EVIDENCE TO SUPPORT THE DEVELOPMENT OF $PM_{2.5}$ TARGET PROPOSALS IN WALES

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1. INTRODUCTION

Clean air is a key priority for the Welsh Government (WG), who have introduced an Environment (Air Quality and Soundscapes) (Wales) Act 2024. The Act sets out an air quality target-setting framework that gives Welsh Ministers powers to make regulations setting long term targets in respect of any matter relating to air quality in Wales. There is a duty on Welsh Ministers to make regulations setting a target for $PM_{2.5}$ within 3 years of Royal Assent. There is a further duty for Welsh Ministers to make regulations within 6 years of Royal Assent to set a long-term target for one of the following pollutants: ammonia (NH_3); particulate matter (PM_{10}); ground level ozone (O_3); nitrogen dioxide (NO_2); carbon monoxide (CO); or sulphur dioxide (SO_2). The Act also requires Welsh Ministers to obtain independent advice from experts and have regard to scientific knowledge before setting or amending targets, including World Health Organisation (WHO) air quality guidelines. This requirement ensures that targets are informed by sound scientific evidence and expert recommendations. New national air quality targets will provide a strong mechanism to deliver positive long-term ambitions for clean air and associated public health and environmental outcomes, building upon progress towards the objectives of the Clean Air Plan for Wales.

In this context, the Welsh Government commissioned Ricardo to provide independent evidence and advice to support the setting of new air quality targets within two projects. The two phases of work comprised:

- Phase 1: Ricardo worked with the Welsh Government to assess technological and behavioural multi-pollutant emission reduction measures across different sectors that may be put in place up to 2040. The work included identifying the policies or changes to policy that could be implemented by 2040. The potential future pollutant-specific emission reduction trajectories for these measures were calculated based on the latest National Atmospheric Emissions Inventory (NAEI) data. In addition, the costs of implementing each measure were also estimated. Details of the approach and results from this phase of the project are summarised in Appendices A.
- Phase 2: Ricardo modelled the dispersion of air pollutants to determine the combined effect of optimised combinations of policy measures ('scenarios') in achieving future concentration-based target levels. The outputs of the modelling enabled the production of concentration maps for each pollutant considered and for each year of concern. These concentration maps were then compared to the WHO target levels and interim target levels (where available) for each pollutant. These maps were used to assess which potential target levels could be achieved across Wales in each modelled year. Phase 2 of the project also aimed to investigate the health, environmental and other potential benefits associated with each of the scenarios for 2025, 2030, 2035, and 2040. Details of the approach and results from this phase of the project are summarised in Appendices B – D.

The Welsh Government commissioned Ricardo to **build on this work to conduct an appraisal or Cost-Benefit Analysis of eight agreed Air Quality Target Scenarios for $PM_{2.5}$** as part of its plan to meet the legal targets set in the Air Quality and Soundscape Act. The eight targets are described in Section 3. The appraisal has been conducted over 2025-2040, and annualised costs and benefits are presented for years 2030, 2035 and 2040 for comparison.

This report presents the results of this appraisal in the following structure:

- Section 2 contains an overview of air quality in Wales as determined in Phase 2 of this project.
- Section 3 specifies the Air Quality Target Scenarios under consideration.
- Section 4 presents the appraisal of these scenarios, including health impact and economic assessments, and distributional analysis.
- Section 5 sets out the findings and limitations.
- The Appendices present an overview of the methodologies employed to conduct these analyses, primarily linking to previous studies commissioned by the Welsh Government.

2. AIR QUALITY IN WALES

2.1 CURRENT TARGET AND GUIDELINE LEVELS

Air Quality Standards are scientifically determined acceptable concentrations of a pollutant over a specific period of time. They serve as benchmarks to assess air pollution trends and health effects. An **Air Quality**

Objective is the target date on which exceedances of a standard must not exceed a specified number. **Limit values** are legally binding limitations set for individual pollutants that must not be exceeded.[1] These are expressed as concentrations, rather than emissions, to reflect the levels of pollutants present in the air that people are exposed to and therefore to provide a direct measure of the potential associated health risks and environmental impacts.

Table 2-1 presents current Air Quality Objectives in Wales for $PM_{2.5}$. Monitoring and reporting of fine particulate matter ($PM_{2.5}$) is encouraged but not mandatory in Wales. However, a limit value for $PM_{2.5}$ of 25 µg/m^3 was set in the Air Quality Standards (Wales) Regulations 2010,[2] to be met by 1 January 2015.

