Waste treatment and disposal
Agriculture
Other sources and sinks

Figure 10: Breakdown of England PM2.5 emissions by sector for 2040 scenarios

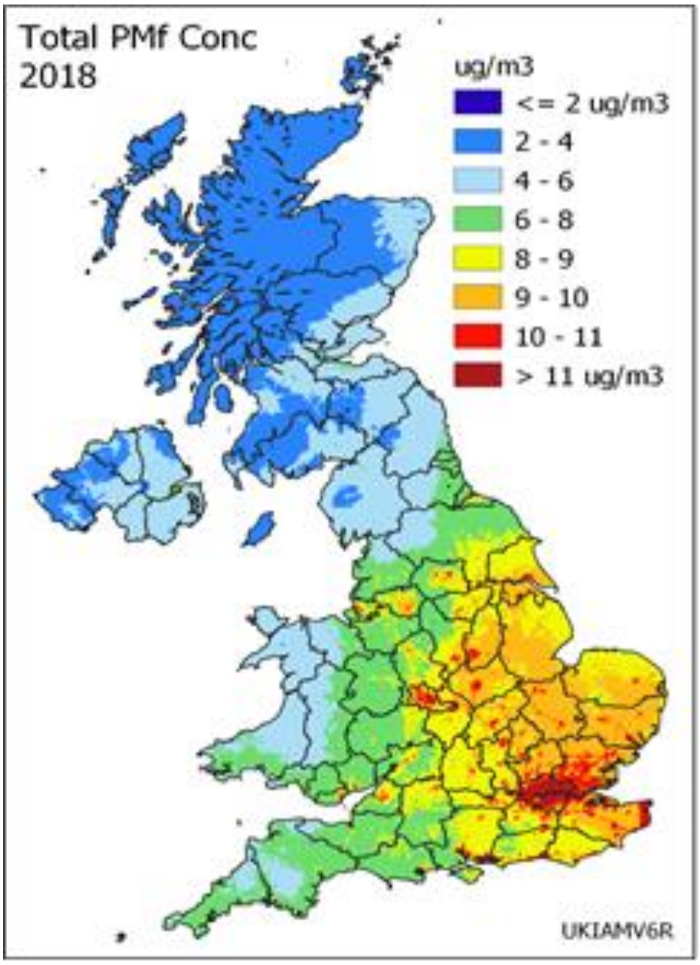


Air quality modelling approach

UK Integrated Assessment Model (UKIAM)

Internationally recognised experts in air quality modelling from the Integrated Assessment Unit in the Centre for Environmental Policy at Imperial College London (ICL) were commissioned by Defra to carry out modelling to inform the development of the new $PM_{2.5}$ targets. ICL have developed the UK Integrated Assessment Model (UKIAM) for Defra over many years to enable the impacts of different policies on air quality to be modelled. The model uses emissions data and dispersion modelling to produce pollutant concentrations by 1 kilometre grid square across the UK. Figure 11**Error! Reference source not found.** is an example of UKIAM output and depicts $PM_{2.5}$ concentration for the 2018 base year (i.e., based on the NAEI 2018 emissions for the UK). The spatial variation across the country can be seen, with higher levels in the south east, in part due to higher natural and transboundary affects, and the peaks in major towns and cities where the majority of primary UK $PM_{2.5}$ is emitted.

Figure 11: Example UKIAM output - modelled PM2.5 concentration for 2018



Modelling the target scenarios

The main input data for the three target scenarios were UK emissions (based on modified SMT data), the International Institute for Applied Systems Analysis (IIASA) scenarios[29] for European emissions and the natural $PM_{2.5}$ components developed for the Pollution Climate Modelling (PCM)[30]. Unlike the SMT, UKIAM models individual years so 2018 (the base year), 2025, 2030, 2040 and 2050 were modelled for each scenario and the target baseline to provide a timeline.

Modifications were made to the SMT data by ICL in order to improve upon it and for it to be in a form suitable for UKIAM to model air quality concentration changes. For example, ICL have developed a separate sub-module to UKIAM called BRUTAL, which enables the spatial variation in road transport emissions to be estimated in more detail than is possible in the SMT. It uses data on the specific road links within individual grid squares and breaks vehicle types down into Euro standard sub-types. For shipping too, ICL use more detailed modelling of emissions using vessel type and location (see their shipping report (20) for the methodology employed). The UKIAM modelling includes international shipping emissions as an input, as vessels which transit near to the UK contribute to its air quality even if they do not call into British ports. Other measures were not included due the difficulty of applying them compared to their very low impact on emissions. Figure 8(b) shows the UK $PM_{2.5}$ emissions modelled; this can be compared to the SMT outputs in (a).

Spatial influences

The type of measure affects where it is applied. In practise, some measures would need to be applied at a national or even international level, whereas others such as traffic or domestic burning restrictions can be targeted at specific locations. In modelling the main target scenarios all the measures were applied at a UK level but will affect the emissions from specific sources based on existing locations and activities. For example, measures affecting point sources such as power stations or large industry were applied to the appropriate location, some traffic measures were applied to only urban centres and other measures such as construction were applied proportionally in relation to population. These are indicative allocations; in practice a number of different considerations would be taken into account when determining where measures are applied. This re-emphasises that these scenarios are developed to consider the degree to which $PM_{2.5}$ concentrations can be reduced and not detailed pathways to deliver such levels.

Another point to note is that in practice some measures are likely to be applied to England only (i.e. as they relate to devolved policy areas and the new targets are for England only). As the UK is collectively committed to meeting existing emissions reduction commitments, it is not realistic to model no emissions reduction measures in the devolved administrations but for clarity**, these scenarios do not constitute devolved administration policies**. See the Impact Assessment for more information on how the individual nations and

[29] The International Institute for Applied Systems Analysis (IIASA) developed scenarios to model European emissions to evaluate progress against international emission reduction commitments. (35)

[30] The Pollution Climate Mapping (PCM) model was developed for the reporting of pollutant concentrations against the EU Directive requirements. See Modelled air quality data - Defra, UK

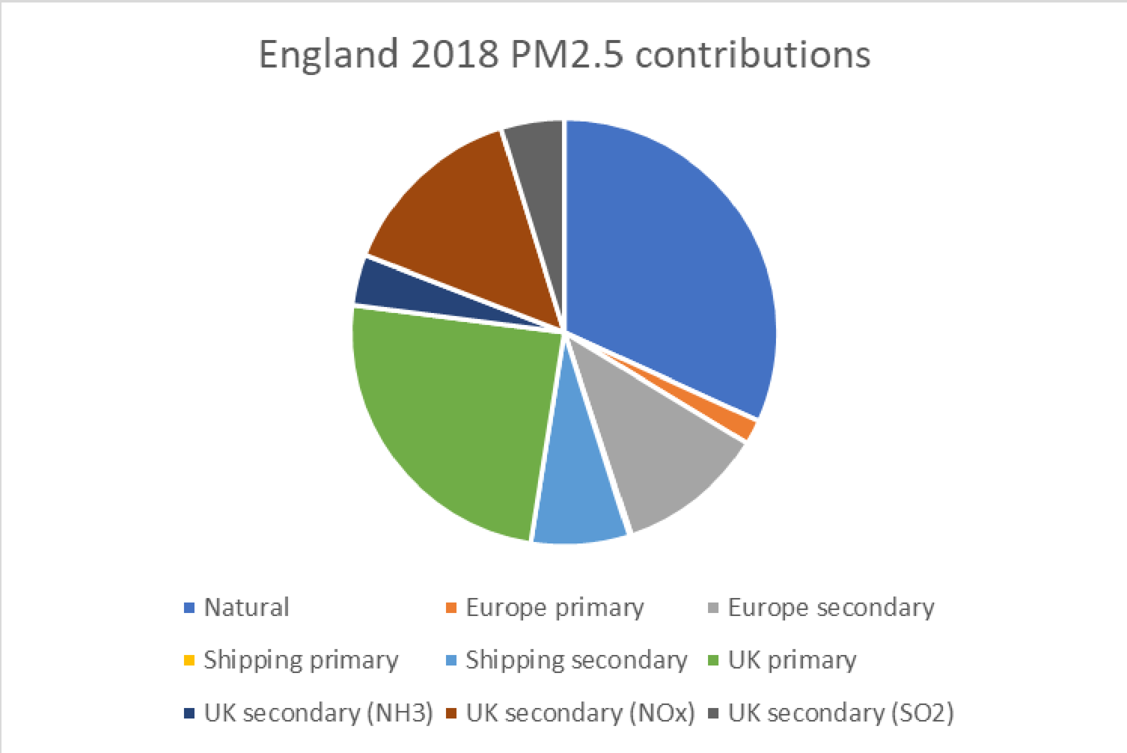
regions affect each other's $PM_{2.5}$ concentrations. It is to be expected areas close to borders would influence each other and that the prevailing wind direction will play a part in determining interactions. This simplification does not materially affect the levels that can be achieved in England, which is the main purpose of this modelling.

To understand if focusing measures on urban hotspots would impact significantly on average exposure as well as the highest concentrations, given the regional nature of $PM_{2.5}$, a number of hybrid scenarios were modelled. In these hybrid scenarios one scenario was applied to the UK nationally, and a different scenario applied to London only, as the area with the highest $PM_{2.5}$ concentrations. Such scenarios might be considered to reflect prioritisation of the concentration target over population exposure reduction, with greater emissions reduction focus on London (to reduce the highest concentrations), rather than applying the higher emissions reduction across all of the country, where concentrations are already lower than in London. However, as we are setting both a concentration target and a population exposure target, it is important to compare such scenarios with measures applied universally, as although many of the measures would have benefits if applied across England there may be reasons such as the availability of existing infrastructure that would make it easier to apply only in urban centres.

$PM_{2.5}$ components and sources

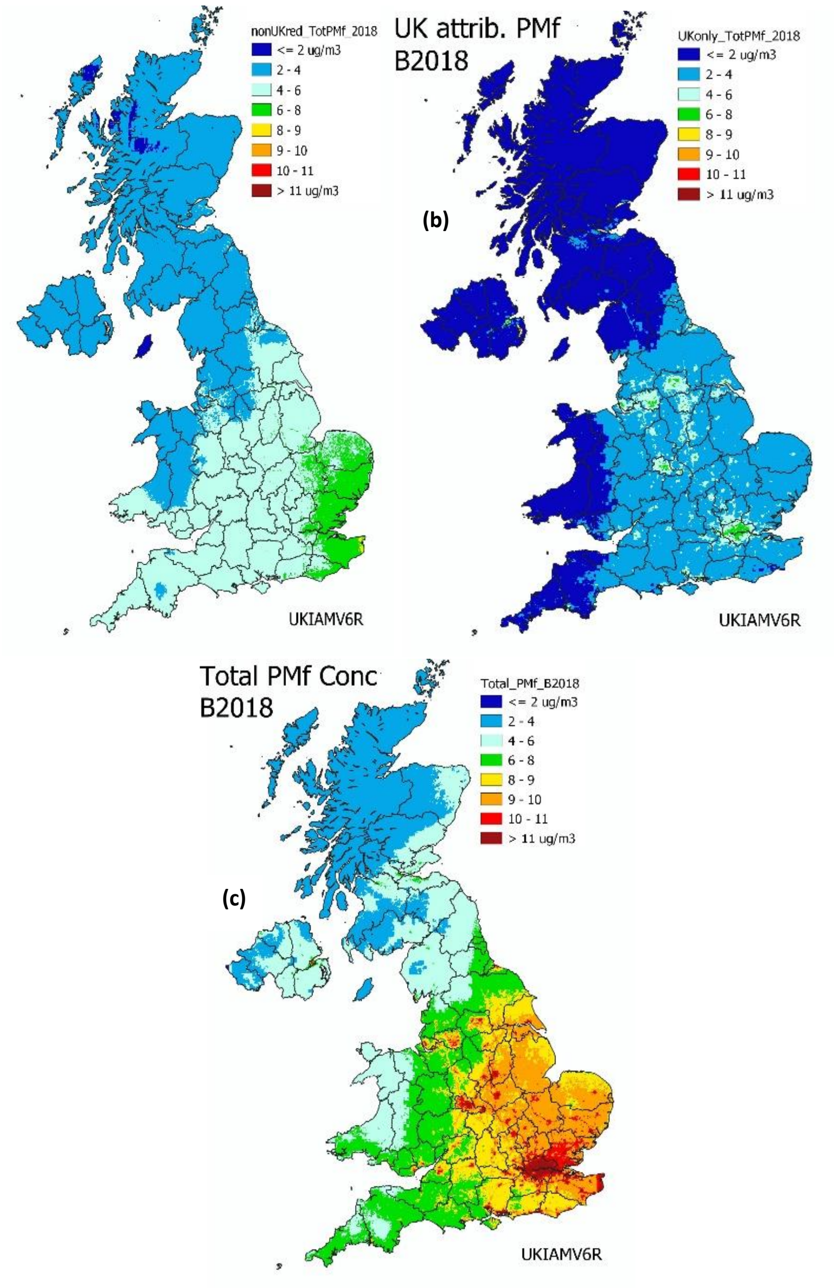
The modelling enables some speciation of $PM_{2.5}$ components and this can be used to apportion contributions back to key sources. In terms of the contributions to the England 2018 population weighted mean concentration (PWMC), primary emissions from the UK make the largest contribution to $PM_{2.5}$, followed by secondary emissions from the UK (see Figure 12). However, natural and secondary transboundary emissions from Europe and shipping make a significant contribution. The natural categorisation used here includes sea salt, dust from soil erosion and crops, biogenic secondary organic aerosol contributions from vegetation and resuspension of deposited natural and manmade dust. Whilst we have a degree of influence on land use and dust resuspension by traffic, to a large extent this component is outside of our control.

Figure 12: Contributions to PM2.5 concentrations, England 2018



Contributions from natural, transboundary and UK manmade sources all vary across the country. Figure 13 shows how contributions from natural and transboundary sources combine with UK manmade sources to produce the total $PM_{2.5}$ concentrations people are exposed to.

Figure 13: (a) Contributions outside UK control from natural and transboundary sources, (b) UK manmade contributions (c) total PM2.5 from all sources



The modelling also enables differences between urban and rural $PM_{2.5}$, and different English regions to be identified. Urban areas tend to be several µg m^{-3} higher than the surrounding area, and southeast regions have higher concentrations than North-West. A 1km grid square in this context was categorised as rural if the resident population is less than 500.

Analysis of output data

Additional analysis was carried out on the modelling outputs to understand the impact of the scenarios in terms of health benefits, economic costs, disparities in exposure and ecosystems impacts, as described later.

Uncertainties and sensitivity analysis

There is a large degree of uncertainty inherent in air quality modelling, due to assumptions that are required to be made both in the model itself and the input emission data.

Uncertainties relating to the model itself were addressed by commissioning a second modelling group based at UKCEH to model selected scenarios / years. They use a different model called EMEP4UK, which is an air quality model that takes account of both meteorological data as well complex atmospheric interactions. This type of model is termed a Chemical Transport Model (CTM) and is more complex than the UKIAM model. The model allows for the use of different meteorological data to be applied to different emissions scenarios (i.e., meteorology for a particular historic year, such as when there were adverse conditions for air quality). This enables comparison of the same emissions under different meteorological conditions, giving an assessment of how variable levels may be under high and low years, with the same emission levels.

EMEP4UK is a lower resolution model, takes longer to run and is not able to be adjusted so readily, so was used for comparison to UKIAM and to help understand the impact of weather conditions on $PM_{2.5}$ concentrations rather than to model all scenarios. As the model explicitly calculates secondary interactions in the atmospheric, with respect to different weather conditions, it is useful to validate performance of the UKIAM model particularly with respect to secondary $PM_{2.5}$ formation where there are significant non-linearities with respect to emissions reduction and concentrations. The UKIAM model is not driven by weather so essentially produces estimated concentrations for average weather conditions and has no ability to consider how concentrations may vary under different weather scenarios. In contrast, EMEP4UK is explicitly driven by a meteorological dataset, so can model the same emissions under different meteorological conditions. In reality, different meteorological conditions would also be associated with different levels of emissions – due to associated changes in demand for heating, for example, so this does not fully reflect all weather influences on $PM_{2.5}$ concentrations. There are also other differences between models such as how the natural $PM_{2.5}$ components and underlying chemistry are calculated. The outputs of the different models, modelling the same emission scenarios were compared to understand how different modelling approaches might affect the results.

Sensitivity analysis was used to examine in more detail some of the assumptions and uncertainties behind the scenarios and the impact these have on the results. Emissions from some sources are more difficult to estimate than others, for example it is easier to obtain data on regulated emissions from a limited number of large industrial point sources than from diffuse sources such as domestic wood burning which are not able to be directly measured and are spread throughout the country. However, it is worth noting here that if as suggested by some studies (18) the wood burning contribution is overestimated in the NAEI, this would mean greater reductions would have to be found from other sectors. Also cooking emissions are not currently included in the NAEI, and the sensitivity analysis carried out by ICL suggest that this is quite a significant contributor. As this source is missing, measures to reduce commercial cooking emissions could not be included in the main scenarios, but they could be considered as part of future decisions on actions for target delivery.

There are limitations in the way secondary organic aerosols (SOAs), formed from biogenic sources (i.e. vegetation) and anthropogenic VOCs, are represented in UKIAM. EMEP4UK modelling predicts SOA formation from biogenic and anthropogenic VOCs, taking account of the influence of land cover and meteorology on the biogenic component, and includes a constant for the background organic component. Whereas UKIAM uses one constant value for SOA taken from the NAME model. EMEP4UK modelling suggests that there will be a very small reduction in SOA under the future scenarios, however the SOA component of secondary $PM_{2.5}$ is much smaller than the SIA component (around 0.7 - 0.9 µg m^{-3}) and as the projected change is small overall this does not greatly affect the UKIAM results. However, this limitation does mean measures addressing these sources are missing from the scenarios. For example, biogenic emissions can be limited by planting appropriate species of trees when meeting afforestation targets, and reductions in anthropogenic SOA can be obtained by decreasing VOC emissions from products containing solvents and electrification of road vehicles (VOC emission reduction commitments are part of the NECR). It will be important to ensure future analysis considers how contributions to SOA can be appropriately controlled alongside measures to reduce other components of $PM_{2.5}$.

The five-yearly review cycle will enable up-dated evidence to be considered and actions revised accordingly.

Review and scrutiny

AQEG provided oversight and advice on the modelling approaches and was kept informed of progress throughout, with updates during its regular meetings. Members had the opportunity to ask questions on the different stages of the work and provide recommendations.

There were also a number of bespoke events relating to the target modelling. A call for evidence (CfE) on modelling future $PM_{2.5}$ concentrations was launched by AQEG at Defra's request in November 2020[31]. The call requested evidence on the range of $PM_{2.5}$ concentrations that could be expected under different future scenarios, the main drivers of future $PM_{2.5}$, differences in population exposure across the country and the level of uncertainty in modelling results[32].

Following this call a workshop was held in which ICL presented their model and planned approach and respondents selected by AQEG presented more detail on their written response to the CfE. AQEG produced a note based on the call responses and evidence providing recommendations which fed into the ICL modelling. This note largely focussed on the key messages in terms of the direction of travel for $PM_{2.5}$ in future years, the key drivers or change and the key uncertainties that must be considered when using modelling to assess future concentrations (Annex E: AQEG summary of the Call for evidence on future PM2.5 concentrations in England) and was used to inform the modelling that was undertaken.

[31] Call for evidence on fine particulate matter air quality targets - GOV.UK (www.gov.uk)

[32]- Defra, UK

Once the modelling was complete a workshop was held where ICL and UKCEH presented the results, and AQEG had the opportunity to scrutinise the approach taken and the interpretation of models outputs. AQEG prepared a note summarising their views following this workshop and this is also published as part of this evidence pack (Annex F: AQEG summary of the modelling results workshop). The group were largely content with the modelling approach taken and interpretation, given the accepted uncertainties in modelling and the bounds of time available. AQEG indicated that a generally conservative approach had been taken to the interpretation of model data and how each emissions scenario might meet future targets.

In addition to the review and scrutiny specific to the target work, ICL and UKCEH have produced many peer-reviewed journal and conference papers describing their models and results over the years.

Modelling results

The results of the modelling need to be considered as indicative of the changes in magnitude and spatial variation in $PM_{2.5}$ that could be expected under different emission scenarios at a national scale. They are not an accurate local forecast of the future concentrations at specific locations and points in time. There are many uncertainties in modelling future $PM_{2.5}$ concentrations. UKIAM produces average concentrations of 1km grid squares and locations within the squares will have higher or lower values depending on the local environment. For example, although UKIAM models road emissions explicitly, the results are incorporated into the grid square average, so it would be expected that a monitoring station close to a busy road could measure a higher annual mean concentration than the average for the grid square.

UKIAM provides concentrations for average meteorological conditions, annual mean concentrations for future years will depend on the weather conditions experienced. There are also data artefacts which can give a false view if taken out of context. The model uses NAEI data which assigns emissions to a particular grid square, in some cases all emissions relating to a particular industry may be assigned to one grid square rather than spread-out over all locations and this can result in some erroneously high values if not appropriately scrutinised. Therefore, although the modelling provides a good indication of national changes in concentrations over time, care should be taken in drawing conclusions based on changes in individual grid squares. In contrast, whilst higher resolution modelling can provide concentrations on a finer scale, often such modelling is limited by the granularity of emissions data (spatially and temporally) so again care must be taken with regards to interpretation (i.e., higher resolution is not always better).