Table 2-1 Air quality objectives in Wales for $PM_{2.5}$.[3]

Pollutant	Concentration	Type	Measured as
Particles ($PM_{2.5}$)	25 µg/m^3	Limit value	Annual mean

The World Health Organization (WHO) Air Quality Guidelines (AQG) provide health-based recommendations for managing air quality, focusing on long- or short-term concentration levels of key air pollutants. Exceeding these guidelines poses significant health risks to the public. In response to evidence of the threat of air pollution to public health at even lower concentrations than previously understood, the AQG were updated in 2021 to reduced values. For example, the recommended annual AQG levels for $PM_{2.5}$ were reduced from 10 µg/m^3 in 2005 to 5 µg/m^3 in 2021.[4] While the values are not legally binding, they inform legislation and policy, aiming to reduce air pollution levels and mitigate global health impacts caused by air pollution exposure. However, it may not be feasible to meet these concentrations or accurately to be able to monitor at these low concentrations. A summary of WHO guidelines for the pollutants of concern within this report is shown in Table 2-2.

Table 2-2 World Health Organization (WHO) air quality guidelines updated in 2021[5]

Pollutant	Averaging time	Interim target				AQG level
		1	2	3	4	
$PM_{2.5}$	Annual	35	25	15	10	5
	24-hour[a]	75	50	37.5	25	15

The target and limit values set out in Table 2-1 and the WHO air quality guideline values detailed in Table 2-2 have formed the starting point from which to compare the modelled concentrations, in order to provide Welsh Ministers the evidence they need to set new Air Quality Targets in Wales.

2.2 SUMMARY OF EVIDENCE SUPPORTING A NEW AIR QUALITY TARGET FOR $PM_{2.5}$

Welsh government have previously commission Ricardo to assess technological and behavioural multi-pollutant emission reduction measures across different sectors that may be put in place up to 2040.

Working with a range of stakeholders, including regulators and industry sector leads, policies or changes to policy that may affect emissions of the pollutants of concern and that may be brought in by 2040 were identified. This led to the development of a list of potential measures and emission reduction scenarios that were consulted on with a wide range of stakeholders including colleagues from Transport for Wales, Welsh Government domestic burning team, industrial policy teams and energy teams, National Farmers Union, Welsh

[1] https://www.legislation.gov.uk/wsi/2002/3182/made
[2] https://www.legislation.gov.uk/wsi/2010/1433/contents/made
[3] National air quality Standards and Objectives
[4] https://www.who.int/news-room/feature-stories/detail/what-are-the-who-air-quality-guidelines
[5] WHO global air quality guidelines: particulate matter (PM2.5 and PM10), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide

Government agricultural team, local authorities, Environment Agency, Welsh Government transport decarbonisation team, RSK ADAS, UKCEH, Local Authorities and the Chartered Institute for Environmental Health.

Following consultation, a final list of measures was developed, including uptake rates for each measure. The potential future pollutant specific emission reduction trajectories for these measures were calculated based on the latest National Atmospheric Emissions Inventory (NAEI) data. In addition, the costs of implementing each measure were also calculated.

The measures were grouped into three ambition scenarios, 'Medium', 'High' and 'Speculative'; these groupings are based on the likelihood of the measures taking place.

The scenarios were used to evaluate the feasibility of new targets for a number of pollutants ($PM_{2.5}$, PM_{10}, NO_2, NH_3, CO, SO_2, NMVOC and O_3). The feasibility study used a combination of air quality dispersion models to predict concentrations of each pollutant across Wales, which was combined with economic models to calculate the cost benefits of each scenario. The feasibility assessment tracked pollutant concentrations, and cost benefits across five year intervals between 2025 and 2040 (2025, 2030, 2035 and 2040). The baseline was also modelled in 2019.

Advice from the Clean Air Advisory Panel (CAAP) to the Welsh Government suggested that an Annual Mean Concentration Target (AMCT) and Population Exposure Reduction Target (PERT) should be used for $PM_{2.5}$. The AMCT would be focussed on reducing concentrations at hotspot locations where there is relevant exposure. The inclusion of the PERT would encourage improvement in air quality in all areas of Wales including those that are already meeting any proposed AMCT. Here, we present an overview of the modelled $PM_{2.5}$ annual mean concentrations and potential compliance with PERT.

2.2.1 Annual Mean Concentration Targets

Predicted pollutant concentrations were compared with the existing Air Quality Objective target and limit values for each pollutant and with the more stringent WHO guideline levels. These limit values and levels are set as Annual Mean Concentration Targets (AMCTs).