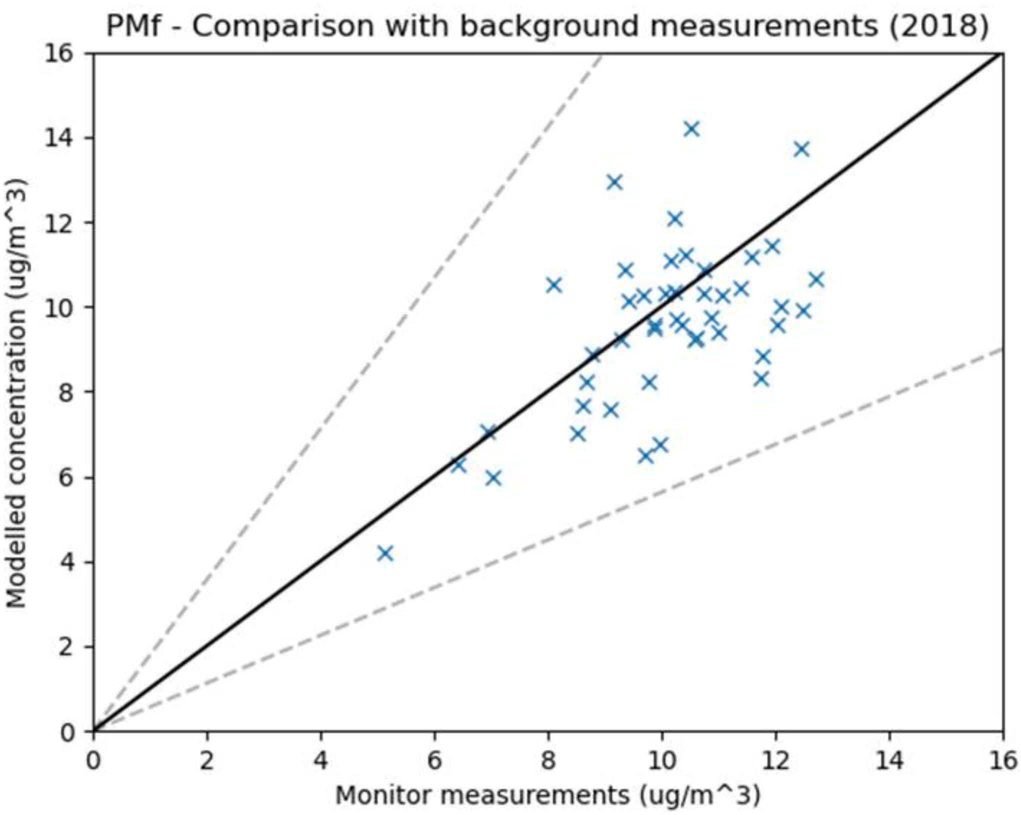
Comparison with monitoring

The modelling results for 2018 were compared with background monitoring measurements (not near source monitoring such as those made at roadside or industrial locations) for 2018. Figure 14 shows a plot of the modelled grid square values where monitoring sites are located against monitoring measurements made at those locations during 2018. The average modelled data shows a good alignment with the average measured data (full line).

The root mean square error (a standard statistical measure of deviation) is 1.7 µg m^{-3}. This means on average a modelled value can differs by up to 1.7 µg m^{-3} compared to the corresponding measured value. However, there is little bias (i.e., it is not consistently higher or lower), so the modelled average is much closer to the measured average (a difference of 0.5 µg m^{-3}). There are a number of factors that may contribute to this difference for individual sites:

- emissions data artefacts may result in some grid squares being modelled erroneously high
- the location of a monitoring site may not be representative of the whole grid square (i.e. conditions could be atypical or there could be micro-climate influences at the monitoring site).
- inherent variability due to weather conditions (2018 may not have been an average meteorological year)
- variability in monitoring equipment (measurements have an inherent uncertainty/spread due to measurement error)
- modelling uncertainty and assumptions

Figure 14: Comparison on UKIAM modelling results with monitoring in 2018 (produced by ICL)

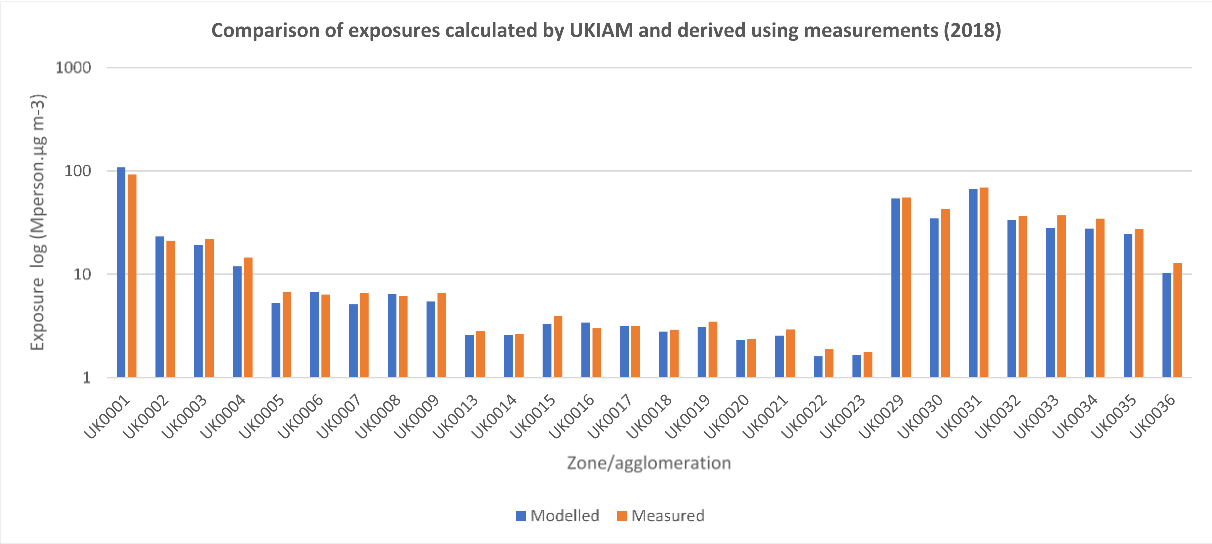


It is worth stating that both modelling and monitoring have a level of uncertainty related to the concentrations calculated or measured, and whilst it is important to compare models with measurements, measurements only provide information at a particular fixed location and may not be representative of the wider area. In addition, measurement uncertainty can vary with instrument type, location and the composition of $PM_{2.5}$ being measured, so there are a number of factors related to both the modelling and the measurements as to why the comparisons are not closer to the 1:1 line and that a degree of spread to be expected. The difference is small compared to the difference between years due to variable meteorological conditions.

A comparison of population exposure calculated for each zone by either modelling or by using the available monitoring data in each zone (i.e. using measurements as a surrogate indicator of population exposure in a region) illustrates good comparability, although measurements tend to give higher estimates of exposure for each zone and agglomeration (see Figure 15) compared to modelling. This is to be expected as monitoring sites are normally located in areas of higher concentrations. This type of analysis will be used to consider where additional monitoring may be needed as the network is considered for future expansion. More information is presented in the modelling section.

Overall, comparing the modelled and measured data shows that the modelling provides a good representation of the base year data and is a robust means to calculate national metrics like the PERT. However, such comparisons do highlight that it is much more challenging to model concentrations for individual monitoring sites, even in the base year, using a national model of this type. Predicting how changes to emissions will then affect concentrations at specific locations in future years is extremely challenging and susceptible to quite significant uncertainties. Therefore, evaluating the achievability of the AMCT is much more difficult than predicting changes in the national exposure reduction (PERT).

Figure 15: Comparison on population exposure calculated for each zone and agglomeration in the UK (not just England) using UKIAM modelling compared to exposures derived from monitoring located in each zone/agglomeration (2018).



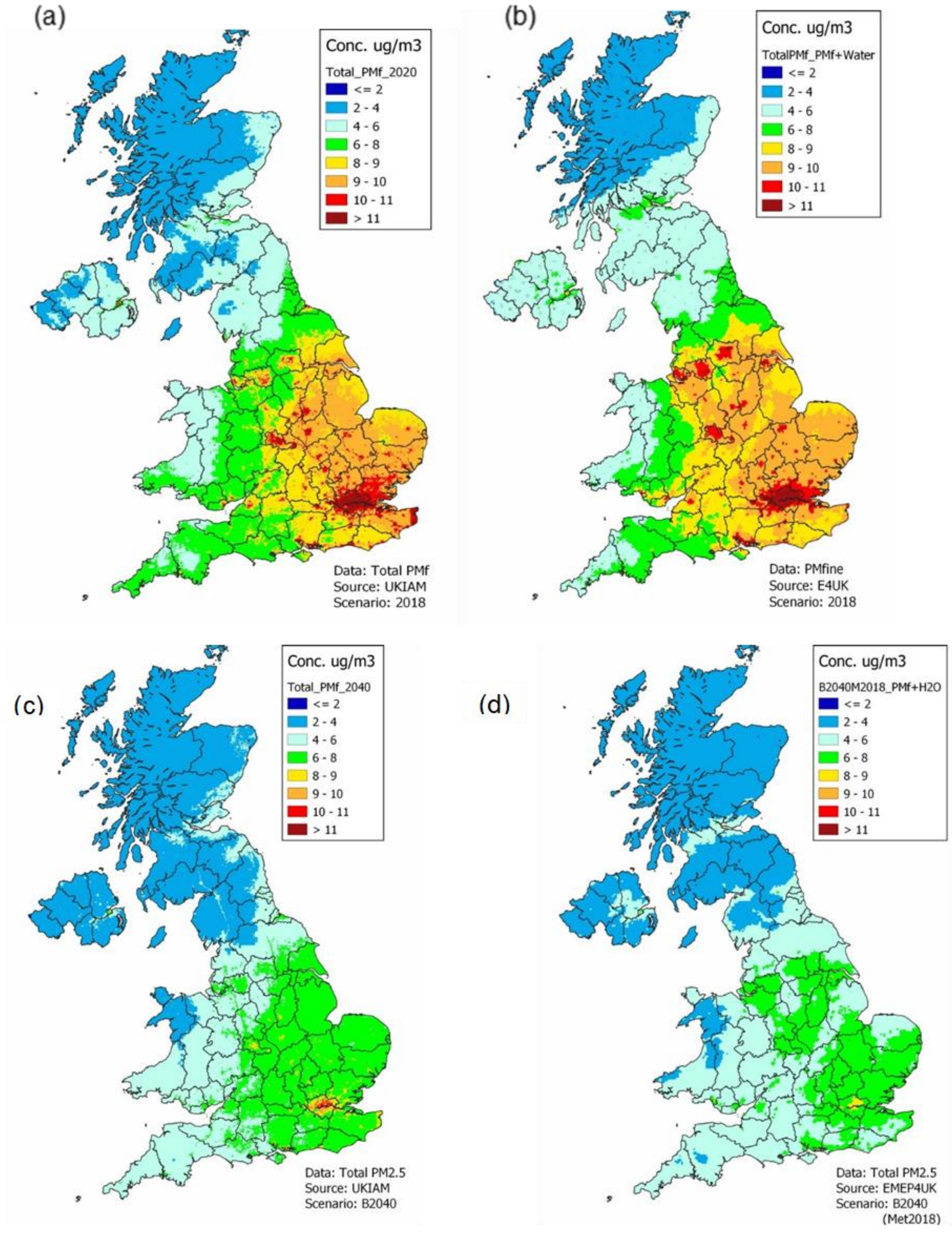
UK0001	Greater London Urban Area	UK0014	The Potteries	UK0023	Preston Urban Area
UK0002	West Midlands Urban Area	UK0015	Bournemouth Urban Area	UK0029	Eastern
UK0003	Greater Manchester Urban Area	UK0016	Reading/Wokingham Urban Area	UK0030	South West
UK0004	West Yorkshire Urban Area	UK0017	Coventry/Bedworth	UK0031	South East
UK0005	Tyneside	UK0018	Kingston upon Hull	UK0032	East Midlands
UK0006	Liverpool Urban Area	UK0019	Southampton Urban Area	UK0033	North West & Merseyside
UK0007	Sheffield Urban Area	UK0020	Birkenhead Urban Area	UK0034	Yorkshire & Humberside
UK0008	Nottingham Urban Area	UK0021	Southend Urban Area	UK0035	West Midlands
UK0009	Bristol Urban Area	UK0022	Blackpool Urban Area	UK0036	North East

Comparison with EMEP4UK and PCM models

Model outputs from the UKIAM model have been compared to two alternative models to aid interpretation of its outputs. When predicting future concentrations there is no true value with which to compare as there are for historic years. Comparisons of this sort were undertaken as part of the evidence development and were discussed both as part of the call for evidence and modelling review meeting with AQEG. Some key examples are used to illustrate performance in this section.

Figure 16 compares the results of the UKIAM model with EMEP4UK for 2018 and 2040, using the same emissions inputs. For 2018 the levels of concentration and spatial variation across the country are broadly similar, with the same UK population weighted mean concentration of 9.2 µg m^{-3} produced by both models. There are greater differences with 2040, as the EMEP4UK model shows a larger response to the projected reductions in emissions than the UKIAM model. The UK population weighted mean concentration for the EMEP4UK using 2018 meteorology is 6.2 µg m^{-3} compared to 6.8 µg m^{-3} with UKIAM. However, using 2003 meteorology it is 6.7 µg m^{-3}, which is more similar to UKIAM illustrating the important role weather plays in determining $PM_{2.5}$ levels in any one year.

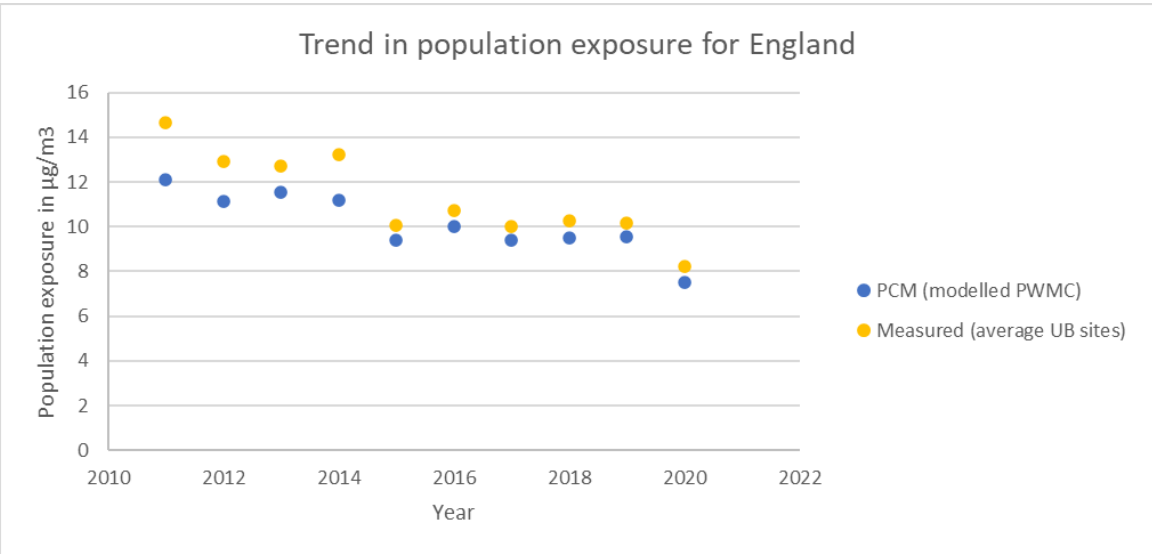
Figure 16: A comparison of (a) UKIAM and (b) EMEP4UK results for 2018, and (c) UKIAM and (d) EMEP4UK for baseline 2040



An alternative model used by Defra for assessing compliance with current air quality standards in combination with monitoring is the Pollution Climate Mapping model (PCM). This model differs significantly from both the UKIAM and EMEP4UK model in terms of how it calculates concentrations, so is a useful comparator. The PCM model, as it is a compliance model, is routinely calibrated against monitoring data to allow for consistent reporting between monitoring and modelling. Modelling is undertaken every year so provides a useful dataset for comparison of trends over time. Concentrations are calculated at 1km grid square scale, alongside explicit modelling of roadside concentrations of over 9000 road links across the UK. The 1km grid squares can be used to calculate the population weighed mean concentration (indicative of average population exposure) for England and in 2018 was calculated from the PCM results as 9.5 µg m^{-3} compared to 9.7 µg m^{-3} from the UKIAM and EMEP4UK models. It is useful to plot the trend over time based on the PCM data and this can be seen in Figure 17**Error! Reference source not found.**. The PWM $PM_{2.5}$ metric decreased up to around 2017 and then started to plateau at just under 10 µg m^{-3} thereafter. From 2011 to 2019 there has been a decrease of 21%. This is comparable with how the average monitored levels have decreased over a similar time period (29% between 2009 and 2019).

Measurements located to be indicative of wider population exposure across a town or city are termed urban background monitoring sites. The average of these sites, like modelled PWMC is indicative of population exposure. Figure 17 compares the average urban background measurements and modelled PCM data. They follow a similar trend, but with measured values giving slightly higher values than modelled.

Figure 17: Population exposure for England over time as modelled by the PCM and measured



A comparison of modelling and measurements shows that the current population exposure in England is around 10 µg m^{-3} and that there is good agreement on this between different models, and between modelling and monitoring (see summary in Table 10). It is to be expected that population exposure calculations based on measurements are likely to be slightly higher than those based on modelling, as the modelling averages across the whole country, including in locations where concentrations and exposure are lower, whereas monitors are predominately located in urban centres where concentrations are often higher.

Table 10. Comparison of population exposure for England in 2018 modelled and measured in different ways

PWMC modelled by UKIAM	PWMC modelled by EMEP4UK with 2018 meteorology	PWMC modelled by PCM	Measured PE (3-year average of UB and SB)	2018 measurements (average of UB and SB)	Modelled values at UB and SB monitoring sites by UKIAM
9.7	9.7	9.5	10.34	10.29	10.16

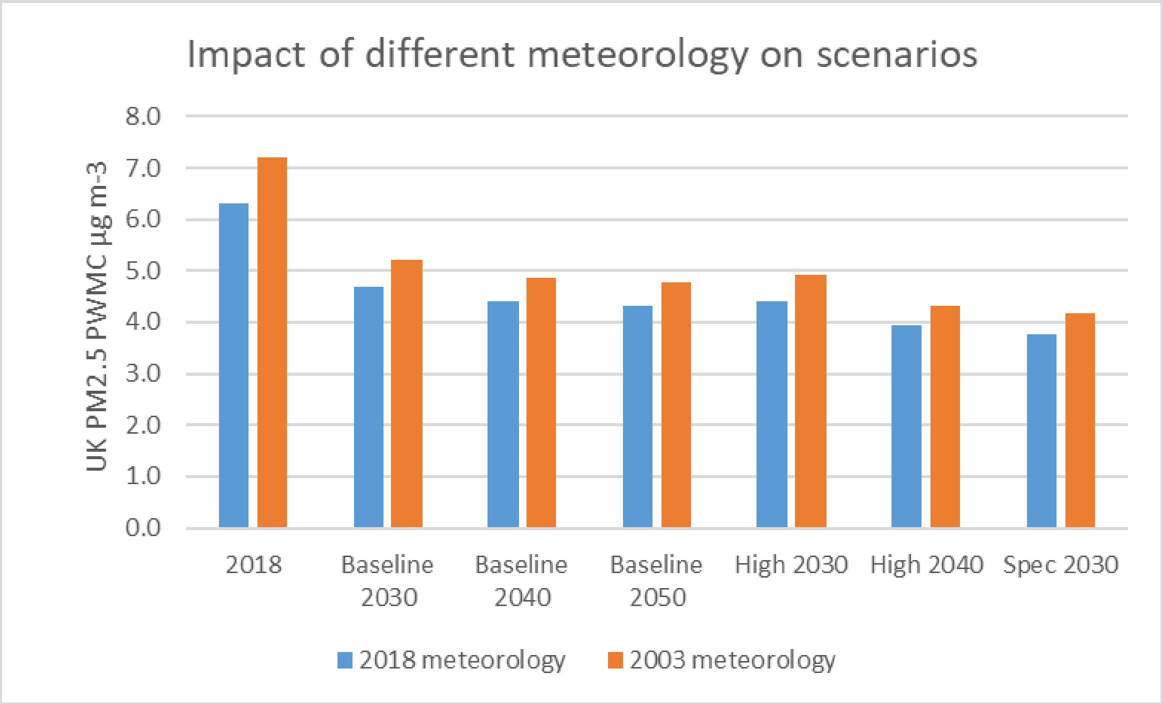
Impact of meteorology

Annual mean concentration measurements vary year by year not just as a result of emissions changes, but also due the weather conditions experienced. This means when looking at measurements to determine air quality improvements it is better to look at the overall trend rather than data from individual years. There can be a large difference in the PWMC for an individual year compared to the three-year average trend, due to weather conditions.

There are many features of weather that impact $PM_{2.5}$ levels, but a significant impact is from south easterly winds. These are often responsible, alongside high-pressure systems, for elevated $PM_{2.5}$ particularly in springtime. This largely affects more southerly areas of England, due to long range transport of pollutants from northern Europe but affects much of the country to some degree. Regardless of conditions responsible for long range transboundary impacts, weather conditions are not uniform across the country. For example, adverse meteorological conditions may be present in the southeast resulting in higher-than-average $PM_{2.5}$ concentrations but be still average in the North-West. Different weather conditions also influence different aspects of $PM_{2.5}$, for example blocking systems may result in still conditions which does not disperse primary emissions from urban centres or warm weather may increase the amount of secondary PM formed in rural areas.

To evaluate the scale of impact of different weather in a single year, the same emissions scenarios were run on the EMEP4UK model using 2018 and 2003 weather. The weather in 2003 was more unfavourable for air quality than 2018, with conditions producing elevated nitrates from February to April, increasing the annual average. Figure 18 shows the impact of the different meteorology on different scenarios. The average UK concentration varies by 2 µg m^{-3} in 2018 to 1 µg m^{-3} in 2040 (there is less weather impact with lower emissions).

Figure 18: Comparison of the UK annual average PM2.5 concentrations using 2018 and 2003 meteorology for different scenarios



Models can be helpful for considering these impacts but cannot account for them all, as future meteorology is uncertain. Potentially changes brought about by climate change could influence air quality. At the workshop following the call for evidence on modelling it was discussed how some of the projected changes in weather conditions from climate change are likely to have both positive effects on air quality and others that were negative. It is currently unknown which impacts will dominate and it is not possible to simulate such conditions alongside or within an air quality model but in setting targets we must be mindful to this potentially impactful issue.

Comparing scenarios based on population weighted mean concentration (PWMC)

A useful way of comparing scenarios which uses average modelling data, rather than specific grid squares, taking better account of population exposure, is using population weighted mean concentrations. These are calculated by taking the concentration of each grid square and multiplying by the resident population within that grid square, these values are then summed for an area (region or the whole of England, for example) and then divided by the total population of the area selected. This provides an estimate of the average concentration that the population living within that area would be exposed to. It is a useful metric as it normalises changes relative to the populations that experience them, and therefore is used in health impact calculations. PWMC changes can also be associated to changes in emissions from different sources so efficacy of measures can be readily calculated.

Table 11 lists the PWMC for the different scenarios and years modelled. Under the baseline scenario average exposure is projected to decrease up to 2040 and then plateau. This decrease is a result of emissions reductions from regulations already in place (e.g., on domestic burning of wet wood and coal) and expected changes in technology, for example, the changes in the UK road transport fleet as newer vehicles with tighter emissions standards replace older vehicles.

All of the target emission scenarios developed produce lower than baseline PWMC exposure metrics, reflecting the associated emissions reductions in each scenario. The divergence increases as measures requiring longer lead times are implemented and all scenarios continue to reduce exposure after the baseline plateaus, reflecting the continued reduction in emissions beyond that timepoint in all the emissions scenarios. By 2030, the differences in exposure as a result of the different levels of emissions can be seen and these differences increase up to 2050.

It should be noted that relatively small reductions in PWMC, can denote large health benefits when multiplied up across the total population within an area, particularly when they are calculated on a national scale. For example, reducing average exposure in England by just 1 µg m^{-3} could prevent an estimated 50,000 cases of coronary heart disease, 16,500 strokes, 9,000 cases of asthma and 4,000 lung cancers over 18 years (21). Similarly, Defra's damage costs for a 1 µg m^{-3} reduction in PWMC is currently £62.79 per person, meaning that a 1 µg m^{-3} reduction in the national PWMC with a population of 56 million people in England (22) is akin to a monetised annualised health benefit of £3.5 billion. So, although the difference in numbers look small in terms of changes to absolute levels of $PM_{2.5}$, they represent significant health benefits.

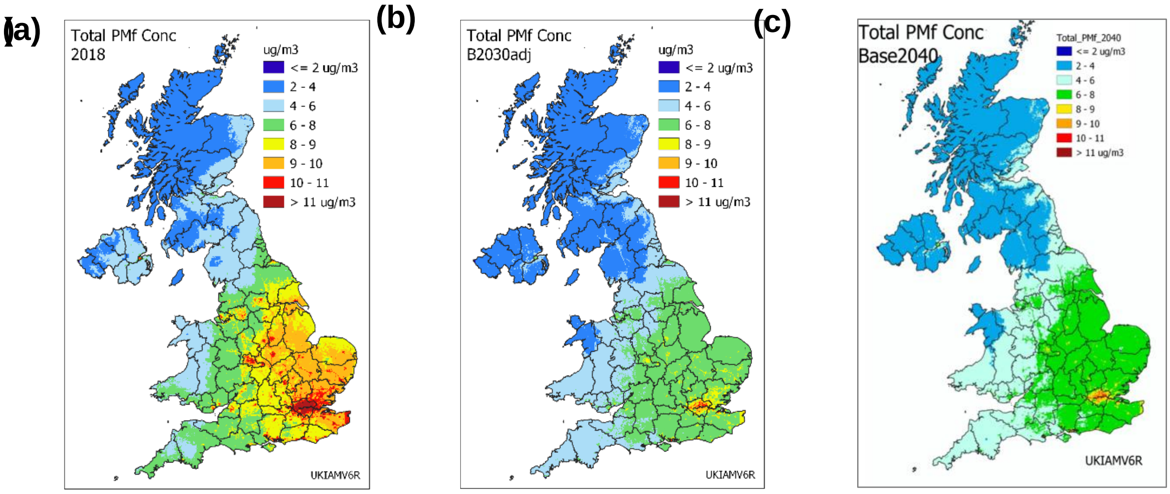
Table 11. Summary of modelled PWMC for England

	2018	2025	2030	2040	2050
Baseline	9.7	8.0	7.5	7.1	7.1
Medium		7.8	7.2	6.7	6.4
High		7.7	7.0	6.3	6.1
Speculative		7.7	6.5	5.9	5.7

Maps

Although useful when comparing between years and scenarios, the PWMC does not provide an indication of the large variation across the country or how that variation changes over time. A time series of maps enables this to be seen. The results for the baseline scenario (Figure 19) shows how many of the highest peaks in large cities are likely to diminish over time as UK emissions reduce. The South-East to North-West gradient due to the natural and transboundary components remains, but the concentrations in the South-East are much reduced and more of the north of the country has lower levels.

Figure 19: Baseline time series of PM2.5 concentration maps (a) 2018, (b) 2030, (c) 2040

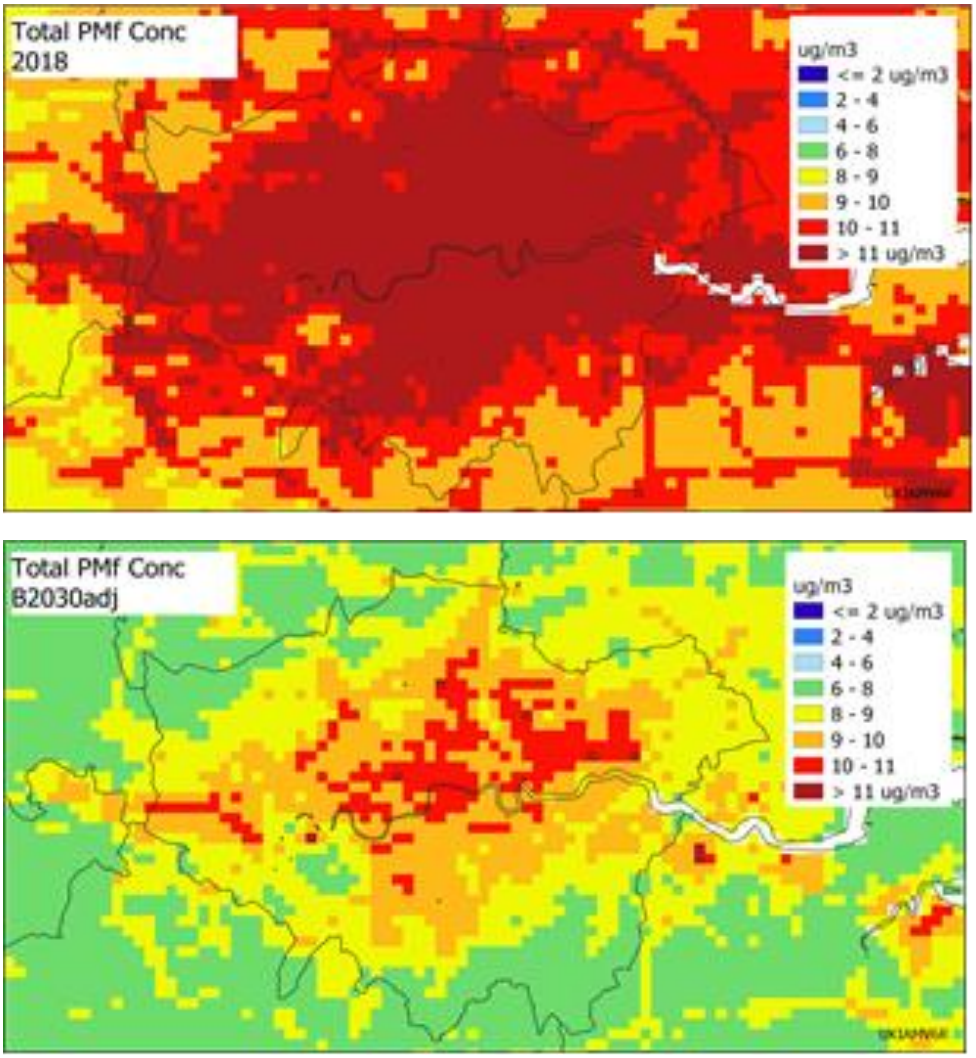


A closer look at the baseline map for 2030 for London (Figure 20) shows that although much improved, the concentrations remain in the 9-10 microgram banding (orange) and there are central areas remaining in London in the 10-11 and over 11 bandings (red).

Figure 20: Maps of modelled PM2.5 concentration in London for the baseline scenario (a) 2018 and (b) 2030

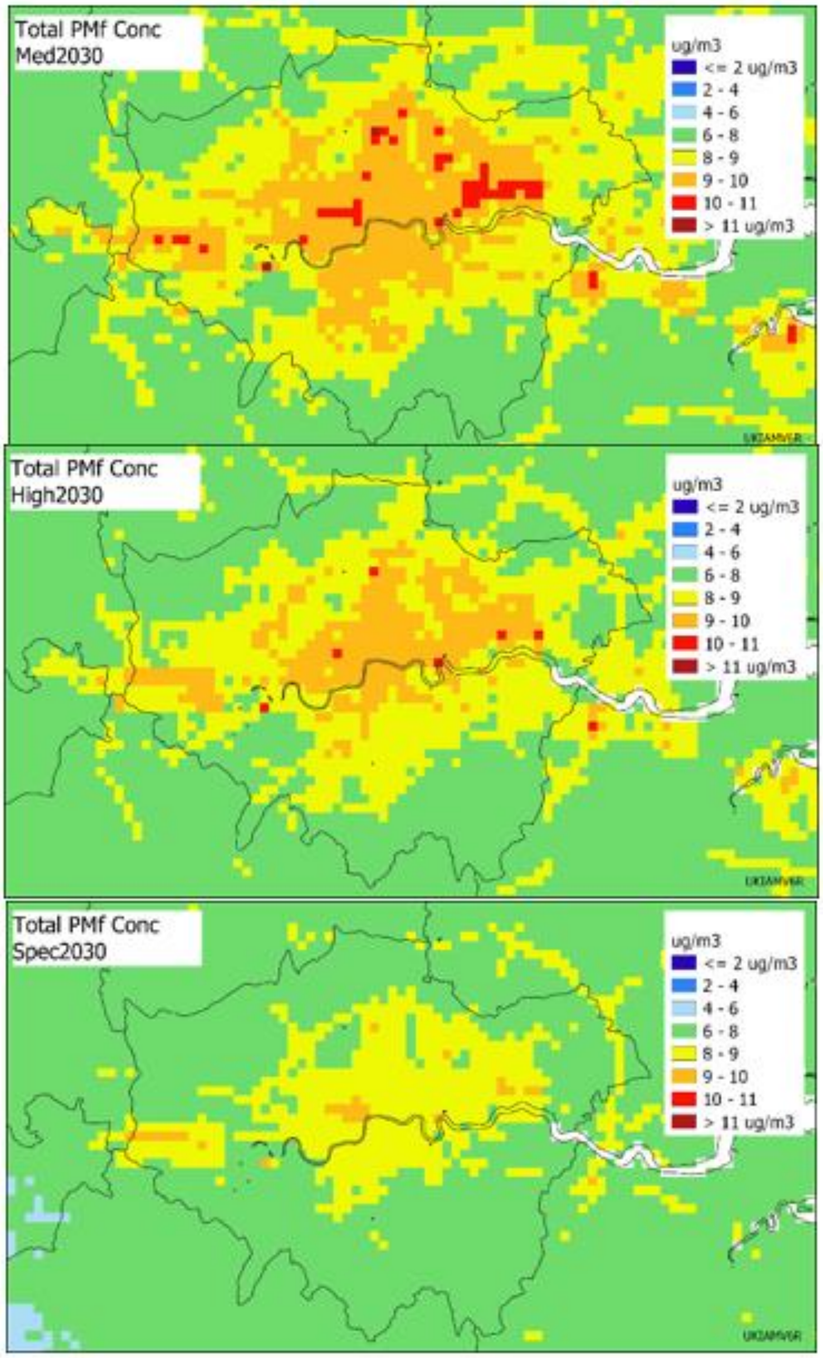
(a)

(b)



The target scenarios for 2030 (Figure 21) show that even with significant intervention, hot spots remain in London in 2030. Under the speculative scenario some areas are 9 µg m^{-3} to 10 µg m^{-3} assuming average weather conditions and averaged across $1km^2$, so in adverse weather conditions or at particular locations near to sources of pollution, concentrations are likely to be higher. The areas surrounding London are significantly lower, e.g., around 8 µg m^{-3} showing the impact of the local primary emissions in large urban areas such as London. The much higher emissions in London and other large cities than the surrounding areas is one of the reasons why the PERT is so important. Setting a limit value that is achievable in London will not drive action in other areas of the country where it can be more easily met and reductions in $PM_{2.5}$ exposure have health benefits whatever the level i.e., a reduction from 7 µg m^{-3} to 6 µg m^{-3} is not less beneficial than a reduction from 11 µg m^{-3} to 10 µg m^{-3}.

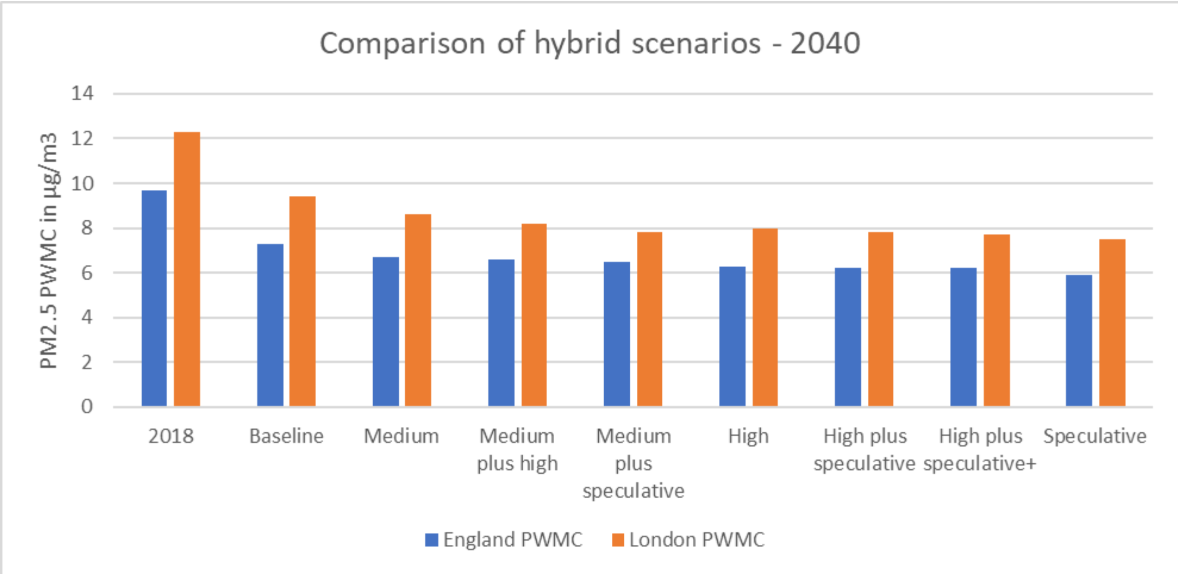
Figure 21: Maps of modelled PM2.5 concentration in London in 2030 for (a) medium, (b) high and (c) speculative scenarios



London emission scenarios

A combination of its large, dense population and geography means that the highest $PM_{2.5}$ concentrations are found in London as illustrated above. The city is also different to the rest of the country in characteristics such as public transport use. A number of hybrid scenarios (Figure 22) were modelled to see what the impact would be of applying higher uptakes/additional measures in London alongside lower ambition scenarios in the rest of the country. These are aimed at considering what impact focussed measured would have on progress towards different target levels, accepting perhaps that such approaches would not maximise progress in reducing the PERT nationally. In these hybrid scenarios one emissions scenario was applied nationally with a greater emission reduction scenario applied only to London. Speculative+ includes greater traffic reductions within the London Ultra Low Emission Zone than in the speculative scenario.

Figure 22: The population weighted mean concentration for London and England under different hybrid scenarios in comparison with the main scenarios for 2040.

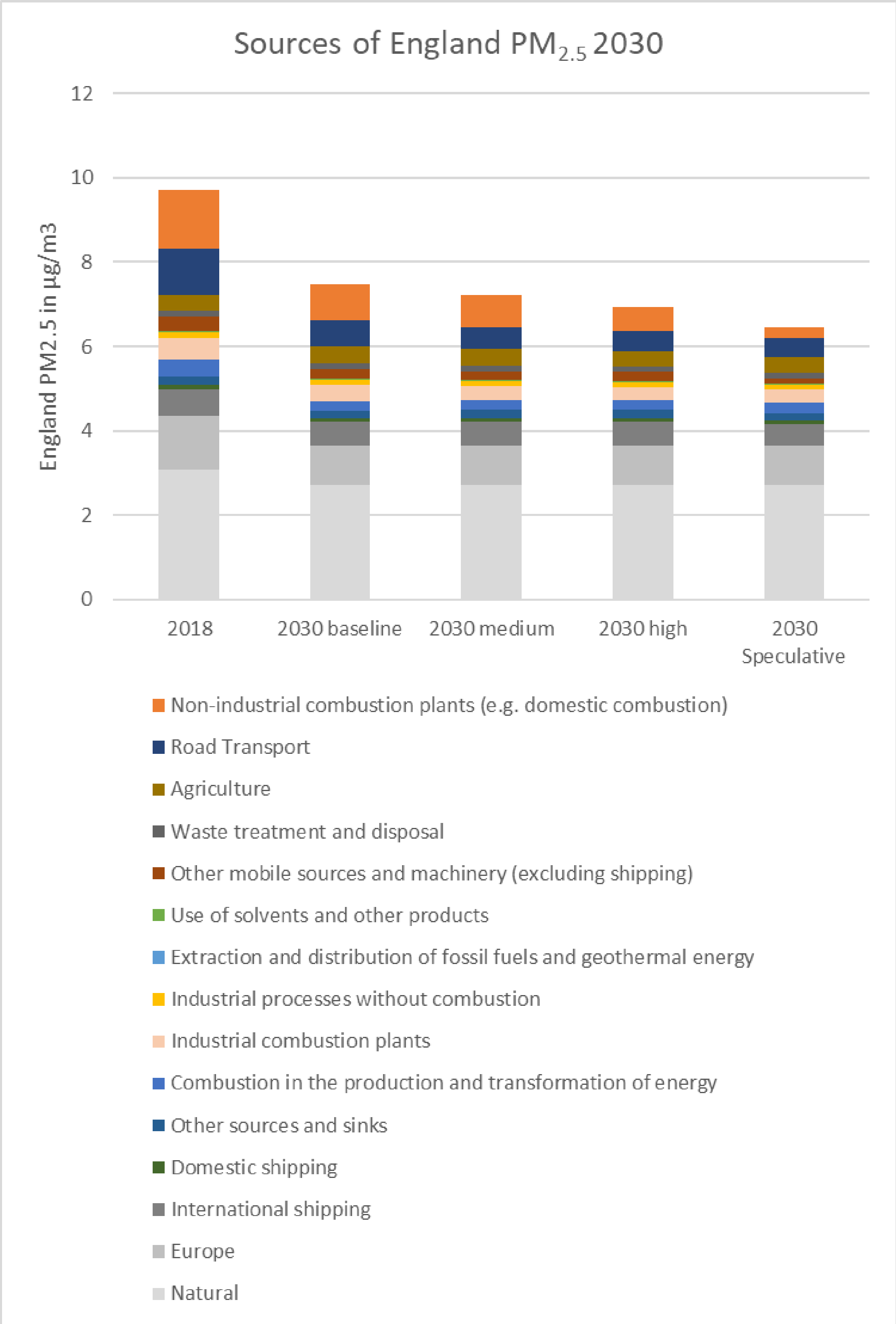


The national medium and high London scenario produces an England 2040 PWMC of 6.6 µg m^{-3}, slightly less than medium (6.7 µg m^{-3}) and a lower PWMC for London of 8.2 µg m^{-3} compared to 8.6 µg m^{-3}. The medium national with speculative London produced a 2040 PWMC of 6.5 µg m^{-3} for England and 7.9 µg m^{-3} for London. The high national with speculative London produces a PWMC for England of 6.2 µg m^{-3} slightly less than the high scenario (6.3 µg m^{-3}) and a lower value for London (7.8 µg m^{-3} compared to 8.0 µg m^{-3}). A further scenario going beyond speculative for London with a further reduction in traffic to 60% of baseline the ULEZ produced 6.2 µg m^{-3} for PWMC for England and 7.7 µg m^{-3} for London. This is compared to 5.9 µg m^{-3} and 7.5 µg m^{-3} for speculative. This shows there is some value in applying additional measures only in London, for both the city and to a lesser extent the country as a whole. It must be noted that the significant traffic reductions modelled in the more speculative scenarios would likely be extremely difficult, costly, and disruptive to deliver.

Contributions, sources and spatial variations

The modelling results also provide information on the main sources of $PM_{2.5}$ and how these vary across each scenario. Figure 23 compares the breakdown for 2018 and how the proportions of $PM_{2.5}$ could vary in 2030 and 2040 depending on the scenario. Unlike the graph of emission sources this includes the contribution of secondary sources.