Annual mean $PM_{2.5}$ concentrations were predicted to be compliant with the Welsh National Air Quality Objective across Wales in 2019. This indicates that a more stringent target could be brought in to help reduce concentrations of $PM_{2.5}$ within Wales.

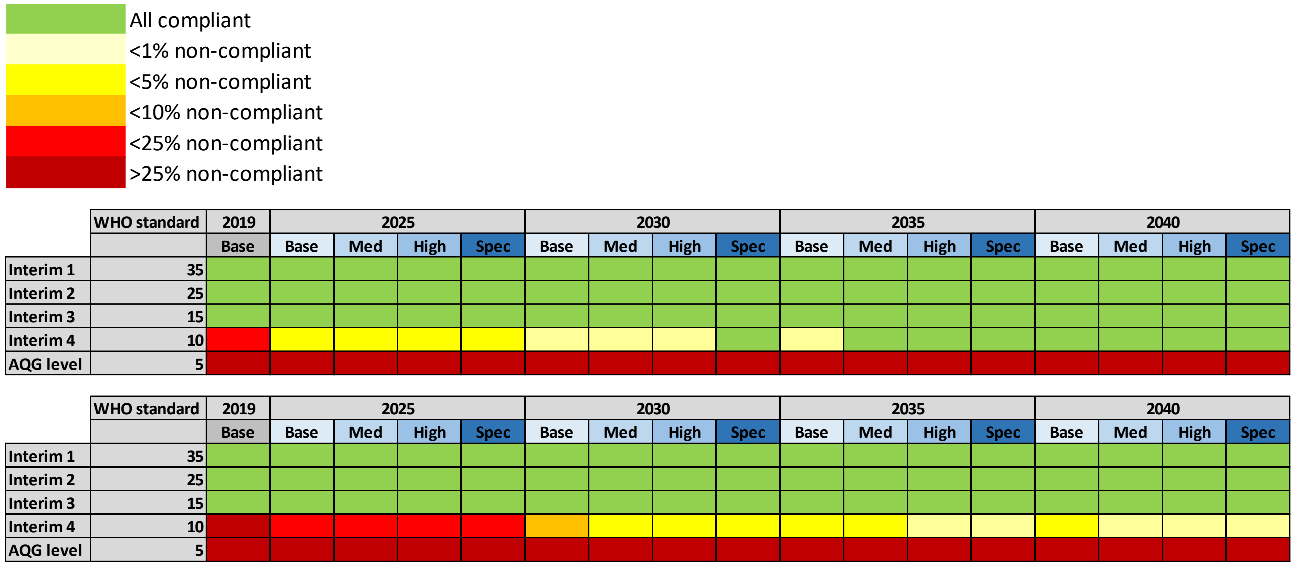
However, modelled concentrations were predicted to exceed the significantly stricter WHO AQG (5 $\mu g.m^{-3}$) across south Wales and along the border with England in the northeast. Exceedances of the WHO AQG are common in countries in Europe, where regional concentrations historically exceed the WHO AQG across many locations as the result of local, national and transboundary emissions sources.

As $PM_{2.5}$ is a regional pollutant, exceedances are predicted across wide areas of Wales rather than being restricted to the vicinity of local sources such as roads, ports, or industry. The maximum predicted concentrations are seen near major roads near to Cardiff and Newport, where regional and local contributions coincide to produce annual mean concentrations up to 16 $\mu g.m^{-3}$ in 2030. In mid and northwest Wales, concentrations are mostly below the WHO AQG, with small-scale exceedances of up to 7 $\mu g.m^{-3}$ within towns including Aberystwyth and Amlwch. The total area in Wales predicted to exceed the annual mean WHO AQG in the 2030 baseline is 4850 km^2, corresponding to 23% of the total area of Wales.

Modelled concentrations in the three ambition scenarios were compared with the WHO Air Quality Guideline (AQG) and the interim targets within the second phase of the work to provide evidence to Welsh Ministers that supports them setting an AMCT.

Figure 2-1 shows the percentage of Lower Layer Super Output Areas (LSOAs) compliant with WHO targets for annual mean $PM_{2.5}$, unadjusted and adjusted to account for intrinsic model uncertainty. The modelling demonstrates that the WHO Air Quality Guideline level will not be met across all LSOAs in Wales in any modelled scenario, but that the Interim 4 Target Level of 10 $\mu g.m^{-3}$ could be met across the majority of LSOAs in 2035 or 2040.