Figure 23: Sources of PM2.5 concentration in England for 2030 and 2040 under different scenarios



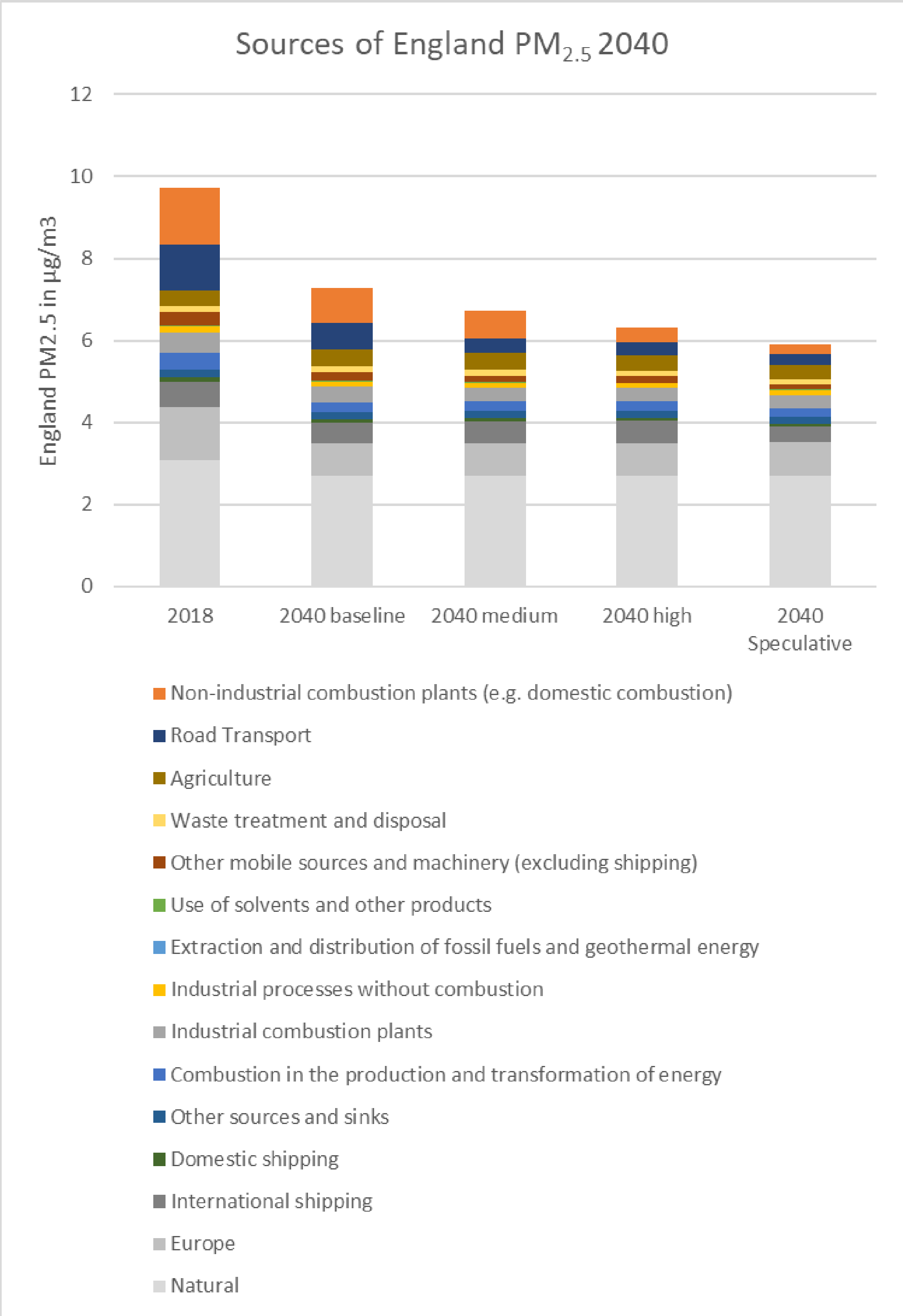


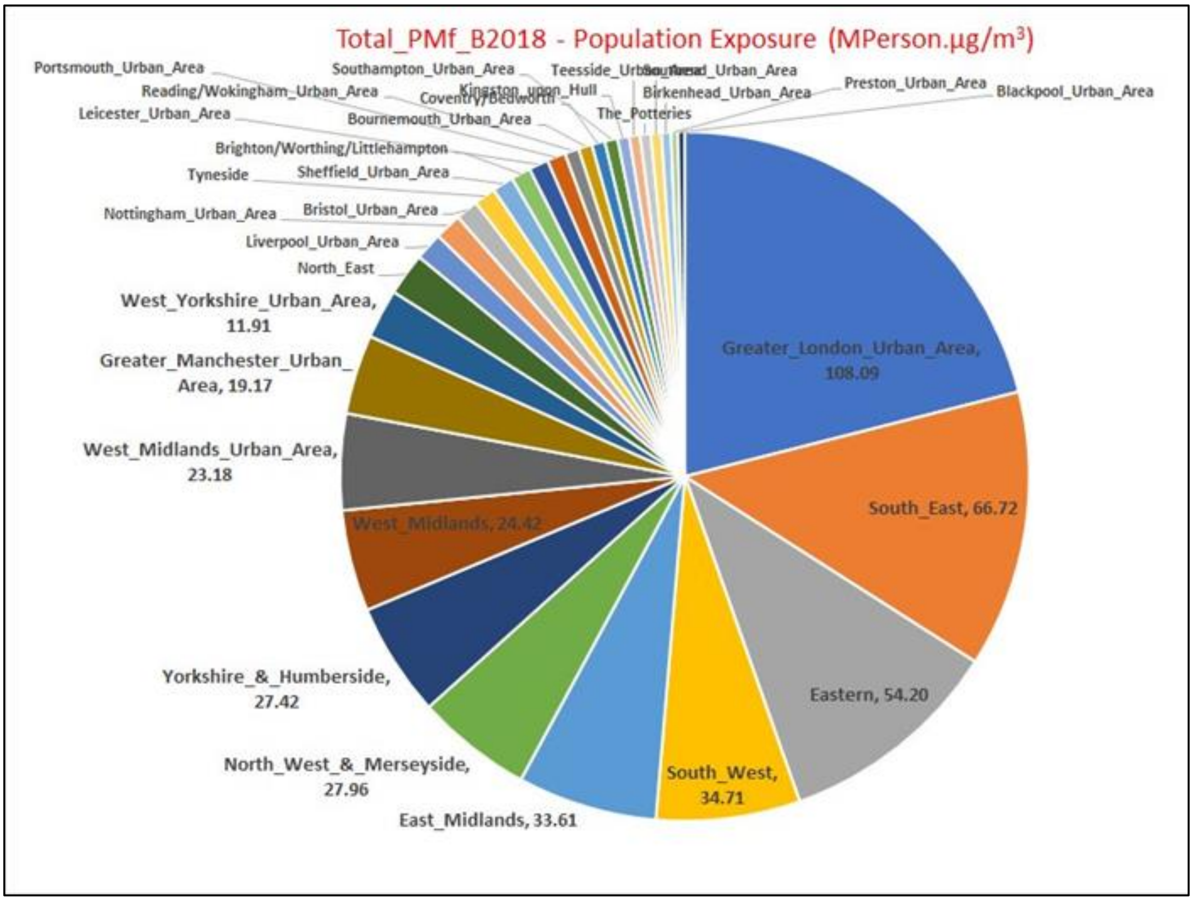
Figure 23 indicates that on average in 2018 around 3.1 µg m^{-3} of England's PWMC comes from natural sources (it is higher in the South-East), 1.3 µg m^{-3} from Europe (also higher in the SE) and 0.63 µg m^{-3} from international shipping. That is nearly 5 µg m^{-3} (over half the current PWMC for England) which is outside of the UK's direct control, although some degree of influence could be exerted on European emissions and international shipping through international agreements. The scenarios include a reduction in the contributions outside of UK control of around 19% by 2040, mainly because European and international shipping emissions are expected to reduce with improved technology and regulation.

UK sources contribute 4.7 µg m^{-3}. The largest sources are domestic wood burning (29% of the UK manmade contribution) and road transport (23%). The other 48% is made up of a range of sources including industrial combustion (11%), energy production (9%) and agriculture (8%). The reduction in UK contributions compared to 2018 modelled for the baseline, medium, high and speculative scenarios in 2040 is 30%, 43%, 52% and 58% respectively. The majority of the reduction (e.g., 72% for the high 2040 scenario) is due to the inclusion of actions within the scenarios which address these two sectors (there is a 54% reduction in the contribution of these two sectors compared to baseline 2040).

The PWMC for London in 2018 is 27% higher than the average for all England. This is due to both a higher UK contribution (35% more than the England average) and higher non-UK contribution (20% more than the England average). This means the proportion within UK control is slightly higher for London than for the rest of the country (48% of the 2018 PWMC is outside of UK control compared to 51% for all England). Road transport contributes 31% of the PWMC within UK control and domestic combustion contributes 30%. Road transport is the largest source in London, whereas for the country as a whole domestic combustion is the highest contributing sector. The baseline, medium, high and speculative scenarios reduce the UK contribution to London PWMC by 29%, 42%, 51% and 58% respectively by 2040. In the high 2040 scenario the contribution to London PWMC from road transport is 21% and domestic combustion 18%. The combined contribution of the two sectors is reduced by 50% compared to the 2040 baseline.

As can be seen in Figure 19 urban areas have higher concentrations than the surrounding regions (as well as higher population density), so there is greater $PM_{2.5}$ exposure in these areas. In 2018 urban areas in England (defined as grid squares with greater than 500 residents) have a PWMC 1.5 µg m^{-3} higher than the rural PWMC. PWMCs were calculated for the zone and agglomerations used for air quality reporting (see map of zones – Figure 3). The PWMC for a zone/agglomeration depends mainly on geography and population, with a limited number of point sources relating to other activities such as industry. The Greater London Urban area has the highest PWMC as would be expected with its location and high population, and Tyneside the lowest. The South-West has a relatively low PWMC despite quite a high population and Eastern a high PWMC despite a lower population, due to their geography i.e., higher transboundary and natural contributions in the east. This information will aid in the development of the future monitoring capacity to assess the PERT as described in this document. Figure 24 shows the proportion each zone and agglomeration contribute to England’s population exposure.

Figure 24: Proportions of England's 2018 exposure contributed by the different air quality reporting zones and agglomerations



This difference between the PWMC for urban and rural areas changes depending on scenario and year. The speculative scenario in 2050 has only a 0.2 µg m^{-3} difference between urban and rural PWMC, as the urban primary emissions have been substantially reduced. Within urban areas a greater proportion of the concentration is attributable to UK primary sources than in rural areas. The measures within the scenarios reduce the contribution of primary UK emissions (Figure 25), and to a lesser extent the formation of UK secondary $PM_{2.5}$ from ammonia, sulphur dioxide and nitrogen oxides (Figure 26) make to the England PWMC. Natural contributions are mostly unchanged[33] throughout the scenarios and time series, but European and international shipping contributions also reduce over time depending on the scenario. This means the measures reduce the average exposure across the country but have the largest impact on reducing the urban uplift. In the speculative 2050 scenario domestic wood burning contributes only 0.08 µg m^{-3} and road transport 0.19 µg m^{-3}, compared to 0.98 µg m^{-3} and 0.57 µg m^{-3} in the base year.

[33] Apart from water vapour which decreases with SIA.

Figure 25: Graph showing the UK primary contributions to England's PWMC for different scenarios

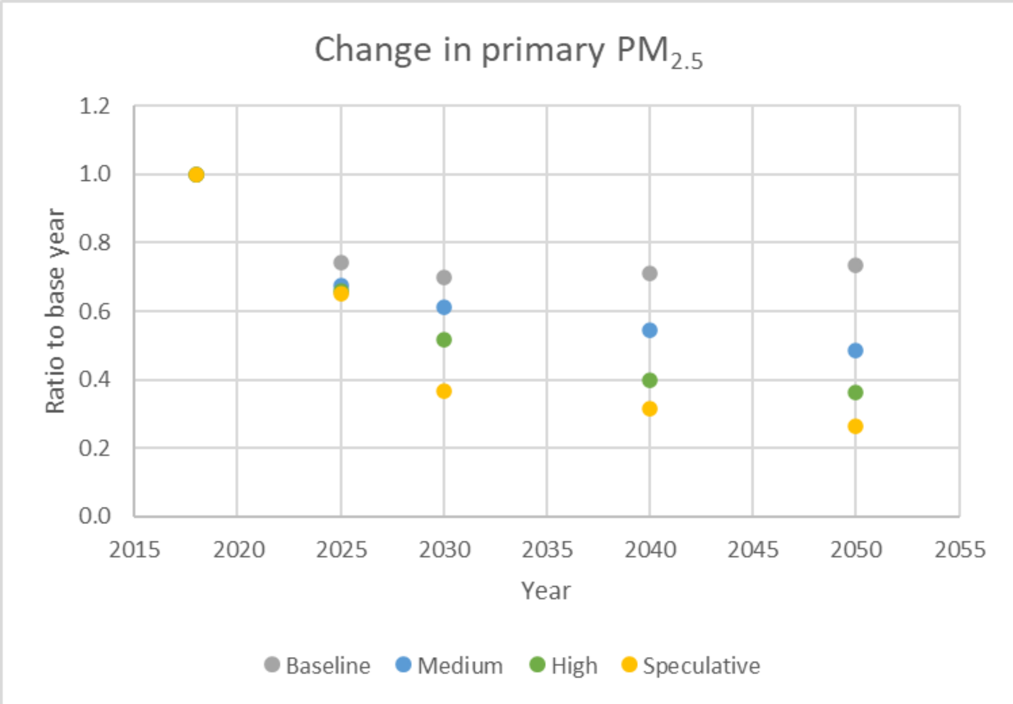
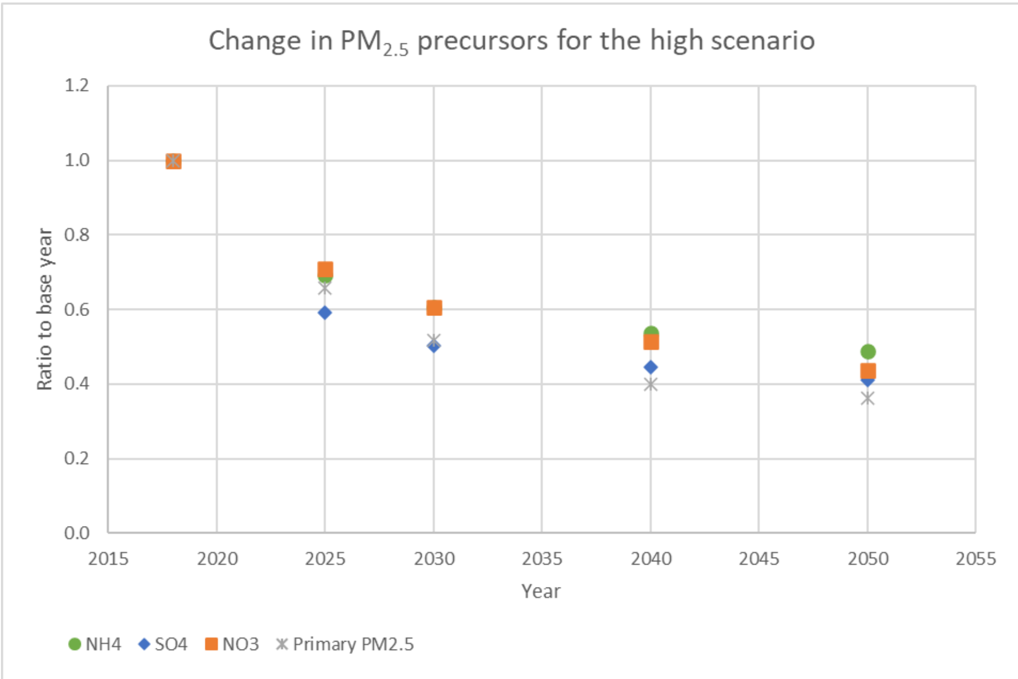


Figure 26: Contributions to England's PWMC from UK NH4, NO3 and SO4 and primary PM2.5 for the high scenario



National Emissions Ceilings Regulations (NECR)

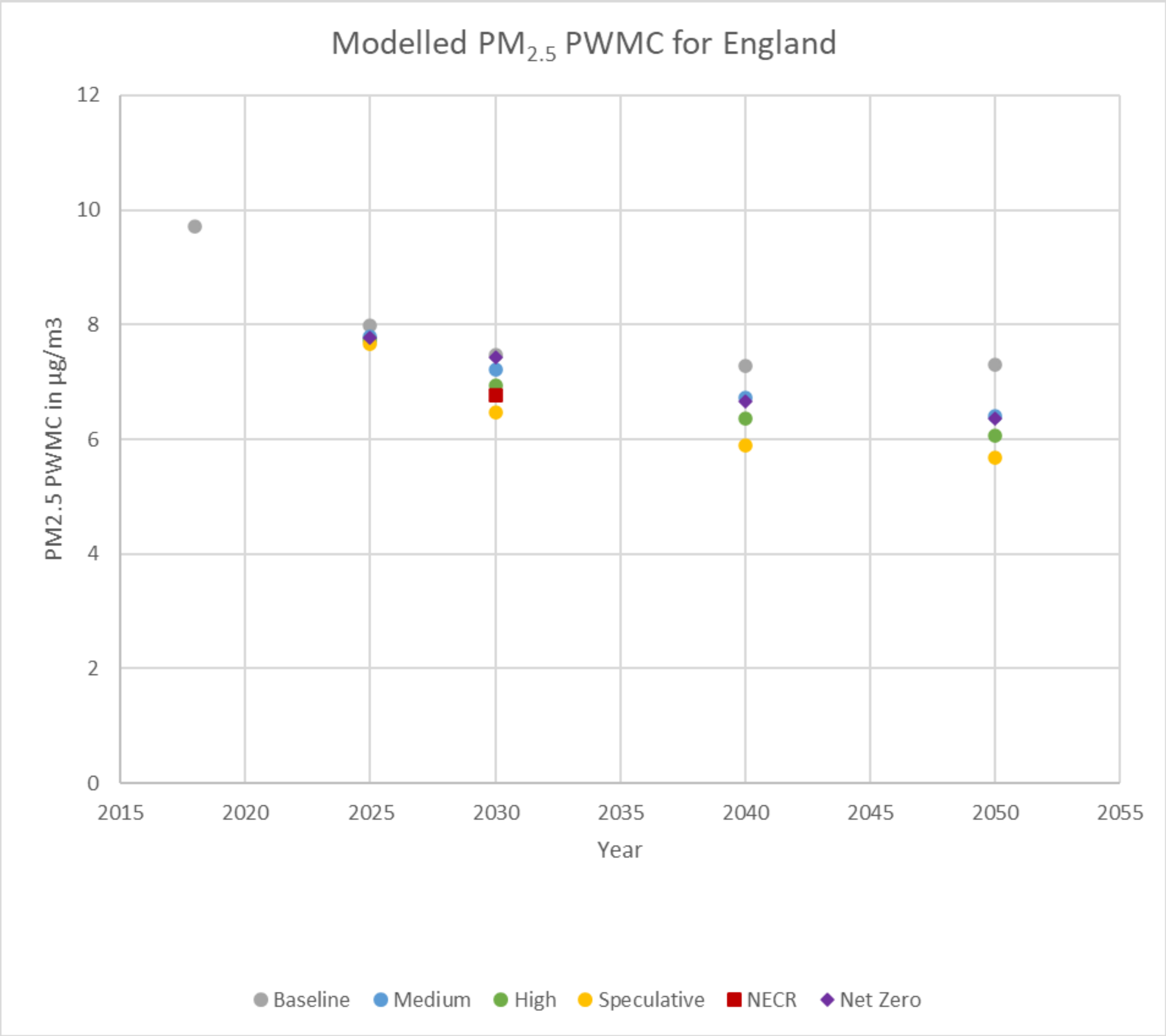
The UK's international commitments to reduce its emissions of key air pollutants under the Gothenburg Protocol to the UNECE Convention on Long Range Transboundary Air Pollution (CLRTAP) prior to leaving the EU were laid out in the EU National Emission Ceilings Directive. These were transposed into UK legislation in the National Emissions Ceilings Regulations 2018 (23) (NECR), and the UK remains a party to the Protocol as an independent country. The Regulations set targets for total UK emissions of NO_x, SO_2, Non-Methane Volatile Organic Compound (NMVOC), NH_3 and $PM_{2.5}$ to be met by 2020 and 2030 and work is ongoing to meet these targets in the most cost-effective manner. Meeting these commitments will have a direct impact on future $PM_{2.5}$ concentrations so as a comparison exercise, a scenario where the UK met these ceilings for all pollutants by 2030 was modelled. The electrification of road transport measure was also added to this scenario. The results showed that meeting all the ceilings would result in $PM_{2.5}$ concentrations in 2030 similar to the high target scenario with a PWMC of 6.8 µg m^{-3} for England (see Figure 27). The medium, high and speculative scenarios all meet the primary $PM_{2.5}$ emissions ceiling required under NECR, but as the key aim of the scenarios was to reduce $PM_{2.5}$ concentrations, emissions reductions commitments for all other NECR commitments are not modelled to be met in all scenarios.

Net zero

The UK government is committed to achieving net zero by 2050 and many of the actions which could be implemented to meet this goal will have direct impacts on air quality. Therefore, it was important to consider the implications for $PM_{2.5}$ concentrations of meeting net zero by 2050 as part of the target analysis. The BEIS core pathway prepared for carbon budget 6 was used as the basis for this scenario. The net zero scenario does not include any measures specifically designed to address air pollution. The scenario is based on a large number of potential cross-sector measures, with some uncertainty with respect to both measures required to achieve net zero as well as the spatial impacts of such measures. For these reasons the net zero scenario presented here is only illustrative, as the modellers had to make some broad assumptions about how the scenario would be delivered but it provides a useful comparator.

The results of this modelling showed that if actions to reduce GHG emissions include increased biomass combustion without suitable mitigation in place as in the core pathway $PM_{2.5}$ concentrations are close to baseline (see Figure 27**Error! Reference source not found.**) around 2030. Many of the actions to meet net zero will take time to implement, so do not start to influence emissions until after this date. Also, the impact of the biomass combustion counter-act the reductions of the other measures in the scenario. Of particular concern is smaller industrial sources that may be located in urban areas, as these are close to areas of high population and emissions from these are projected to increase under the scenario. However, on the whole, net zero ambitions should be beneficial for air quality in the long term and the modelling shows that by 2040 the net zero scenario is similar to the medium target scenario. This highlights the interconnectivity of many environmental issues, and the need to consider multiple complex implications of different policies in reaching net zero.

Figure 27: PWMC of the NECR and net zero scenarios compared to the main target scenarios



Interpretation of evidence

The analysis and modelling carried out were considered alongside expert views and advice to map out what targets are feasible. This interpretation considered the indicative nature of the modelling results and its limitations, the extensive sensitivity analyses that has been undertaken, as well as the uncertainties and challenges with respect to monitoring. Historic trends are briefly discussed to provide context.

Trends in $PM_{2.5}$ concentrations

$PM_{2.5}$ concentrations have been routinely measured since 2009, with near real time measurements reported through the UK Air website and metrics such as the trend in annual means across the measurement network are published annually as part of national statistics[34]. As Figure 28 shows, over 10 years, the average $PM_{2.5}$ concentrations have reduced by 29% (2009 – 2019). Although in recent years the average of concentrations measured across the network has been relatively steady at around 10 to 11 µg m^{-3}. The average concentration dropped significantly in 2020, most likely due to a combination of a particularly mild, wet winter and the covid pandemic lockdowns. As discussed previously, concentrations can vary from year to year as a result of the weather conditions or other external factors. It is not only annual UK emissions which determine the $PM_{2.5}$ concentrations measured in England. To determine progress in improving air quality it is the underlying trend that needs to be considered rather than the difference between individual years. The PERT metric is designed to measure this underlying trend and is aligned to overall population exposure.