Figure 2-1: Percentage of LSOAs compliant with WHO targets for annual mean $PM_{2.5}$, unadjusted (top) and adjusted (below) for model uncertainty



2.2.1.1 *Population Exposure Reduction Targets*

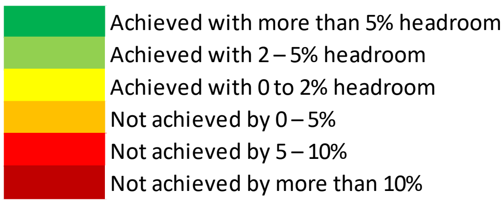
By their nature, measures to achieve AMCTs will target near-source locations across Wales, where maximum concentrations occur. While some members of the population may be exposed to these maximum concentrations, these near-source locations are not necessarily representative of wider population exposure, which is more likely to be driven by concentrations across urban background locations.

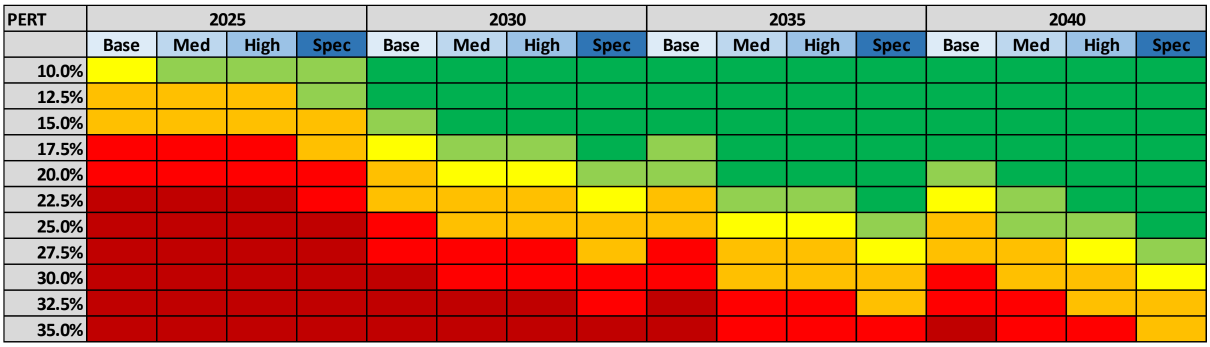
As a result, the introduction of an AMCT in isolation might result in policies which only address concentrations at a relatively small number of hotspot locations without benefitting the wider population. Concentrations would also be allowed to increase at locations where concentrations are lower than the AMCT. To alleviate these issues, the Welsh Government will also consider the introduction of a Population Exposure Reduction Target (PERT) to enable wider population exposure to air pollution to be addressed.

In England, the PERT for $PM_{2.5}$ is to be assessed using multi-year monitoring data at urban background monitoring sites. However, the number of urban background monitoring stations in Wales that monitor $PM_{2.5}$ concentrations is too low to allow meaningful estimation of population exposure from monitoring data at present.

In order to provide a summary of compliance with potential PERTs across all modelled years and scenarios, the achievement of potential PERTs based on population-weighted mean concentrations across Wales was represented as compliance matrices. Figure 2-2 presents the PERT compliance matrix for $PM_{2.5}$.

Figure 2-2: PERT compliance matrix for annual mean $PM_{2.5}$ concentrations





The modelling suggests that the maximum feasible PERTs under each scenario are:

- Medium: 25% by 2040
- High: 28% by 2040
- Speculative: 30% by 2040

3. AIR QUALITY TARGET SCENARIOS

This report seeks to present estimates for the costs and benefits of measures that can be implemented to achieve specific Air Quality Targets. This report presents estimates for achieving $PM_{2.5}$ targets in isolation.

The subsections provide an overview of the scenario development process, the scenarios selected for appraisal, and the specific actions or measures assumed to be implemented under each of these scenarios.

3.1 OVERVIEW OF THE SCENARIO DEVELOPMENT PROCESS

The potential AMCTs and PERTs used for this assessment were derived from a body of supporting evidence used to develop the approach for revising air quality targets in Wales. This considered a full range of potential policy measures through a ‘Medium’, ‘High’ and ‘Speculative’ feasibility analysis. Each scenario was assessed to determine the AMCT and PERT that could be achieved in each year. For the AMCT targets, a Root Mean Square Error (RMSE) uncertainty adjustment was applied.

Scenarios and years where a ‘new’ AMCT or PERT could be reached across the majority of LSOAs in Wales directly as the result of the measures in that scenario were identified.