[34] Air quality statistics - GOV.UK (www.gov.uk)

Figure 28: UK annual mean PM2.5 concentrations from 2009 to 2020

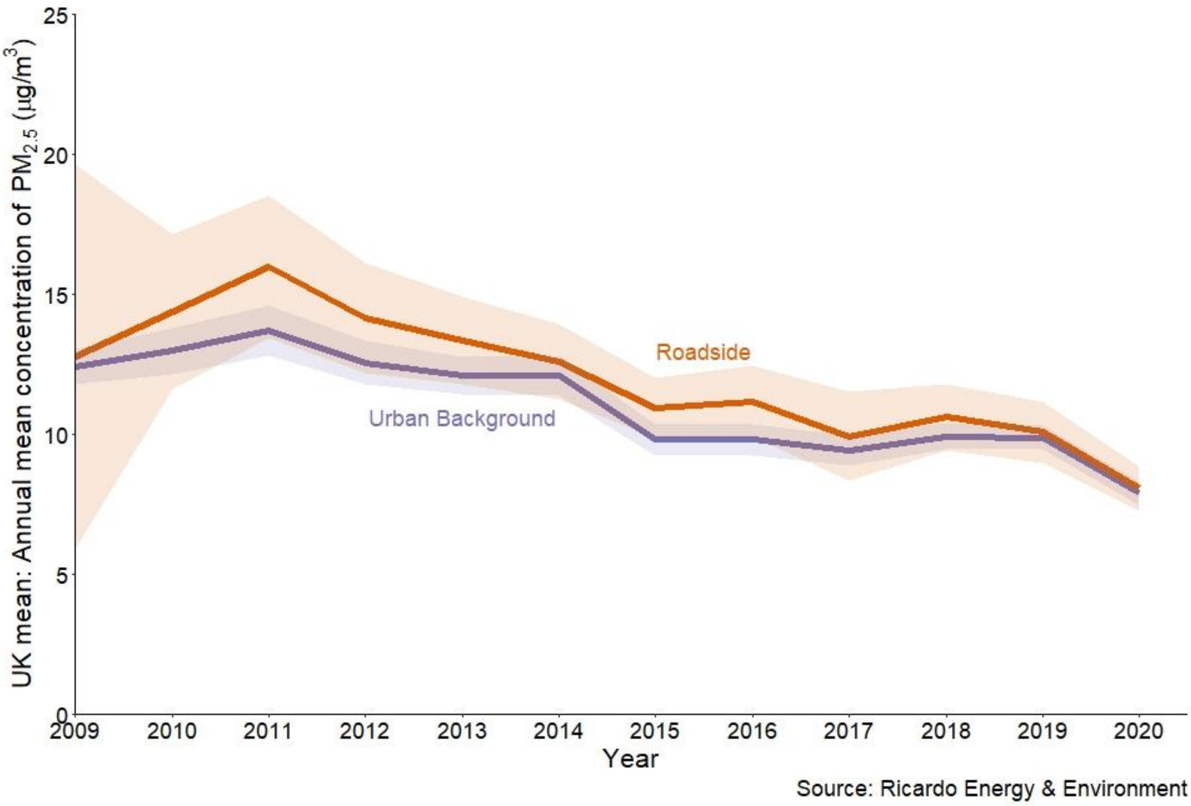


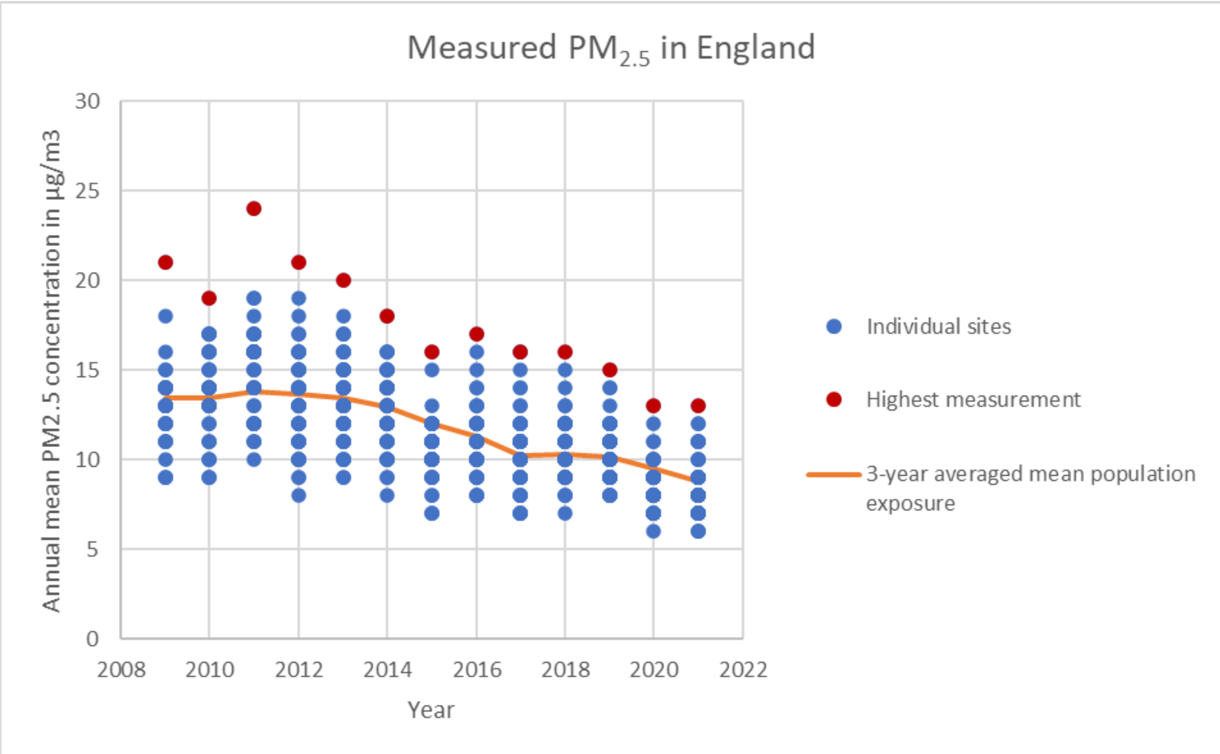
Figure 28 shows the average of concentrations at all UK AURN sites (that are over the data capture threshold), however, there is a great deal of variation between sites. Although the highest values still tend to be measured at roadside sites, the difference between the average roadside and average urban background concentrations has decreased as vehicle tailpipe emission standards have tightened. In setting two targets, it is important to consider that for the PERT it is the average urban background which is important, but for the AMCT, it is the highest measured value across all AURN sites in England.

Figure 29 shows the difference between the highest and lowest measured values in England compared to the mean for the same time period. Although the highest and lowest values mirror the mean, the difference between the two has decreased over time (it was 14 µg m^{-3} in 2011, and 7 µg m^{-3} in 2020). As primary $PM_{2.5}$ emissions reduce the difference between higher urban concentrations and regional concentrations decreases and concentrations become more homogenous across regions. Having said that it will always be the case that measurements made in the vicinity of significant sources of $PM_{2.5}$ will be likely to report higher concentrations than locations away from such sources, but the regional nature of $PM_{2.5}$ means this is less significant than for other pollutants such as NO_2.

If 2020 is discounted due to the impact of covid lockdowns, for the past five years the highest measured concentration was in the range 15 – 16 µg m^{-3}. This is well below the current $PM_{2.5}$ concentration limit value, transferred from EU standards, which is 20 µg m^{-3}.

Figure 29 shows the relationship between the average and highest concentrations from measurements made on the $PM_{2.5}$ network, where the red dots (highest measured value) are more relevant to the AMCT and the orange line (three-year mean) is most relevant for the PERT. A reduction in $PM_{2.5}$ emissions will reduce both, but the highest concentration will remain more variable across the country and over time as it can be affected significantly at a single location by changes in emissions within its vicinity. It is also more influenced by external, temporary and localised influences, so is a less clear indicator of overall national progress. In the last 10 years the highest concentrations have been measured in London eight times. This mirrors the findings of the modelling that reducing concentrations in London, particularly where concentrations are highest, is key to achieving the AMCT.

Figure 29: Measured PM2.5 concentrations in England



Average $PM_{2.5}$ reductions for all England are mirrored in the concentrations of all long running urban background monitoring sites, which are as shown in Figure 30 reproduced from Defra's Air Pollution in the UK report 2020 (24). This illustrates that 11 out of 12 long running sites show a statistically significant downward trend. Similarly, trends plotted for roadside monitors in Figure 31**Error! Reference source not found.** illustrate statistically significant trends for 10 out of 12 of the long running sites.

Figure 30: De-seasonalised[35] Trends in Ambient PM2.5 Concentration, 12 Long-Running Urban Background AURN Sites 2009-2020

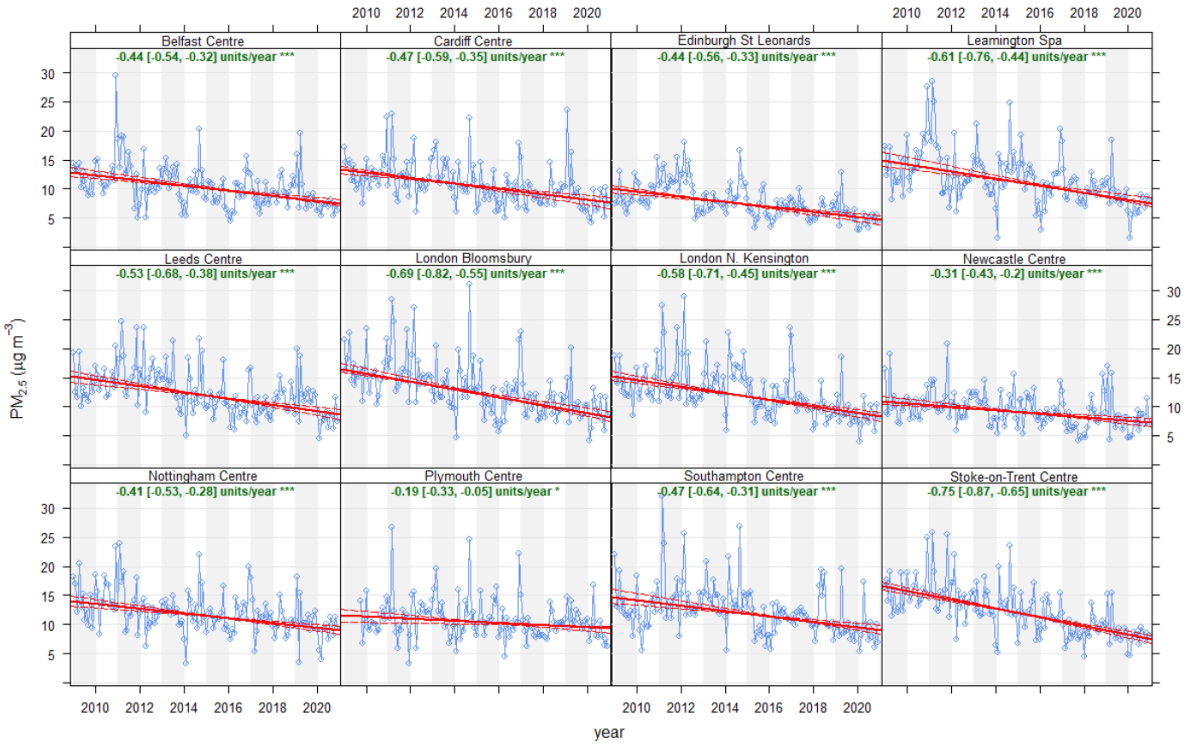
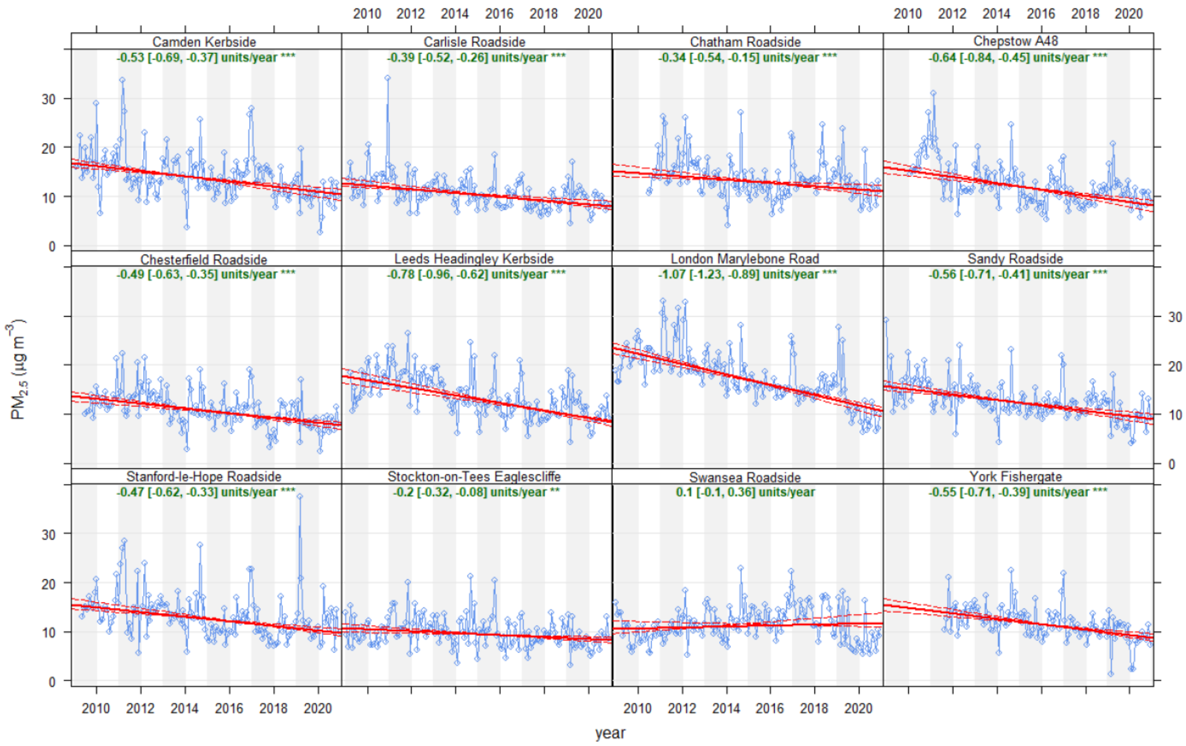


Figure 31: De-seasonalised Trends in Ambient PM2.5 Concentration, 12 Long Running Urban Traffic AURN Sites 2009-2020



Population Exposure Reduction Target (PERT)

The average of the annual mean concentration at all urban background sites in England is an indicator of population exposure. A three-year average is used to smooth annual variation and better determine the underlying trend. For 2018 this metric would be 10 µg m^{-3} (using years 2016, 2017 and 2018 to calculate the three-year calendar mean). By measuring the change in the average measurements, the reduction in population exposure can be tracked over time. Comparing the percentage change in population exposure for the target year e.g., 2040 (using years 2038, 2039 and 2040), with 2018 will determine if the PERT is met.

The population weighted mean concentration (PWMC) for England is a good indicator of future population exposure that can be obtained from the modelling results. This was 9.7 µg m^{-3} for 2018, so very close to the value derived from the average of urban background measurements. The modelled concentrations are for an average meteorological year so do not need to be averaged across multiple years.

An alternative approach is to use the average of the modelled concentrations for each grid square where urban background monitoring sites are currently located. This is less robust than using the PWMC as there may be data artefacts affecting these particular grid squares making it more liable to anomalies. However, for 2018, this approach gives 10.11 µg m^{-3} so is also close to the measured value. It is to be expected that the monitoring-based population exposure would be slightly higher than that calculated from modelling as monitoring site locations tend to be located in areas of higher concentration, whereas the PWMC includes all grid squares (although weighted by population which is higher in urban areas).

Both approaches assume that background monitoring sites are representative of the population exposure of the grid square in which they are located, and so align to the average grid concentration. An additional comparison was made between modelled 1km grid concentrations and the outputs of a higher resolution (10 metre grids) model (ADMS urban) for London to better understand the variation in concentrations within a 1km grid square, and how representative the UKIAM value is likely to be of all locations within the grid. This comparison showed that for most grids the standard deviation is within 10% of the mean. This means that the vast majority of London is within 10% of the relevant UKIAM 1km grid square value. The presence of particularly busy roads, junctions or other sources of emissions within a grid may mean the variation is higher for a small number of grid squares.

Target achievability

The PWMC for each scenario is presented in Table 12. Not all years were run for all scenarios. The PWMC for London is shown in brackets to illustrate how the concentrations in the location of the highest concentrations is reduced as well as the England average.

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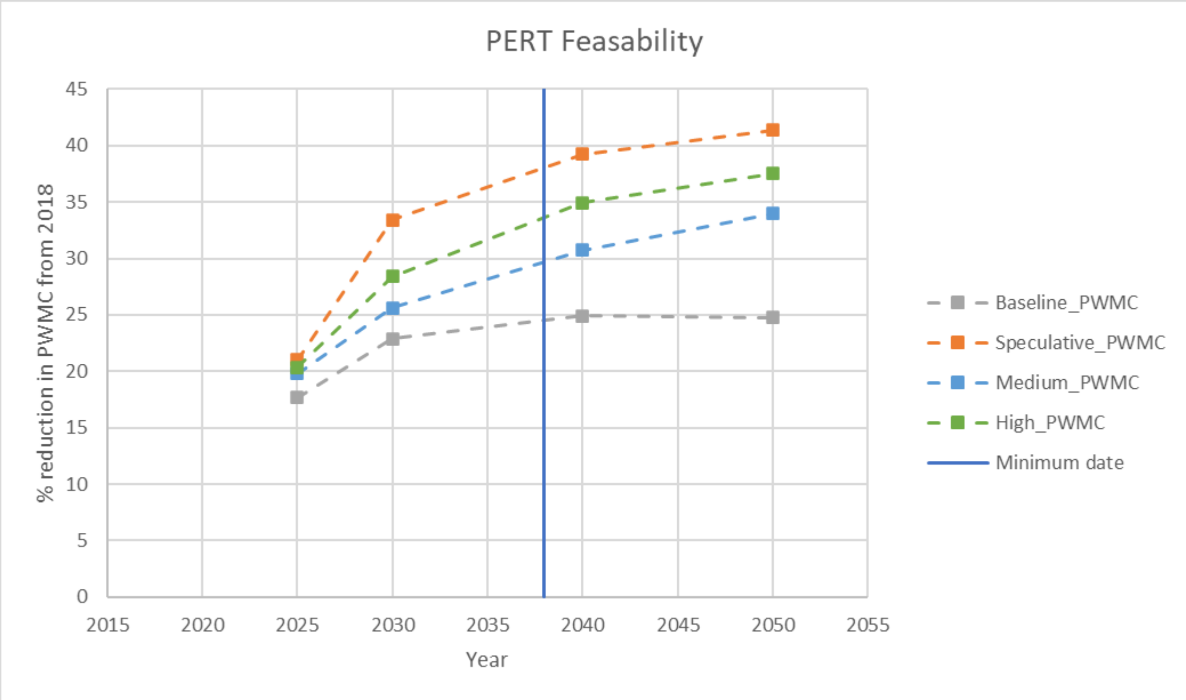
[35] The weather affects removed – using OpenAir tools - https://uk-air.defra.gov.uk/data/openair

Table 12. England PWMC in µg m^{-3} for each scenario and year modelled using UKIAM (London PWMC in brackets)

	2018	2025	2030	2040	2050
Baseline	9.7 (12.3)	8.0 (10.3)	7.5 (9.6)	7.3 (9.4)	7.3 (9.4)
Medium	NA	7.8 (9.9)	7.2 (9.2)	6.7 (8.6)	6.4 (8.4)7.0
High	NA	7.7 (9.8)	7.0 (8.8)	6.3 (8.0)	6.1 (7.6)
Speculative	NA	7.7 (9.8)	6.5 (8.2)	5.9 (7.5)	5.7 (7.1)
Medium UK/ High London	NA		7.1 (8.9)	6.6 (8.2)	
Medium UK/ Speculative London	NA		7.1 (8.5)	6.5 (7.8)	
High UK/ Speculative London	NA		6.9 (8.4)	6.2 (7.8)	
High UK/ Speculative+ London	NA		6.8 (8.3)	6.2 (7.7)	
NECR	NA		6.8 (8.7)		
NZ	NA	7.8 (9.9)	7.4 (9.5)	6.7 (8.5)	6.4 (8.1)

The percentage change in England PWMC compared to 2018 was calculated for each scenario year and plotted (Figure 32). The grey plot indicates the progress made without further action beyond that already committed to, whereas the coloured lines illustrate progress made under each emissions scenario, with the greatest population exposure achieved with the speculative emissions scenario and all scenarios reducing population exposure up until 2050.

Figure 32: Future PERT calculated from modelling outputs



The PERT needs to be set for at least 15 years in the future to drive long term improvement and to meet the requirements of the Environment Act 2021 Environmental Targets, so only dates to the right of the blue line in the graph are possible for target setting. The modelling suggests that the maximum feasible PERTs under each scenario are:

- Medium – 31% by 2040
- High - 35% by 2040
- Speculative - 39% by 2040

As described in the modelling section, there is considerable uncertainty in the modelling, and this may affect the percentage reduction between 2018 and 2040. Sensitivity analysis suggested that if wood burning emissions were closer to that reported in the DUKES 2021 digest (a low estimate) rather than NAEI 2018 (a high estimate) the percentage reduction would differ by up to 5% for the high scenario. This is because illustrative measures affecting emissions from wood burning (e.g., the impact of eco design stoves) would act on a much smaller proportion of UK $PM_{2.5}$ emissions. Conversely applying actions on measures not included in the modelling such as commercial cooking would increase the PERT that could be achieved compared to the modelling. It is also noted that using the grid squares where monitoring sites are located rather than PWMC to estimate the PERT would increase the reduction by around 2%, because monitoring sites are generally located in larger urban areas where there will be greater reduction. This uncertainty means that the five yearly reviews will play a key role in ensuring that the most up to date information is used in projections of $PM_{2.5}$ concentrations to enable actions to be focused on the highest emitting sources.

The reductions that the modelling suggests are technically feasible under different scenarios, although important, are only one of the aspects to consider when setting the final targets. The health benefits need to be carefully weighed up against the types of actions required and their economic cost. The impacts are discussed in later section of this report and are provided in more detail in the Impact Assessment.

Taking into account all the evidence, **we are proposing a 35% reduction in population exposure by 2040.** This will require emission reductions similar to that in the high scenario and we will review this in the light of new emissions data in the EIPs. We believe this target represents the best balance between delivering health benefits and restrictions to people's lives. However, this will be reviewed after obtaining the results of the public consultation.

Annual mean concentration target (ACMT)

The annual mean concentration target (AMCT) requires that all measured concentrations meet the target level by the target date. This places a greater challenge on modelling as individual measurements at specific locations are more difficult to predict with models than national averages, both because modelling uncertainties have a larger impact and also because individual measurements are subject to greater variation from changes in weather or local conditions which are difficult to replicate. This means the assessment of AMCT achievability is less straight forward than the PERT assessment.

Target achievability

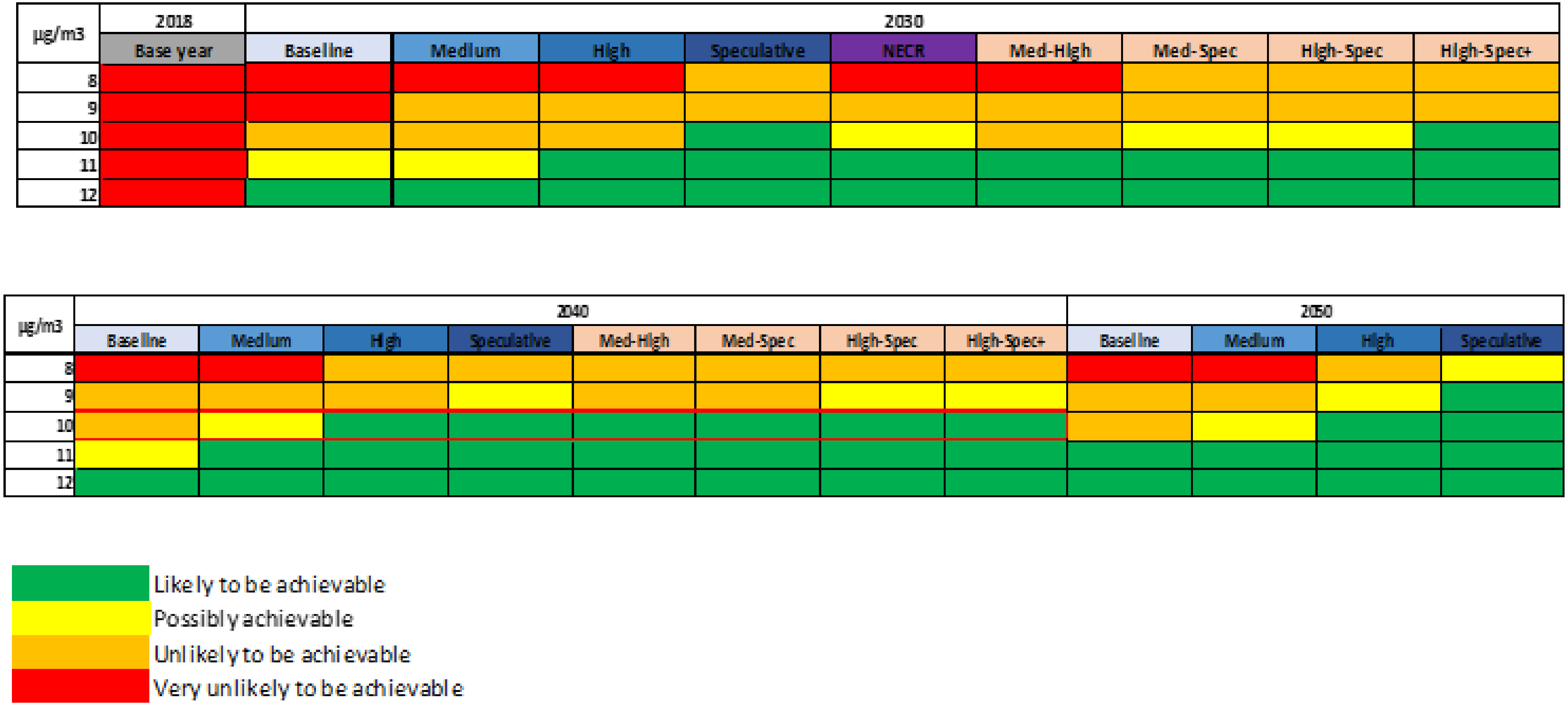
For the AMCT to be met all individual AURN monitoring sites including those near sources need to measure an annual mean $PM_{2.5}$ concentration below the target value by the target date. As discussed previously the modelled concentrations for individual grid squares are subject to data anomalies. UKIAM modelling provides the annual average value for a grid square and so there is no need to average across years to account for meteorological variability. Two approaches were taken in order to interpret the modelling.

The first was to take the concentrations for the grid squares at each monitoring site location and apply a 1 µg m^{-3} buffer to account for near-source uplift. As mentioned previously, values of individual squares can be subject to data artefacts and provide erroneous values. It should also be noted that the intention is to expand the monitoring network, so the use of grid squares of existing monitoring sites needs to be viewed with caution. The locations of the expanded network will incorporate sites that are currently unknown, so it is not possible to include these in the evaluation.

The second approach is to take the accumulated exceedance of different thresholds across all grid squares and assign a risk of exceedance based on this value. This means if the concentration of a grid square is close to a threshold it contributes less to the metric, than if it is exceeded by a large degree. The lower the accumulated exceedance across all grid squares the greater the likelihood that the country will meet a particular target. This approach is not reliant on the monitoring site locations and seeks to avoid the risks associated with using individual grid squares, however it is less intuitive and requires judgement on the level of exposure exceedance which would align with different subjective risk categories. When assessing whether a concentration can be achieved it is useful to also consider the achievability of a concentration level 1 µg m^{-3} below (i.e. when considering the achievability of 12 µg m^{-3}, it is useful to also consider 11 µg m^{-3}). The accumulate exceedance in London was used as the basis of the assessment as this is the region where concentrations are highest.

Both approaches provided similar results enabling a matrix of feasible targets for each scenario and year modelled to be produced (Figure 33). The colours represent the likelihood of all measurements being below the indicated maximum by the given date under different scenarios.

Figure 33. Matrix of feasibility of different AMCTs



When considering this matrix based on modelled outputs it is also useful to compare it to real world observations to provide some context. The highest measured value in 2018 was 16 µg m^{-3}, therefore any target under 16 µg $m^{-3}$is likely to require emission reductions compared to 2018 emissions. It is also worth noting that in 2018 46% of monitoring sites in England measured over 10 µg m^{-3}. To provide some additional context, during 2020 (a particularly low year due to covid restrictions and weather conditions) the highest measured value was 13 µg $m^{-3}$and only 6% of sites were above 10 µg m^{-3}.

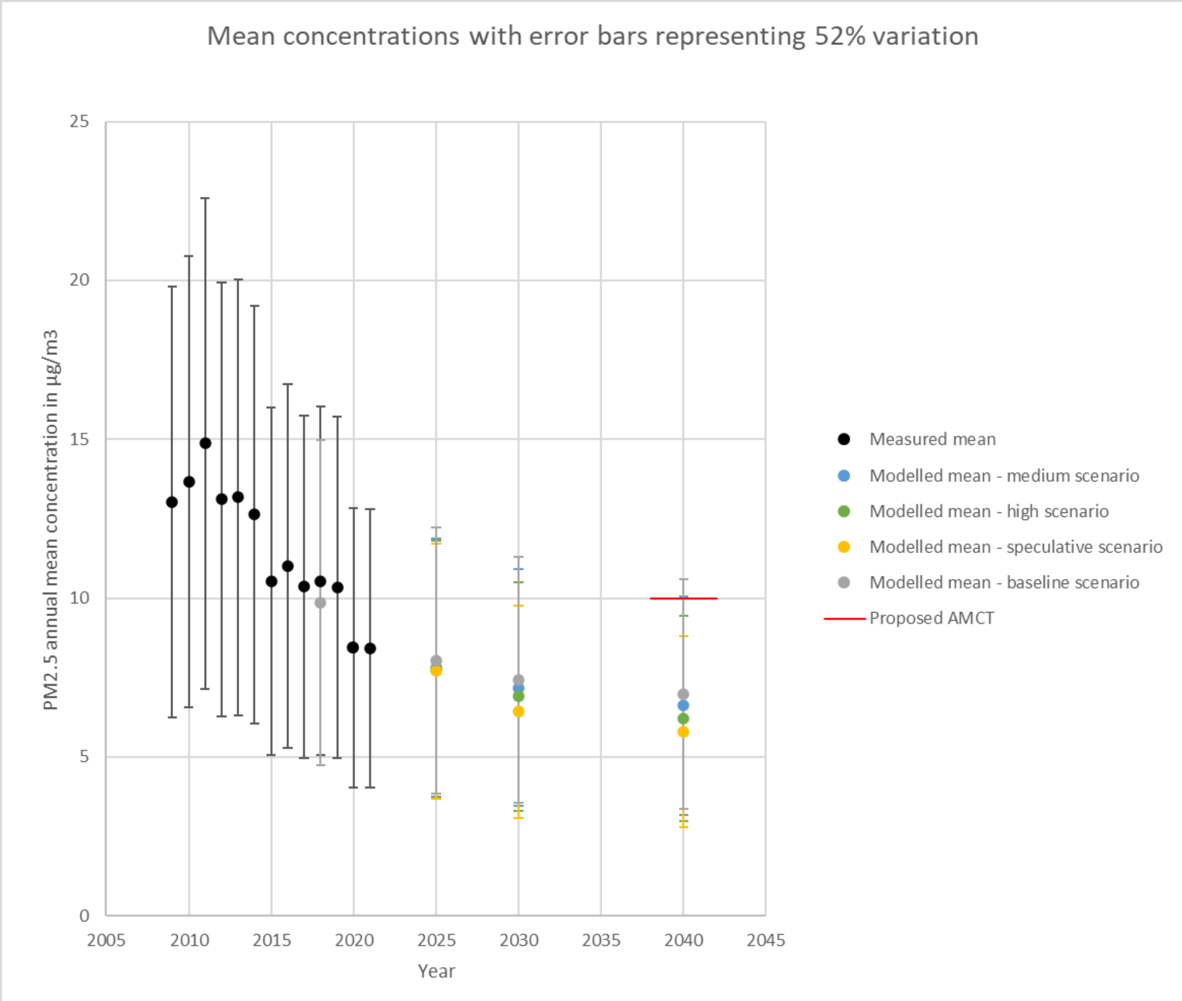
There is greater overlap between scenarios when considering the AMCT, than for the PERT, as the values are so close and selecting a target depends on the risk of failure that is deemed acceptable as well as the emissions scenario. For example, if the AMCT is set for 2040, then the modelling suggests a target of 10 µg m^{-3} is likely be achievable under the high scenario and is possibly achievable under the medium scenario.

Figure 34 shows the modelled trajectories compared to historic measurements. A third indicator of the potential maximum concentration is historic variations between the mean measurements and the highest measurement. This gives some indication of the future span of measurements, but the variation between the highest and mean varies based on weather, local conditions, sites that meet the data capture threshold. It also decreases over time as primary emissions are reduced and the difference between urban hotspots and the surrounding region decreases.

In the plot the dots represent the mean values for each year and the top of the error bar the likely highest value. The medium scenario may reach a target of 10 µg m^{-3} by 2040, but this is more likely to be achieved under the high scenario. The speculative scenario or high national with speculative+ in London may reach 10 µg m^{-3} by 2030 but includes substantially more restrictive measures with little time for consultation or implementation. The speculative scenario also contains technology still under development, substantial behaviour change and implementation timescales at the boundary of that which stakeholders considered feasible.

In the public consultation we are proposing an AMCT of 10 µg m^{-3} by 2040, which modelling suggests is likely to be achieved with emission reductions akin to the high scenario but this doesn't mean all the highly stretching measures in the high scenario are required, as there is scope to achieve the same outcome with hybrid approaches. Furthermore, no decisions on future policy pathways have yet been made.

Figure 34: Measured data up to 2020, then modelled scenarios. Error bars are fixed as 52% of mean based on historic difference between mean and highest value.



The modelled data calculated for average meteorology, however as discussed in unfavourable weather conditions can increase annual concentrations by approximately 1 µg m^{-3} or more for the same emissions. It will be a requirement that each monitoring site reports concentrations that are equal or below the target level by the target date. If the target level is not achieved at a site in the target year, but it was achieved in three out of the previous four calendar years, then the target will be considered to have been met. This allows for the possibility that the target year is an anomalous year e.g., due to particularly adverse weather conditions or an external local event such as a fire or construction site next to a monitoring site. Such factors could result in measurements for an individual year which do not reflect the previous assessments or the underlying trend. Subsequent years will be assessed in the same manner. This means if it becomes clear that the reason for not meeting the target was not transient, but due to a change in circumstances or trend, then the target will not be met in future years. This approach also allows for the impact of exceptional events such as volcanic eruptions in Iceland or Saharan dust that could impact the concentrations for a particular year.

Achieving the targets

Three emissions scenarios were modelled to provide a range of plausible emissions reductions; however, this does not mean that a particular scenario needs to be followed to meet the proposed targets or that all measures within a scenario would need to be implemented. Policies to meet the targets will be developed and consulted on separately and could include measures from any scenario or none. It should not be interpreted that by selecting a particular target that this will definitely mean a particular measure will be needed or implemented. However, it is possible to say that to reach the targets proposed cumulative emissions reductions akin to the high scenario are required and that action will need to be taken across multiple sectors by government, businesses and individuals in order to achieve those reductions. The scenarios also illustrate the major sources of emissions that contribute most significantly to ambient concentrations and thus may need to be the focus of reductions in emissions in order to reach the new targets.

All the target scenarios, including the baseline, achieve the Clean Air Strategy commitment to halve the number of people living in areas exposed to greater than 10 µg m^{-3} by 2025 compared to 2016. The modelling showed that in 2018 around 27.4 million people in England lived in areas exposed to above 10 µg m^{-3} $PM_{2.5}$ concentration. By 2025 this is modelled to be 9.4 million under the baseline scenario - a reduction of 66%. This metric is very sensitive to small changes in modelled concentrations and changes in population, so is comes with large uncertainties. However, it is clear that large improvements have been made with actions taken to-date and these are reflected in the baseline scenario, and additional action driven by the new targets will build on this.

Focusing on urban areas

Urban areas have higher concentrations than the surrounding region and larger populations (in England 83% of people live in urban areas). This mean population exposure is highest in towns and cities. The urban PWMC for 2018 was 10 µg m^{-3} compared to the rural of 8.5 µg m^{-3}. The action taken to reduce emissions in towns and cities will have a large influence on both population exposure (and so achieving the PERT) and the highest concentration (and so achieving the AMCT). It is therefore likely that more action will need to be taken in cities and large towns than in rural areas and much of that action will need to focus on reducing primary emissions. This is something already seen through interventions such as smoke control areas and clean air zones. That is not to say that action does not need to be taken in more rural locations - ammonia emissions from farms and nitrogen oxide emissions from industry contribute to regional levels of $PM_{2.5}$ pollution.

As the highest concentrations are generally found in London, this was modelled separately as an example. The PWMC of London is 27% greater than the average across the rest of England and the highest measured annual mean concentrations have been in London in eight out of the last ten years. This due to both population density (the UK contribution to PWMC is 35% more than for all England) and its location (the contribution from natural and transboundary is 20% higher than for all England). Of the contribution from UK manmade sources 58% is from London itself and the remainder from other parts of the

UK. A greater proportion of emissions is from road transport than other parts of the country.

The hybrid scenarios showed that applying additional measures to London can help to meet the AMCT but such scenarios have a smaller impact on the PERT. Applying the medium scenario for the UK, but the high scenario in London for 2040 gave a PWMC of 8.2 µg m^{-3} for London and a PWMC of 6.6 µg m^{-3} for England compared to 8.6 µg m^{-3} and 6.7 µg m^{-3} when the medium scenario was applied to all the UK. The risk of failure matrix (Figure 33) suggests that this could be sufficient to meet the proposed AMCT of 10 µg m^{-3} by 2040, but the population exposure reduction would be 32% so insufficient to meet the PERT of 35% by 2040.

Action required to meet the targets

The modelling shows that the proposed targets are achievable, but that action will be required across all sectors of society including transport, manufacturing, construction, agriculture and energy, and to be taken by government, industry and individuals. The same measures will contribute to both targets, but urban measures will have greatest impact on delivery of the concentration targets.

Two areas where further action may be needed are domestic burning and road transport. For instance, changing to cleaner stoves and cleaner and more efficient fuels in domestic burning. The use of electric vehicles will eliminate tailpipe emissions but there is some debate about the magnitude of emissions from non-exhaust sources (brakes, tyres and road wear – as well as resuspension of road dusts from vehicle movements) compared to traditionally powered vehicles. Further assessment is needed to determine the impacts of increased electric vehicle use (e.g. from regenerative braking) and research into innovative abatement technologies is already underway and will need to continue over the coming years to inform our approach.

These are not the only areas where action will be needed – reductions will be needed across all of society as reducing PM2.5 is not a single source issue. We believe that the proposed targets strike an appropriate balance between being ambitious and achievable - delivering significant health benefits through utilising proportionate and viable measures. Achieving these targets by 2040 will require sustained, long-term progress and many actions will require significant investment and behaviour change in order to be effective. However, actions we are already taking (e.g., on burning of wet wood and coal) will contribute to achieving these targets, and interim targets will ensure suitable progress is made towards the final target. Importantly, as policy pathways for achievement of the targets are developed, there will be further opportunities for consultation on specific measures that are tailored to local areas and their sources.

Local authority role in delivery of the targets

The Environment Act 2021 targets are national targets for England as a whole, however there is a role for local authorities in delivery.

The air quality objectives set out in the Air Quality (England) Regulations 2000 (25), as amended by the Air Quality (England) (Amendment) Regulations 2002 (26), provide the statutory basis for the air quality objectives under Local Air Quality Management in England. Currently there is no legislative objective which applies to local authorities in England with respect to $PM_{2.5}$. There is however a flexible role to reduce $PM_{2.5}$ which is set out in the Local Air Quality Management guidance.

We are exploring options to develop an appropriate role for LAs to support the new targets. The current air quality objectives for local authorities are concentration limit values, for example there is an objective for the measured annual mean concentration of NO_2 to be 40 µg m^{-3} or below. After a series of discussions with experts and LA representatives we are considering alternatives to this approach. There are key differences between $PM_{2.5}$ and pollutants such as NO_2, which make a concentration objective less appropriate:

- **$PM_{2.5}$ is a regional pollutant.** A significant proportion of $PM_{2.5}$ concentrations in a particular area is from natural and transboundary contributions and emissions from neighbouring areas. This means that local authorities can influence, but not completely control $PM_{2.5}$ concentrations. Also, the impact of local action may not be directly seen on local concentrations but benefit the whole region/country. This would make it difficult to evaluate progress. It would be difficult to declare air quality management areas as high concentrations are likely to spread over a large area, rather than a specific section of road, for example.
- **$PM_{2.5}$ is from multiple sources**. Unlike NO_2 exceedances which generally occur close to busy roads due to emissions from road traffic, $PM_{2.5}$ is generated from multiple sources and in multiple locations. This means it requires greater collaboration to address.
- **It is more burdensome to monitor $PM_{2.5}$.** Fewer local authorities have $PM_{2.5}$ monitoring equipment than NO_2. This would add to the difficulty of linking action to impact.

One option that has some support among experts is basing the objective on actions taken to reduce emissions rather than on measured concentrations. A number of local authorities expressed initial support for this approach. The role of LAs in delivering the new $PM_{2.5}$ targets is being considered as part of the ongoing review of the national Air Quality Strategy and will be consulted on in due course.

Implications of the targets set

The modelling suggests that the targets proposed cannot be achieved without additional action beyond the existing measures and natural technology turnover included in the baseline. This is action by government, business and individuals and will require both changes to behaviour and technology. This has implications in terms of lifestyle and has an economic cost. Two areas where further action may be needed are domestic burning and road transport. It is therefore important that people respond to the public consultation and provide feedback on the appropriate level of ambition. It is also important that businesses and individuals working in all sectors respond to the consultation.

The benefits to health and ecosystems need to be weighed against the restrictions and costs to individuals, businesses and government. The cost-benefit analysis of the high scenario shows that it is cost beneficial, but that the investment needed is large. However, a significant proportion of this investment also contributes to carbon savings. The measures included in the scenarios have not been assessed individually (that will come later as a pathway to delivery is developed in more detail), and some will be more cost-effective than others. It is likely that removing some high cost, but low impact measures would reduce the cost and have only a small impact on concentrations. Whilst we do not have fully developed pathways, it is important to evaluate the overarching costs and benefits of the targets, and this is considered in the next section.

Interim targets and progress reviews

Although modelling uncertainties, meteorology, transboundary contributions etc. have been taken into consideration as far as possible these do influence the assessment of achievability. For example, the buffer for meteorological impacts may be insufficient for years with particularly extreme weather, emissions for domestic wood burning may be overestimated and other sectors underestimated so that measures do not have the magnitude of impact expected, or the impact of climate change or net zero actions may make the targets more difficult to achieve. Therefore, it is important that progress towards the targets is regularly assessed so that actions can be adjusted, taking into account the latest evidence from modelling and measurements. The setting of the five-yearly interim targets, and the review of actions being taken will be an important part of the targets. The first interim targets will be set following the public consultation in early 2023.

Target impact

When setting any target, it is important to fully evaluate the potential consequences of actions the target will drive. This includes the magnitude of the expected benefits to health, other co-benefits such as reduction in greenhouse gas emissions (GHG) as well as the economic costs of measures that will be required to reach the target and any unintended consequences or trade-offs of associated actions. As the targets are not direct actions, but rather a means to drive action, the results of the described analysis are indicative to enable the comparison of different scenarios and inform the target setting. More in-depth assessment would need to be made for any individual policy put in place to meet the targets and these will form part of Environmental Improvement Plans (EIPs) once the targets are set.

The full Impact Assessment is presented in a separate document, but a summary of the evidence approach and headline results are provided here.

Air quality benefits on health, ecosystems, productivity and other factors

Air quality and impact valuation

Air pollution has damaging impacts on human health, productivity, buildings and other materials and the health of the environment. These detrimental impacts have associated economic and/or social costs (known as external costs or externalities) that are not captured in the market price of the goods or services consumed that produce the pollution. Defra has produced guidance to steer the assessment of air quality impacts and the valuation of external costs such that these can be captured in policy appraisal, based on the work of the Defra-led Interdepartmental Group on Costs and Benefits (IGCB). This guidance supplements HM Treasury's Green Book (27) which provides wider guidance for impact assessment and valuation.

The following factors are accounted for in the valuation of air pollution impact:

The health impacts

The health impact pathways are selected using advice from the Committee on the Medical Effects of Air Pollution (COMEAP) and Public Health England (PHE). These are impacts for which there is strong or reasonable evidence of an association with exposure to air pollutant concentrations. For some impacts there is only weak or emerging evidence of an association – where possible, these impacts are included in the high estimates of damage costs for use in sensitivity analyses.

The environmental impacts

Air pollutants can have a range of negative impacts on the environment and ecosystems and for any particular policy or project there may only be specific pathways that are relevant. Four environmental impact pathways are included in the impact pathway methodology: damage caused by sulphur dioxide to buildings; damage caused by ozone to materials; soiling of buildings due to particulate matter; and ecosystem[36] damages.

The economic impact

Air pollution affects the economy by reducing the ability of workers to attend the workplace and produce efficiently. The effects on productivity are included through a range of morbidity and mortality pathways, and consideration is taken in this research to avoid double counting by including the following: absenteeism and work-days lost for employees, volunteers and carers ($PM_{2.5}$); and presenteeism and minor restricted activity days for employees ($PM_{2.5}$ and O_3).

[36] Ecosystem services included in the damage costs; provisioning services (timber & livestock production), regulating services (carbon sequestration) and cultural services (appreciation of biodiversity). A separate assessment of the ecosystem impacts of nitrogen deposition is provided above.

Air quality appraisal: impact pathways approach

The air quality benefits calculations are based on the Defra impact pathway approach (IPA) methodology (28) which is used to assess the impact of policy interventions on air quality of more than £50 million, as it is the case in this analysis. However, where air quality impacts are less than £50 million, the damage cost approach (29) which provides a set of pre-calculated values, expressed in cost per tonne (£/tonne) of emissions, can be used instead.

The calculation to quantify air quality impacts for the two targets uses the damage cost per unit of exposure approach which identifies the impacts associated with one microgram change in exposure per person. The IPA and application of damage costs per unit exposure are equivalent methods which will give similar results. Other uncertainties, for example in the selection of effects that should be included in the analysis, will be far more significant.