These are listed in Table 3-1 for $PM_{2.5}$, which provide a range of potential targets and years, as well as the percentage of LSOAs that could achieve compliance across all relevant roadside and urban background locations for the AMCT. The tables show AMCT options (i.e. a target level and year of introduction) meeting the following criteria:

- Compliance with the proposed AMCT not achieved in the ‘Do Minimum’ i.e. the baseline scenario for that year;
- Compliance achieved in at least 99% of LSOAs (after rounding) in the intervention scenario.

In discussion with the Welsh Government, it was decided that for $PM_{2.5}$ eight scenarios would be considered within this supplementary evidence work. Scenarios in 2025 were not chosen for detailed analysis as this is no longer a feasible year for implementation. The scenarios to be included within this work are highlighted light blue within the table.

Table 3-1 Potential AMCT options for $PM_{2.5}$

Pollutant	Averaging Time	Annual Mean Concentration Target	Year to be introduced	% LSOAs compliant in baseline	Scenario	% LSOAs compliant in scenario
$PM_{2.5}$	Annual mean	12μg/m³	2025	99.3%	Medium	99.7%
$PM_{2.5}$	Annual mean	12 μg/m³	2025	99.3%	High	99.7%
$PM_{2.5}$	Annual mean	12 μg/m³	2025	99.3%	Speculative	99.8%

Pollutant	Averaging Time	Annual Mean Concentration Target	Year to be introduced	% LSOAs compliant in baseline	Scenario	% LSOAs compliant in scenario
$PM_{2.5}$	Annual mean	11 µg/m³	2030	98.8%	Medium	99.8%
$PM_{2.5}$	Annual mean	11 µg/m³	2030	98.8%	High	99.8%
$PM_{2.5}$	Annual mean	11 µg/m³	2030	98.8%	Speculative	99.9%
$PM_{2.5}$	Annual mean	11 µg/m³	2035	99.8%	Medium	100.0%
$PM_{2.5}$	Annual mean	11 µg/m³	2035	99.8%	High	100.0%
$PM_{2.5}$	Annual mean	11 µg/m³	2035	99.8%	Speculative	100.0%
$PM_{2.5}$	Annual mean	10 µg/m³	2035	96.0%	Medium	98.9%
$PM_{2.5}$	Annual mean	10 µg/m³	2035	96.0%	High	99.3%
$PM_{2.5}$	Annual mean	10 µg/m³	2035	96.0%	Speculative	99.7%
$PM_{2.5}$	Annual mean	10 µg/m³	2040	97.3%	Medium	99.5%
$PM_{2.5}$	Annual mean	10 µg/m³	2040	97.3%	High	99.6%
$PM_{2.5}$	Annual mean	10 µg/m³	2040	97.3%	Speculative	99.8%

A complete discussion of all model uncertainties was reviewed as part of work in support of developing new $PM_{2.5}$ targets. The target of 11 µg.m^{-3} to be met in either 2030 or 2035 has been included as two separate scenarios to account for the increased percentage of LSOAs that are compliant in 2035 (100%) compared to 2030 (99.8%). The remaining scenarios with a target of 10 µg.m^{-3} allow different target years and level of ambition to be compared.

In order to choose potential PERTs for $PM_{2.5}$ the population exposure reduction achieved in each modelled scenario relative to 2019 levels was calculated based on Population Weighted Mean Concentrations (PWMCs). The calculated PWMC results are shown in Table 3-2 alongside the population exposure reduction relative to 2019 levels. Figure 3-1 presents the population exposure reduction relative to 2019 levels for all modelled years and scenarios.