The steps are as follows:

1. Emissions - Modelling the pollutant emissions data
2. Pollutant concentrations – Using the emissions data (from the above step) and dispersion modelling to determine how pollutant concentrations are impacted by the policy
3. Population exposure – Using the pollutant concentration estimates found in the last step, and combining them with the relevant population data, this will produce a population weighted mean concentration for each pollutant.
4. Health & other impacts (internal to Damage Cost) – Identifying how the population weighted concentration changes, estimated in the previous step, will change outcomes associated with health, the environment and the economy. *Health impacts are assessed using concentration response functions (CRFs) which express changes in health outcomes per unit concentration and applying them to their corresponding health impact pathways to derive estimates of life years lost, hospital admissions, cases of disease etc.*
5. Valuing impacts – Final stage involves calculating the damage cost per unit of exposure using the outputs from preceding stages.

The central, low and high sensitivities of the damage cost per unit of exposure have differences in assumptions regarding the set of impacts included, the concentration response functions (CRFs) applied to each health pathway across the sensitivities and valuations. The CRFs link a change in exposure to a pollutant to its consequent impacts by expressing a change in a health, or non-health, outcome for a given change in pollutant concentrations. Also, some impact pathways are excluded from the central damage cost and are only recommended for inclusion in the high damage cost (such as chronic bronchitis associated). The range of the central, low and high damage cost values are included in Table 13.

Table 13. Damage costs for PM2.5 per unit concentration (£2020 per pop. weighted mean 1 µg m-3 change per person), by sensitivity (low, central, high estimates)

	Low estimate	**Central estimate**	High estimate
$PM_{2.5}$	£16.93	**£62.79**	£178.47

Sources: Ricardo; EMRC (Mike Holland)

The damage cost values have been standardised to 2020 prices (using GDP deflators) and uplifted by 2% per annum, in line with Green Book guidance. The uplift captures the higher willingness to pay of the population, and therefore value of health benefits as income (economic growth) rises.

Emissions of NOx, SO_2 and NH_3 contribute to damage costs via the secondary inorganic aerosol (SIA) contribution to ambient PM concentrations and the long and short-term exposure to PM concentration pathways. Emissions of NOx and VOCs also affect ground level ozone concentrations, with associated impacts on health, materials, and ecosystems. A full mapping of the different impact pathways included in each of the damage costs is described in the report by Ricardo for Defra entitled “Air Quality damage cost update 2020” (30).

The methodology used to evaluate the benefits of the two $PM_{2.5}$ targets was taken for consideration and subsequently approved by the **Interdepartmental Group on Costs and Benefits (IGCB)** of air quality during its December 2020 meeting. The IGCB is tasked with undertaking the formal economic analysis of air quality policy. It is responsible for approving any changes to the Defra DC/IGCB guidance. The group consists of a number of cross government stakeholders who ensure that the methodology uses the latest evidence for robustly valuing air quality impacts. Accordingly, the IPA and damage cost per unit of exposure approach has previously received IGCB approval, prior to its publication.

Air quality benefits: summarised results

Table 14 shows how the total air quality benefits derived from reduced damage to health, productivity, ecosystems and soiling of buildings from are split by pollutants from the medium and high scenarios. Benefits associated with reductions in $PM_{2.5}$ exposure and other air quality co-benefits such as reduction in NO_2 are estimated at £23.2 billion for the medium scenario and £37.9 billion for the high scenario.

Table 14. England: Cumulative (2023-2040) air quality benefits from reduced damage to health, productivity, ecosystems and soiling of buildings, broken down by sensitivity (2020 prices, £m)

	Medium Scenario			High Scenario		
	Low	Central	High	Low	Central	High
Total Air Quality Benefits	£5,327	£23,150	£71,255	£9,142	£37,891	£114,332

Other benefits

Other benefits: overview

For many of the measures included in this analysis, although they reduce $PM_{2.5}$ concentrations this may not be the only potential policy driver and most of the measures considered in this analysis have additional impacts which may be beneficial to society (co-benefits) or may have a negative impact on society (trade-offs).

The impact of the measures included in the modelling scenarios on potential co-benefits and trade-offs have been assessed qualitatively against the criteria outlined in Green Book supplementary guidance.

As it is not proportionate to quantify the impact of all co-benefits and trade-offs, attention has been focused on the most relevant and significant impacts highlighted in qualitative analysis.

Carbon saving: summarised results

Table 15 shows how the total benefits derived from reduced greenhouse gas emissions. The GHG saving has been monetised in line with BEIS guidance.

Table 15 England: Cumulative (2023-2040) benefit for GHG savings

	Medium scenario	High scenario
Greenhouse Gas saving ($MtCO_2e$)	475.41	540.23
Carbon saving (2020 prices, £m)	£85,175	£97,118

Economic costs

Economic: overview

As outlined in above the measures identified in the sector review were uploaded into bespoke software developed for Defra called the Scenario Modelling Tool (SMT). The SMT enables the impact of measures on future emissions to be modelled and calculates the costs associated with measures selected under each abatement scenario.

Where possible, the relevant cost data is drawn from existing tools and information in previous Defra projects, such as the Multi Pollutant Measures Database (MPMD) (31). Where this has not been possible additional research has been undertaken by external consultants to identify relevant cost data through several methods including literature reviews as well as interviews and workshops with stakeholders.

For most measures there is both a capital cost and operating cost. For the purposes of comparison, the equivalent annualised cost of measures is calculated by distributing capital costs over the lifetime of the measure and combining with operational expenditure. This allows for a representative cost per year of the measures to be compared where lifetimes of costs differ. In some cases, the cost is negative as there is a cost saving due to reduced fuel consumption.

Table 16 shows how the total costs corresponding to the measures included in the two scenarios.

Table 16 Equivalent Annualised Cost, 2023 – 2040, discounted (2020 prices, £m)

In £m	Medium Scenario	High Scenario
Total	£17,915	£27,074

Source: Defra, 2021

A more detailed discussion of the costs and benefits of these modelling scenarios, including summary results is available in the Impact Assessment.

Economic: summarised results

Setting the monetised benefits against the social costs we can derive summary appraisal stastics such as the Net Present Social Value and Benefit Cost Ratio, which proivde an indication of the net economic impact of the modelling scenarios.

Table 17 outlines these summary results for the medium and high scenarios under central sensitivity assumptions. It is clear from the evidence in this table that the pathways are very likely to achieve good value for money, with benefits outweighing costs.

Further detailed analysis of the economic costs and benefits is available in the Impact Assessment.

Table 17. Summary Cost Benefit Analysis Results, 2023-2040, discounted (2020 prices, £m)

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

Disparities in exposure: air pollution and deprivation

Research (32) has shown that often areas of higher deprivation have higher $PM_{2.5}$ exposure. One of the aims of the dual targets is to ensure that equity as well as the maximum health benefit is considered. In order to ascertain the results of the scenarios on these disparities the multiple deprivation index was compared with PWMC for each scenario and year. This showed that in all scenarios the gap in PWMC was greatly reduced.

The analysis focused on overall reduction of population exposure (reflected in population weighted mean concentrations, PWMC), and convergence towards a maximum concentration (indicated by calculating the population weighted mean exceedance, PWME). However, there are also equity issues and concerns about higher concentrations coinciding with more deprived members of society. Poor air quality is a particular threat to vulnerable groups, including the elderly, children, and to those with existing health issues, such as respiratory problems. Those living in city centres, and near busy roads, often on the lowest incomes, are most exposed to more dangerous levels of air pollution.

To assess the impact on deprived populations of the various pathways to reduce population exposure to air pollution, $PM_{2.5}$ concentrations in geographical areas are compared with the Index of Multiple Deprivation (IMD).

The index of multiple deprivation

The index of multiple deprivation (IMD) is derived for England from statistical data as a weighted average of seven different components, as summarised below (33).

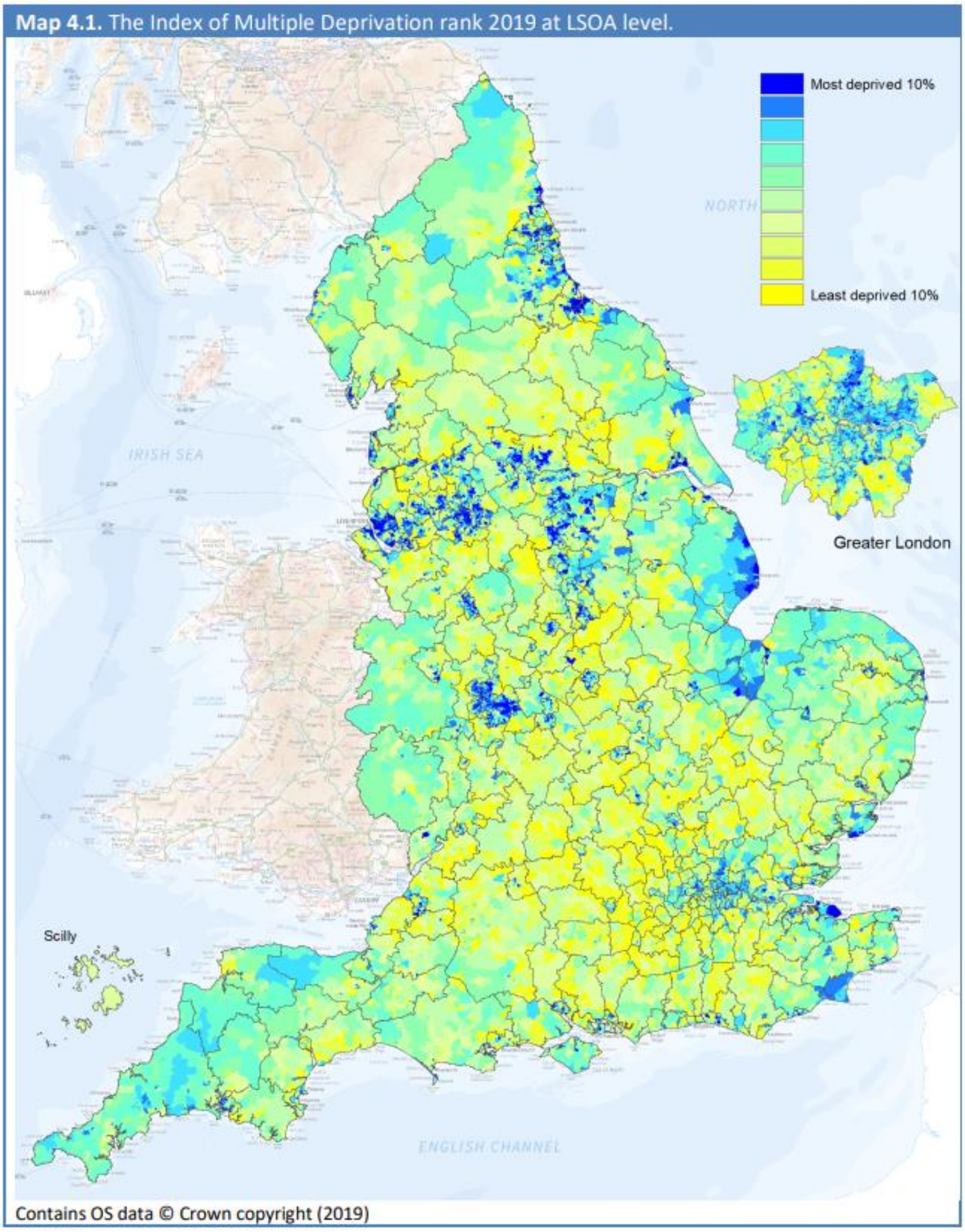
About the English Indices of Deprivation 2019 (IoD2019)

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

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

Figure 35 shows the IMD produced in 2019 at Lower-layer Super Output Area (LSOA) level across England. The areas have been ranked and divided into 10 equal groups (deciles). Areas shaded dark blue are the most deprived 10 per cent of LSOA in England, while areas shaded bright yellow are the least deprived 10 per cent. As was the case in earlier versions of the index, there are concentrations of deprivation in large cities and towns, including areas that have historically had large heavy industry, manufacturing and/or mining sectors, coastal towns, and parts of London (see smaller inset map).

Figure 35: Map Index of Multiple Deprivation (33)



Relationship with $PM_{2.5}$ concentrations

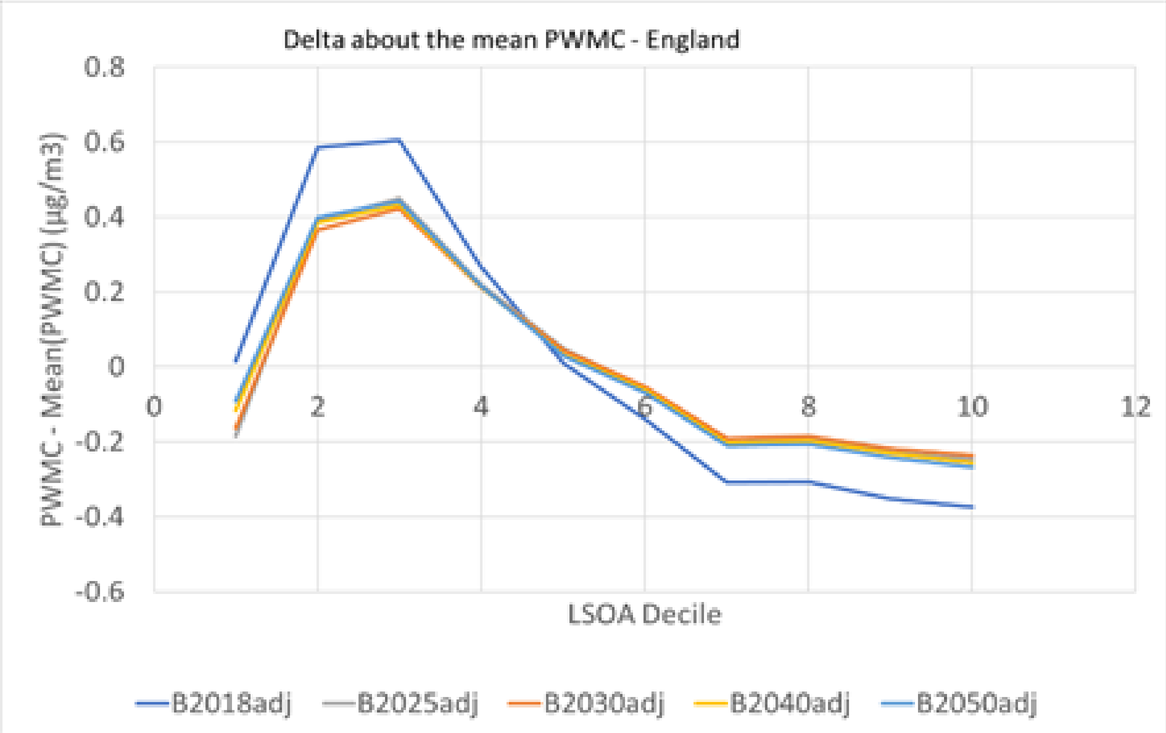
The relationship with $PM_{2.5}$ concentrations can be investigated by overlaying the map of the IMD on the pollutant concentrations calculated by UKIAM on the 1x1km^2 grid used for deriving population exposure and health impacts. The individual tiles of the IMD may overlap different grid-cells; and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

The difference (delta) in the degree of disparity between the different deciles, rather than the absolute concentrations, are calculated by subtracting the mean concentration from the

PWMC for each decile. The delta plot brings out the difference between the deciles more clearly and is used for the remaining analysis.

Figure 36 plots the delta PWMC and the deprivation index, ranging from the most deprived in decile one on the left, to the least deprived decile ten on the right. The graph shows the results for the years 2018, 2025, 2030, 2040 and 2050.

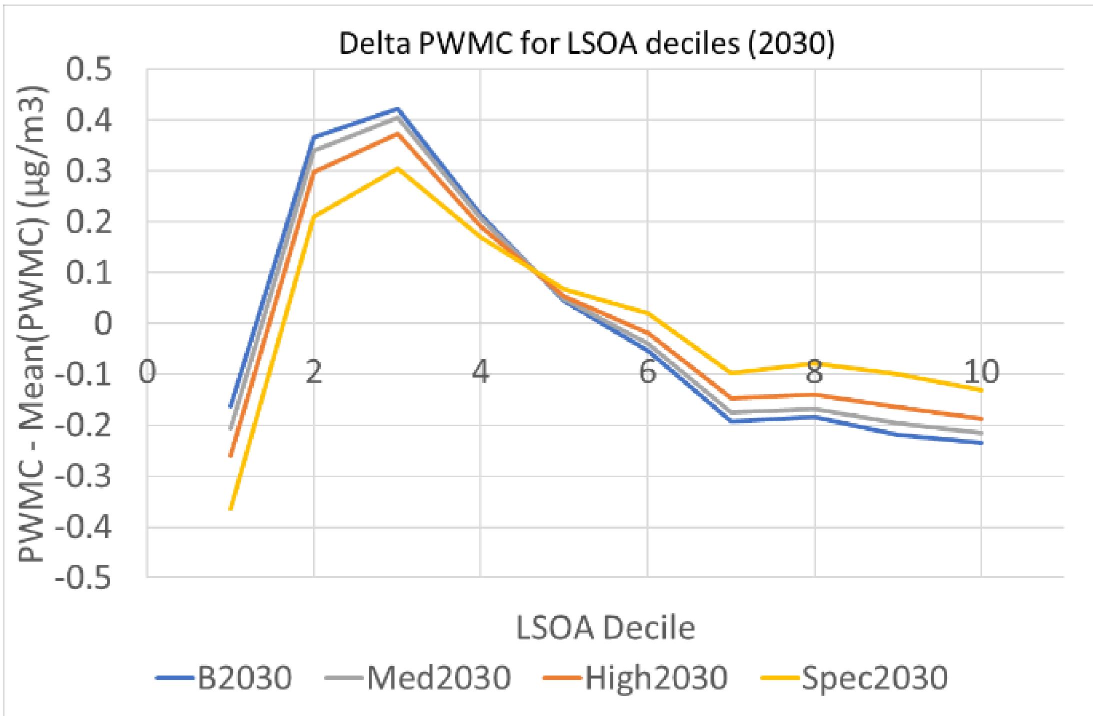
Figure 36: Disparities in $PM_{2.5}$ exposure

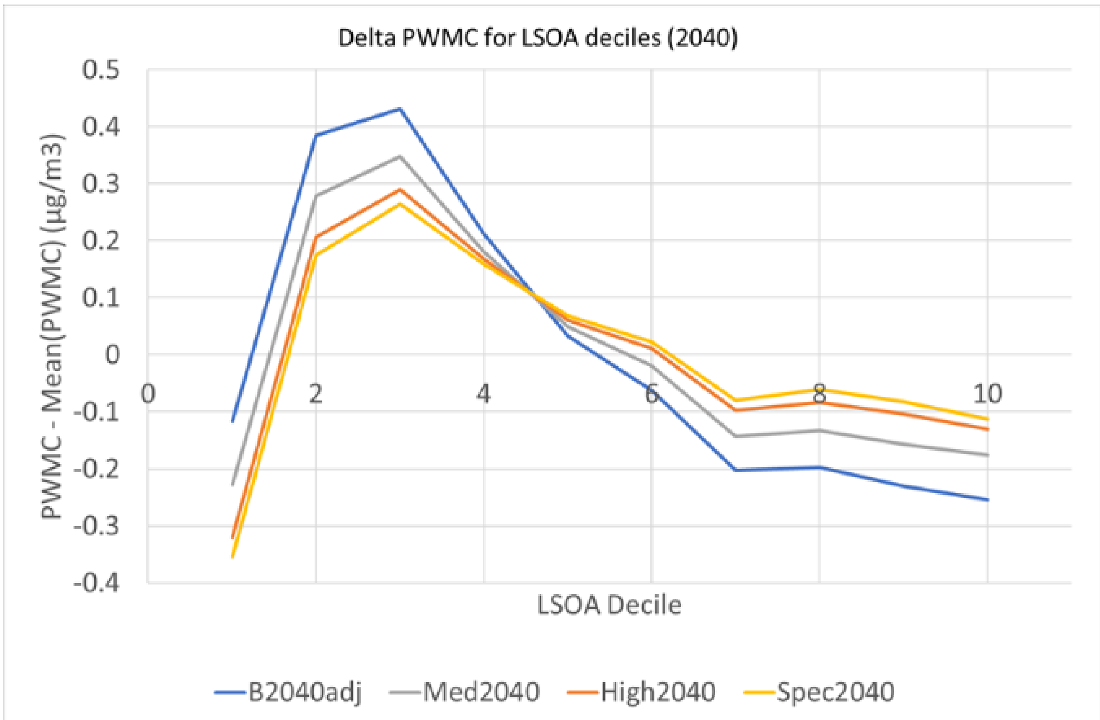


It shows that, across England as a whole the highest exposure does not coincide with the most deprived geographical areas, but with the 2nd and 3rd decile.

Extending the analysis to the medium, high and speculative scenarios we see a progressive reduction in exposure bias with scenario ambition, as shown in Figure 37 below. By 2040 a significant improvement is seen for all scenarios, with similar results seen for high and speculative.

Figure 37: Change in exposure disparities with scenario for 2030 and 2040





Ecosystem impacts

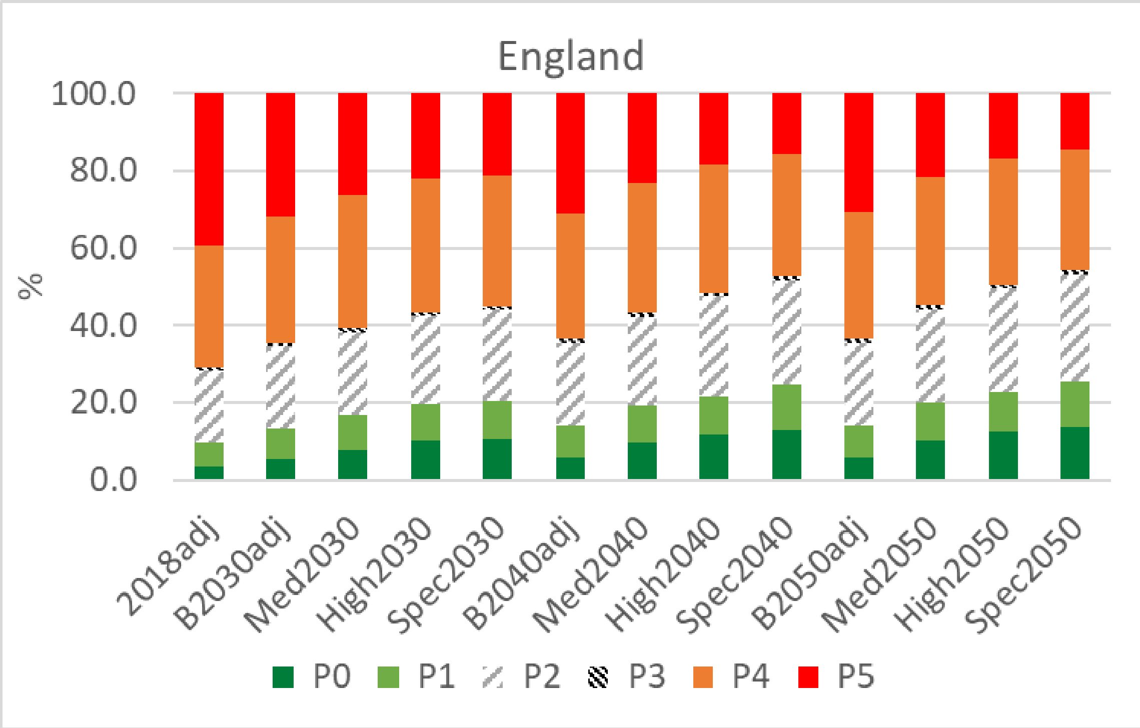
In addition to its impact on human health, air pollution also damages the natural environment. This is mainly through the impact of ammonia, nitrogen oxides and sulphur dioxide (all $PM_{2.5}$ precursors) on ecosystem health. This can be through direct exposure to concentrations in the atmosphere or through deposition onto soils and water, for example when it rains. The main environmental impact is through reactive nitrogen deposition onto sensitive habitats, this results in eutrophication damaging biodiversity.