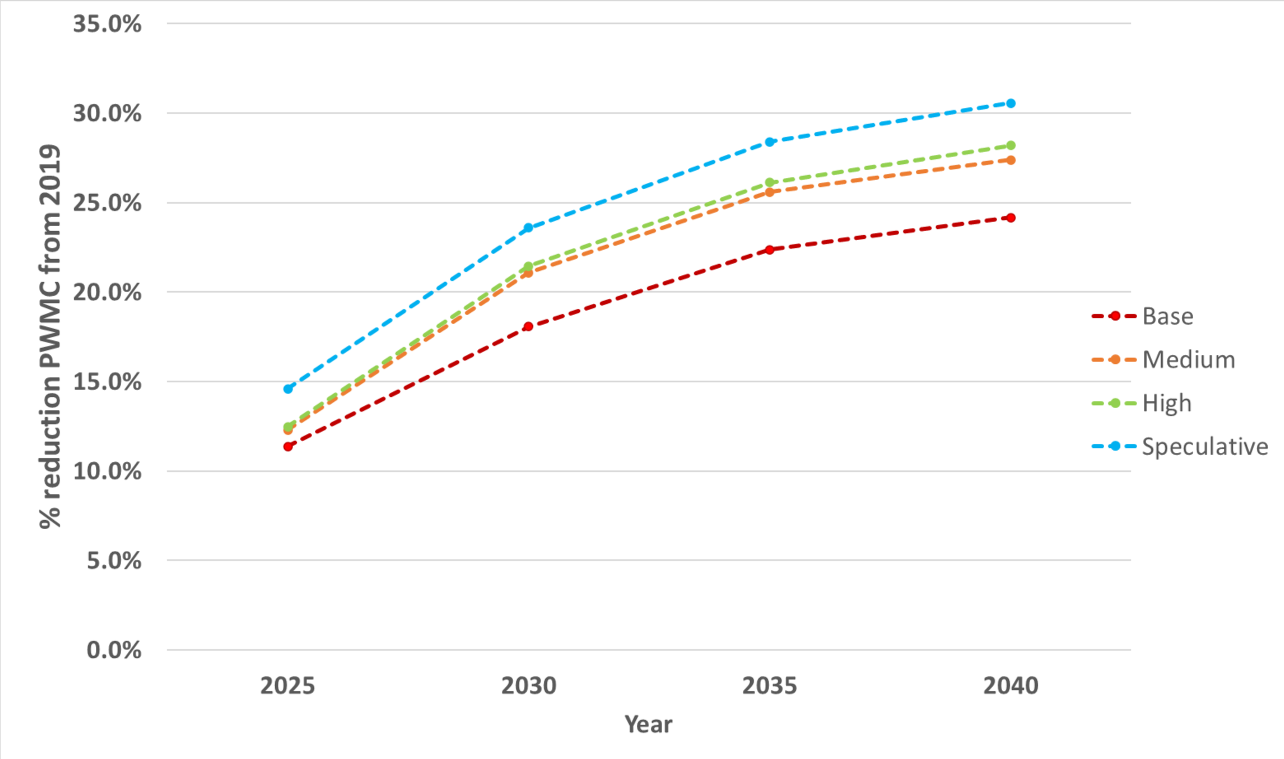
Table 3-2: Population-weighted mean $PM_{2.5}$ concentrations across Wales (µg.m^{-3})

Scenario	PWMC (µg.m^{-3})					% change from 2019 baseline (population exposure reduction)			
	2019	2025	2030	2035	2040	2025	2030	2035	2040
Baseline	7.7	6.8	6.3	6.0	5.8	-11.4%	-18.1%	-22.4%	-24.2%
Medium	-	6.8	6.1	5.7	5.6	-12.3%	-21.1%	-25.6%	-27.4%
High	-	6.7	6.1	5.7	5.5	-12.5%	-21.5%	-26.1%	-28.2%
Speculative	-	6.6	5.9	5.5	5.3	-14.6%	-23.6%	-28.4%	-30.6%

The PWMC of $PM_{2.5}$ across Wales in 2019 is 7.7 µg.m^{-3}. This is significantly lower than the PWMC in England for 2018 of 9.7 µg.m^{-3},[6] because Wales has relatively low emissions of primary $PM_{2.5}$ and its precursors compared to England and is located further from sources in continental Europe. As a result, the predicted reduction in population exposure in the scenarios and years modelled is lower in percentage terms than is possible in England, although the equivalent target PWMCs in absolute terms are lower and therefore more ambitious.

[6] Defra (2022)., Air quality $PM_{2.5}$ targets: Detailed evidence report, 2022. Available at: https://consult.defra.gov.uk/natural-environment-policy/consultation-on-environmental-targets/supporting_documents/Air%20quality%20targets%20%20Detailed%20Evidence%20report.pdf

Figure 3-1: Future PERT calculated from modelling outputs for $PM_{2.5}$



3.2 SCENARIOS FOR APPRAISAL

The following Table 3-5 lists the Air Quality Target Scenarios for $PM_{2.5}$ that have been selected for appraisal in this report. They have been grouped into four overarching scenarios (1-4) and additional sub-scenarios (3.1-3.3, and 4.1-4.3), which are defined by the AMCT and the year of implementation. Each of the scenarios also have equivalent Population Exposure Reduction Targets, as these can be achieved by putting in place the same measures required to achieve the corresponding AMCT.

Table 3-3 Air Quality Target Scenarios for $PM_{2.5}$

Scenario group	Annual Mean Concentration Targets (referencing scenarios from previous work)	Population Exposure Reduction Target
1	11 µg/m³ by 2030 (‘medium’)	20% reduction from 2019 concentrations
2	11 µg/m³ by 2035 (‘medium’)	25% reduction from 2019 concentrations
3	3.1. 10 µg/m³ by 2035 (‘medium’) 3.2. 10 µg/m³ by 2035 (‘high’) 3.3. 10 µg/m³ by 2035 (‘speculative’)	25% reduction from 2019 concentrations
4	4.1. 10 µg/m³ by 2040 (‘medium’) 4.2. 10 µg/m³ by 2040 (‘high’) 4.3. 10 µg/m³ by 2040 (‘speculative’)	25% in 4.1/4.2 and 30% reduction from 2019 concentrations in 4.3.

3.3 SPECIFICATION OF MEASURES TO ACHIEVE THESE SCENARIOS

As part of the work undertaken for the Welsh Government, several measures have been defined and assumed to be implemented as part of the pathways to achieve the different Air Quality Target Scenarios. These include measures for implementation across key emitting sectors such as the domestic, industry, energy, transport, and agricultural sectors. Appendix A contains a list of the measures that were assumed to be implemented across the selected scenarios targeting $PM_{2.5}$.

4. APPRAISAL OF AIR QUALITY TARGET SCENARIOS

This section summarises the work undertaken to appraise these Air Quality Target Scenarios and the findings, comprising the health impact assessment, the economic assessment and distributional analysis. Please note that this builds on previous work commissioned by the Welsh Government and more detailed references to this as well as an outline of how this work has been used can be found in Appendix D.

4.1 HEALTH IMPACT ASSESSMENT

There is a strong body of evidence[7,8,9,10,11,12,13] linking human exposure to air pollution and adverse effects on human health. For example, particles smaller than 2.5 µm can reach the lower respiratory tract, with research indicating greater resulting adverse health effects, including respiratory and cardiovascular issues.

This HIA quantifies the potential **health benefits of reducing air pollutant concentration in Wales under each scenario in 2030, 2035 and 2040**. The assessment has focussed on air pollution from $PM_{2.5}$, and the following health benefits: statistical (all-cause) mortality avoided, and morbidity prevented (especially associated with asthma, Chronic Obstructive Pulmonary Disease, Lung Cancer, Stroke, Ischaemic Heart Disease, and diabetes).

Table 4-1 Health Impact Assessment Scope

Dimension	HIA scope
Geography	Wales
Population (Mid-Year 2023)	3,164,404[14]
Pollutants	$PM_{2.5}$
Health pathways / endpoints covered	• Mortality (all-cause mortality) • Morbidity (hospital admissions associated with respiratory and cardiovascular disease and incidence and non-market disease burden of asthma -younger and older children, and adults-, Chronic Obstructive Pulmonary Disease or COPD, Lung Cancer, Stroke, Ischaemic Heart Disease or IHD, and diabetes)

This section details an overview of the methods and results of the health impact assessment of the Air Quality Target scenarios.

4.1.1 Methodological overview

The health impact assessment was conducted in six steps, as follows:

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[7] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/197900/pb13913-impact-pathway-guidance.pdf

[8] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1061492/COMEAP_Statement_on_PM2.5_mortality_quantification.pdf

[9] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1060762/COMEAP_statement_on_short-term_coefficients_for_hospital_admissions.pdf

[10] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1060762/COMEAP_statement_on_short-term_coefficients_for_hospital_admissions.pdf

[11] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/492949/COMEAP_Ozone_Report_2015__rev1_.pdf

[12] COMEAP (2018a): 'Associations of long-term average concentrations of nitrogen dioxide with mortality'; https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/734799/COMEAP_NO2_Report.pdf