Although the focus of the evidence gathering was $PM_{2.5}$ and its impact on human health, the benefits of the scenarios on ecosystem damage was also evaluated. All the scenarios include measures to reduce $PM_{2.5}$ precursors, as well as primary $PM_{2.5}$ so reduce the risk of ecosystem damage. The magnitude of the improvement was estimated by scoring the likelihood of nitrogen deposition exceeding the critical load for sensitive habitats. The critical load is an estimate of the threshold above which a habitat is likely to be significantly harmed and has been agreed by experts at an international level under the Convention on Long-range Transboundary Air Pollution. Different habitats have different critical loads. As it is based on expert views it is subjective, and some studies suggest that there is no threshold but gradual deterioration. Modelling of nitrogen deposition is also very complex and uncertain.

The ICL assessment approach therefore uses risk scoring and minimum and maximum deposition rather than an absolute value. The pollutant concentrations produced by the air quality modelling are used to estimate nitrogen deposition and compared to habitat maps. Each grid square is assessed against the minimum and maximum critical load for the particular habitat and allocated a risk score. The score ranges from P0 (the critical load is highly unlikely to be exceeded) to P5 (highly likely to be exceeded).

Figure 38 shows the combined results for all grid squares for different scenarios and years.

Figure 38: The risk of nitrogen-sensitive habitats exceeding the critical load under different scenarios



The analysis shows a reduction in the risk to ecosystems from air pollution over time, with the benefits increasing with greater levels of intervention. For example, in 2018 around 40% of sensitive habitats are highly likely to exceed the nitrogen deposition critical load, under the high scenario by 2040 this is reduced to 19%.

The Clean Air Strategy set a target of reducing the deposition of reactive nitrogen onto priority sensitive habitats by 17% by 2030. The $PM_{2.5}$ scenarios are not designed to focus on ammonia which is the main air pollutant to contribute to nitrogen sensitive ecosystem damage, however they do contribute towards this target. The high scenario would achieve 15% by 2030 and 19% by 2040. These numbers are crude estimates only. Each site will require a local assessment to determine whether the target is reached, however these reductions give an indication of the degree to which these national emission reductions can contribute towards achieving this target.

Summary

Two new legally binding air quality targets for England are being consulted on, and this document summarises the evidence supporting their development. The aim of both targets is to reduce the exposure of people to fine particulate matter ($PM_{2.5}$) concentrations, the pollutant of most harm to health. The Annual Mean Concentration Target (AMCT) will set a maximum level which should not be exceeded at any AURN monitoring site by the target date. This target will focus actions on reducing levels of $PM_{2.5}$ in the areas with the highest concentrations, reducing disparities in exposure. The Population Exposure Reduction Target (PERT) will set a level of reduction in average exposure for the whole country to be achieved by the target date. This will provide a driver for continuous improvement across the country, focusing reductions where they are most beneficial.

Below is a summary of the proposed target details and evidence covered in the report in relation to the two targets. It is divided into topic areas.

Metric proposals

In relation to metric definition, it is proposed that:

- There will be two air quality targets, an Annual Mean Concentration Target (AMCT) and a Population Exposure Reduction Target (PERT) which will work in tandem. Both targets will relate to $PM_{2.5}$ mass and be based on long term exposure (annual mean concentration).
- The AMCT metric will be annual mean concentration and the population exposure reduction metric will be an average of annual mean measurements from all representative monitors across the country, to provide a surrogate measure of population-weighted mean annual concentration for England.
- Both targets will be national (England) targets and will not differ by region.
- Interim targets will be used to drive and assess short term progress towards the longer-term target. Interim targets may include other indicators of progress such as reductions in UK annual emissions and measured PM component concentration.

In relation to metric calculation, it is proposed that:

- The AMCT will be based on assessment of individual calendar years at each monitoring location.
- The PERT will be calculated by taking the mean of three consecutive calendar year averages, across the population of representative monitoring.
- The PERT baseline will be based on taking the mean of three consecutive calendar year averages.
- The AMCT will be assessed and reported for all individual monitoring sites.
- The PERT will be calculated by averaging annual mean concentrations at urban background and suburban sites (if more representative).
- The existing data capture threshold will be maintained, below which a site’s measurements will not be included. No data modelling or interpolation will be used to fill in missing data.

- The metrics will not account for variable levels of population susceptibility.

Summary of points relating to the metrics in practice

- Communication of the targets needs to be considered alongside the technical aspects. Metrics need to be simply expressed (even if the underlying details are complicated) and with an unambiguous approach to evaluating progress/compliance.
- The targets will be part of a wider air quality policy framework and supported by a cross policy-area system of regular assurance and review.
- There will be join up with local/regional air quality management, and the role of local authorities will be included in the Air Quality Strategy review.

Assessment proposals

It is proposed that:

- Legal compliance will be assessed by monitoring; modelling will play a supporting role.
- The existing $PM_{2.5}$ monitoring network will be extended. During 2022 and 2023 the network of urban background monitors will be expanded to approx. 57 monitors. The site categorisation for monitoring sites will remain unchanged.
- An expanded network will include additional monitors in hotspots (identified through modelling), predominantly at urban traffic/near source locations, but ensuring that monitoring follows a degree of proportionality with respect to the populations within each zone.
- Compliance assessment against the new targets will be undertaken on the basis of the existing zones and agglomerations for England.
- Assessment of the two new targets will be included as part of the long-running series of annual reports from the national air pollution monitoring networks and through access to real-time data and statistics through UKAIR**.**
- The equivalence framework will be reviewed and adapted to reflect the performance of the instruments and expanded uncertainty once assessed with respect to the new target levels.
- Data objective requirements for data capture, standardised reporting and rounding will form part of the new target requirements.
- The rural background monitoring capability will be increased but the data will not form part of the PERT metric.

Target level and date summary

Future $PM_{2.5}$ concentrations

- Modelling has been shown to provide estimates of $PM_{2.5}$ concentrations that are comparable to measurements and is therefore a suitable tool for assessing target achievability.
- Development of future emissions scenarios based on packages of illustrative measures to reduce $PM_{2.5}$ and precursor emissions enables the achievability of targets to be assessed.
- Modelling results suggest that even without additional intervention existing policies, such as the wet wood and coal regulation, alongside expected technology turnover (for example in vehicles) will reduce $PM_{2.5}$ concentrations substantially over the next few years. However, reducing concentrations in large urban centres such as London remains challenging.
- The three scenarios modelled (medium, high and speculative) all produce lower concentrations than the baseline scenario. The greatest change is seen in urban areas, but there are improvements throughout the country.
- Lower concentrations require increasingly more stringent actions, with greater uptake and more rapid implementation.
- The largest, most rapid reductions considered feasible by sector experts and practitioners are unlikely to enable 10 µg m^{-3} to be reached by 2030 in all locations. However, it could be reached by 2040 with emission reductions akin to those in the high scenario.
- Implementing more stringent measures in London than in the rest of the country would enable a lower AMCT to be met, however the impact on the PERT is smaller.

Sources of $PM_{2.5}$

- Around half of current $PM_{2.5}$ concentration is outside of UK control. Modelling suggests that 32% is from natural and irreducible sources (e.g. from sea salt, soil, vegetation and resuspension), 13% from Europe and 6% from international shipping (including ships which do not stop at a UK port).
- Of the contribution from UK manmade sources, wood burning and road transport are the largest contributors (29% and 23% of the UK's contribution respectively). Other sources include industrial combustion and processes, energy production and agriculture.
- A large proportion of $PM_{2.5}$ concentration is not as a result of directly emitted (primary) $PM_{2.5}$ but from particles formed in the atmosphere from other pollutants.

Modelling uncertainty

- The model used produces similar results to the other types of air quality models it was compared against.
- The model also provide a good historical recreation of the average of all measurements made a turban background monitoring sites. It produces averages for 1km grid squares, so cannot model near-source measurements. There is variability between model and observations at individual sites of up to ±1.7 µg m^{-3} due to local factors that are not modelled.

- Unfavourable weather conditions can increase annual mean concentrations by 1 µg m^{-3} or more compared to average conditions.
- Sensitivity analysis was carried out key emission sources including exploring the impact of electric cars, lower wood burning emission figures and adding in cooking emissions.

Baseline sensitivities

- An NECR plus EV scenario where existing commitments for reducing emissions of five key pollutants by 2030, including $PM_{2.5}$ and its precursors are met was modelled. This produced similar results to the high scenario for 2030.
- A scenario where actions were taken to meet the 6th Carbon Budget and net zero was also evaluated. The scenario was close to baseline scenario for 2030, mainly due to the lead time of measures and the increased burning of biofuels which offsets the air quality benefits arising from other actions. However, by 2040 $PM_{2.5}$ concentrations were close to the medium scenario.

Target impacts

Health benefits

- All the scenarios have large health benefits, with the greatest benefits seen with the scenarios with the most extensive and most rapid reductions in $PM_{2.5}$ concentrations.
- People living in more deprived areas are often exposed to greater levels of $PM_{2.5}$ concentration than those in more affluent areas. All the scenarios modelled show a reduction in exposure disparity, so that areas of greater and less deprivation are exposed to more similar, and reduced, concentrations.

Co-benefits

- Many of the actions that reduce $PM_{2.5}$ concentrations also reduce GHG emissions and will contribute towards meeting net zero by 2050. An estimated 541MtCO2e savings in GHG emissions is likely by 2040 under the high scenario.
- Actions taken to reduce $PM_{2.5}$ precursors will benefit the environment, reducing the impact of reactive nitrogen on sensitive habitats and so improving biodiversity.

Economic cost

- $PM_{2.5}$ has a large economic cost, mainly due to the loss of productively due to the health impacts. It is estimated that every 1 µg m^{-3} of exposure per person in each year exerts a cost on society of £62.79.
- Accumulating the cost saved over all people and years as a result of the $PM_{2.5}$ reductions from the high scenario brings results in a cost saving of approximately £32 billion.
- Comparing this to the costs of implementing the scenario with benefits and co-benefits gives the benefit cost ratio. This is 5.0 for the high scenario, which means the monetised benefits are over five times the costs.

- Carbon reduction co-benefits are a large contributor, but the ratio would still be positive based on air quality improvements alone.

Impacts on individuals, businesses and industry

- The scenarios modelled are to evaluate the achievability of the targets, the scenarios are not policy pathways, nor the measures within the scenarios current government policy. Emissions reductions akin to those in the scenarios can be met in many ways, with different emphasis on different sectors or technology/behaviour change. It is likely that both technology and behaviour change will be needed to reduce emissions.
- Two areas where action may be needed are road transport and domestic combustion. However, there remains significant uncertainty with regards to the scale of emissions from domestic combustion and this has been taken into consideration in setting the targets. Other important areas for emissions include agriculture, industrial combustion and manufacturing and construction. Some measures are likely to be applied only in urban areas.
- Action may require additional regulation and enforcement, financial incentives or restrictions to change behaviour, awareness raising and investment in technology by government, industry and individuals. Individual policies or changes will be developed and consulted on separately, but the greater the level of reduction in $PM_{2.5}$, the greater the level of change likely to be required.

Proposed targets

Interpretation

- The reduction in population exposure (needed to assess the PERT) can be calculated from the modelling results. Assessing the AMCT is more difficult, but the accumulated exceedance of different thresholds can be used as an indicator of achievability.
- The medium scenario achieves a population exposure reduction of 31% by 2040 compared to 2018, the high scenario achieves 35% and the speculative 39%.
- The AMCT matrix gives an assessment of the achievability of different targets under different scenarios. The green indicates a target is likely to be achievable and yellow possibly achievable. These are considered to be feasible targets. Those coloured amber (unlikely to be achievable) or red (very unlikely to be achievable) are not.
- In considering which targets are set, the health benefits need to be balanced against the types of measures, implementation times and uptakes likely to be needed to deliver them. The restrictions these represent and likely cost to businesses and individuals.
- They also need to be considered in the context of modelling uncertainties, potential impact of net zero and NECR actions, and current maximum concentrations and population exposure.

The proposed targets are:

- An AMCT of 10 µg m^{-3} by 2040
- A PERT of 35% by 2040 compared to 2018

A public consultation is being held on these targets to seek views on if the balance between health benefits and potential future policy actions is appropriate.

Interim targets will be set to ensure progress towards meeting these targets, and progress will be reviewed every five years.

Next steps

This report provides an overview of the evidence that has been commissioned, collated and utilised in order to inform the target setting process.

It is important that this work is considered as part of the consultation process to enable effective and informed responses from a wide range of participants. Setting targets for $PM_{2.5}$ is complex and challenging, with many different aspects to consider. The targets will require action from everyone but have the potential to drive effective change to improve air quality across the country and reduce the detrimental impacts it has on health.

This is a summary of evidence to date, but the work does not stop here. It will continue to be refined as further evidence is made available and it will be important to reflect on the consultation before targets are confirmed and set into legislation by 31st October 2022.

Work will continue to consider what role local authorities will play in helping deliver the targets, and how the monitoring network will be expanded to support the new targets.

Beyond consultation consideration will be given to the setting of the first interim targets and once targets are set work will move towards developing policies and pathways to deliver progress towards both the interim and long-term targets.

Annual reporting against the targets will begin for 2023 and will be undertaken as part of the 2024 reporting.

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Annexes

Annex A: AQEG engagement meeting on the $PM_{2.5}$ target setting process

https://uk-air.defra.gov.uk/assets/documents/reports/aqeg/PM25_targets_AQEG_feedback_v2.pdf

Annex B: COMEAP engagement meeting on the $PM_{2.5}$ target setting process

https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1002454/PM2.5_targets_COMEAP_feedback_July_2020.pdf

Annex C: Technical workshop on target metrics

https://uk-air.defra.gov.uk/library/reports?report_id=1073

Annex D: Note on the extension of NAEI 2018 baseline projections

https://uk-air.defra.gov.uk/library/reports?report_id=1076

Annex E: AQEG summary of the Call for evidence on future $PM_{2.5}$ concentrations in England

Report: Modelling of future PM2.5 in support of the Defra air quality target setting process - Defra, UK

Annex F: AQEG summary of the modelling results workshop

https://uk-air.defra.gov.uk/library/reports?report_id=1075

Annex G: AQEG advice note on Measurement Uncertainty for $PM_{2.5}$ in the Context of the UK National Network

https://uk-air.defra.gov.uk/library/reports?report_id=1074

Annex H: COMEAP advice on health evidence relevant to setting $PM_{2.5}$ targets

https://www.gov.uk/government/publications/fine-particulate-air-pollution-pm25-setting-targets

Glossary and abbreviations

AEI (Average Exposure Indicator)	The statistic on which the Air Quality Standards Regulations' national exposure reduction target is based, for $PM_{2.5}$ between 2010 and 2020. The AEI for the UK is calculated as follows: the arithmetic mean $PM_{2.5}$ concentration at appropriate urban background sites is calculated for three consecutive calendar years, and the mean of these values taken as the AEI.
Air Quality Standards Regulations 2010 (AQSR 2010)	Prior to 31 January 2020, the UK was a Member State of the European Union. As such, the UK was required to incorporate - or 'transpose' - the provisions of EU Directives into their own national law by a specified date. The Air Quality Standards Regulations are the legislation by which the UK fulfilled this requirement. These standards were retained after leaving the EU.
Air Quality Strategy	The UK's National Air Quality Strategy, containing policies for assessment and management of air quality in the UK. This was first published in 1997, as a requirement of The Environment Act 1995.
Ambient air	Air outside of buildings.
AMCT (Annual mean concentration target)	One of the new $PM_{2.5}$ targets being set for England under the Environment Act 2021. A $PM_{2.5}$ concentration target is a requirement of the Act. The AMCT is based on measurements at individual monitoring sites averaged over a calendar year.
AURN	The AURN is the UK's largest automatic monitoring network and is the main network used for compliance reporting.
BAM (Beta Attenuation Monitor)	A type of instrument used for monitoring concentrations of particulate matter.
Black carbon	A component of $PM_{2.5}$. Small particles of carbon formed by combustion of fossil fuels and biomass i.e. a key constituent of soot. It has been linked to human health damage and contributes to climate change.
CAS (Clean Air Strategy)	Published in 2019, this is the UK Government's framework document setting out policy action to drive down national emissions of five damaging pollutants to achieve statutory emissions reduction commitments, reduce background pollution, and minimise human exposure to harmful concentrations of pollution.

Concentration	The amount of pollutant in a given volume of air. Measured in mass per volume e.g. µg per m^3. Varies over time and by location.
Environmental Improvement Plan (EIP)	The preparation of an environmental improvement plan is a requirement of the Environment Act 2021. It is defined in the Act as a plan for significantly improving the natural environment in the period to which the plan relates.
EMEP4UK	An atmospheric chemistry transport model used to estimate concentrations of air pollutants. EMEP was developed to support European policy by the UNECE Convention on Long-range Transboundary Air Pollution (CLRTAP) and the European Commission. EMEP4UK is a version focusing on the UK used by UKCEH.
Emissions	Pollutants released into the air by a particular source or country over a specified time. Measured in weight. E.g. kilotonnes emitted by the UK over a year.
Exceedance	A period of time when the concentration of a pollutant is higher than an air quality standard/objective/target.
Exposure	The concentration of pollutant people experience. This can be individual exposure determined by where someone lives, works and their lifestyle or population exposure which is the average pollution a country's population is exposed to.
FDMS	This stands for 'Filter Dynamic Measurement System' and refers to a type of instrument for monitoring concentrations of particulate matter. The FDMS is a modified form of Tapered Element Oscillating Microbalance (TEOM).
FIDAS	A type of instrument which uses an optical technique for monitoring concentrations of particulate matter.
Microgramme per cubic metre ($\mu g\ m^{-3}$)	A unit often used to express concentration of a pollutant in air. 1 µg = 1 millionth of a gramme or 1×10^{-6} g
NAEI (National Atmospheric Emissions Inventory)	The official inventory of UK emissions of air pollutants and greenhouse gases. It follows internationally agreed report methods and is what is used to determine if the UK has met its international commitments.
NECR (National Emission Ceiling Regulations)	The legislation which puts into UK law the emissions targets that the UK have committed to under international agreements.
Net zero	Net zero emissions are reached when anthropogenic (i.e., human-caused) emissions of greenhouse gases to the

	atmosphere are balanced by anthropogenic removals over a specified period.
NH_3	The chemical formula for ammonia. A pollutant released mainly from agriculture.
NO_x (nitrogen oxides)	Compounds formed when nitrogen and oxygen combine. NO_x, which comprises of nitric oxide (NO) and nitrogen dioxide (NO_2), is emitted from combustion processes. Main sources include power generation, industrial combustion and road transport.
NO_2 (nitrogen dioxide)	One of the oxides of nitrogen formed in combustion processes. At high concentrations NO_2 is an irritant to the airways. NO_2 can also make people more likely to catch respiratory infections (such as flu), and to react to allergens.
Particulate matter (PM)	Small airborne particles. PM may contain many different materials such as soot, wind-blown dust or secondary components, which are formed within the atmosphere as a result of chemical reactions. Some PM is natural and some is man-made. Particulate matter can be harmful to human health when inhaled, and research shows a range of health effects associated with PM. In general, the smaller the particle the deeper it can be inhaled into the lung.
PCM (Pollution Climate Mapping)	A collection of models designed to fulfil part of the UK's EU Directive (2008/50/EC) requirements to report on the concentrations of particular pollutants in the atmosphere.
PERT (Population Exposure Reduction Target)	One of two new $PM_{2.5}$ targets proposed under the Environment Act 2021. It is the reduction in average exposure of the population compared to a base year.
Primary PM	Airborne particles which are released into the atmosphere as particles, in contrast to secondary PM which is formed in the air from reactions of gaseous precursors.
$PM_{2.5}$ or fine particulate matter	Particles which pass through a size-selective inlet with a 50 % efficiency cut-off at 2.5 μm aerodynamic diameter, as defined in ISO 7708:1995, Clause 7.1. This size fraction is important in the context of human health, as these particles are small enough to be inhaled very deep into the lung – described as the 'high risk respirable convention' in the above ISO standard. $PM_{2.5}$ is often described as 'particles of less than 2.5 micrometres in diameter' though this is not strictly correct.

PM_{10} or coarse particulate matter	Particles which pass through a size-selective inlet with a 50 % efficiency cut-off at 10 µm aerodynamic diameter, as defined in ISO 7708:1995, Clause 6. This size fraction is important in the context of human health, as these particles are small enough to be inhaled into the airways of the lung – described as the 'thoracic convention' in the above ISO standard. PM_{10} is often described as 'particles of less than 10 micrometres in diameter' though this is not strictly correct.
Precursors	Chemicals which react to form other pollutants. $PM_{2.5}$ precursors include ammonia (NH_3), nitrogen oxides (NOx), sulphur dioxide (SO_2), ozone (O_3) and volatile organic compounds.
PWMC	Population Weighed Mean Concentration is an indicator calculated from modelling results which represents average exposure across a region. It is calculated by multiplying concentrations of grid squares by the population resident in the grid square and dividing by the total population of the region.
Reference method	The method that the EU uses to define its air quality limit values. If member countries use another method for monitoring, they need to demonstrate that their method gives the same results as the reference method.
Secondary PM	PM which is formed by chemical reactions from other pollutants in the atmosphere.
SO_2 (sulphur dioxide)	An acid gas formed when fuels containing sulphur impurities are burned. SO_2 irritates the airways of the lung.
Transboundary	Pollution which has travelled across a border into the assessment area, e.g. pollution from outside the UK (from other countries or shipping) that affects the UK or from outside a region/city from other parts of the country.
UKIAM (UK Integrated Assessment Model)	A national model developed to assess different strategies for reducing air pollutants. It brings together information from different sources to enable the comparison of pollutant concentrations under different scenarios.
WHO (World Health Organization)	The United Nations agency responsible for international public health.