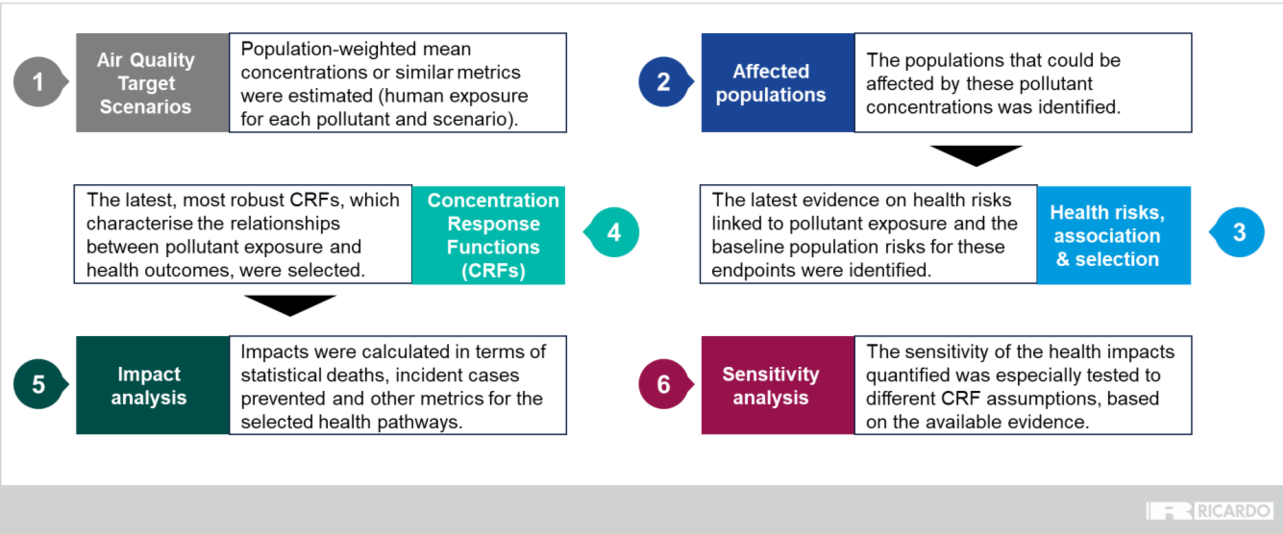
[13] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1060968/COMEAP_Env_Bill_PM2.5_targets_health_evidence_questions_responses.pdf

[14] https://www.ons.gov.uk/peoplepopulationandcommunity/populationandmigration/populationestimates/datasets/populationestimatesforukenglandandwalesscotlandandnorthernireland

- **Step 1: Air Quality Target Scenarios.** The Air Quality Target Scenarios and measures to achieve these were defined (see Section 3) and human exposure for each pollutant under each scenario was characterised, for example, by estimating the relevant population-weighted mean concentration (μg/m^3) of a particular air pollutant or similar and relevant metrics. Please see Appendix A for an outline of the assumptions associated with these Scenarios.
- **Step 2: Affected population.** The populations that could be affected by each of these pollutant concentrations were identified, based on the latest available evidence and understanding of the literature (see Steps 3 and 4).
- **Step 3: Health risks, association and selection.** The latest evidence of health risks associated with air pollutant exposure focussed on $PM_{2.5}$ were considered. The relevant health pathways or endpoints were selected for the analysis. In addition, baseline risks were also documented from a range of sources, including burden of disease studies.
- **Step 4: Concentration Response Functions.** For the selected pathways, the latest and/or most robust concentration response functions (CRFs) were identified, capturing the relationships between pollutant exposure and health outcomes.
- **Step 5: Impact analysis.** The estimated changes in air pollutant concentration for each scenario in μg/m^3 were multiplied by baseline mortality or incidence rates and the CRFs to estimate the potential:
  - **i.** number of statistical deaths avoided and statistical 'Life Years' (LYs) gained;
  - **ii.** the incident cases of ill health avoided and 'Quality-Adjusted Life Years' (QALYs) gained (excluding from preventable mortality already captured under i.; and
  - **iii.** the number of hospital admissions due to respiratory and/or cardiovascular illness avoided.
- **Step 6: Sensitivity analysis.** The sensitivities of the impacts assessed were tested for adjustments to the CRFs, based on the uncertainties across the underpinning studies.

These steps are also summarised in the Figure below.

Figure 4-1 Health impact assessment methodology overview



4.1.2 Summary of HIA results

This section summarises the results of the health impact assessment, including **estimates of the health benefits under each Air Quality Target scenario** described in terms annual average of Quality-Adjusted Life Year gains, mortality and morbidity prevented, and hospital admissions avoided over the period 2025-2040. The estimates presented in this section are a summary of the 'central' values. The results of the sensitivity analysis are presented in Appendix E.

The findings suggest that reductions in annual $PM_{2.5}$ population-weighted concentrations in air across Wales could result in Quality-Adjusted Life Year[15] gains over the period 2025-2040, predominately driven by a reduction in preventable deaths and the prevention of disease onset across a range of health endpoints, including asthma, COPD, Lung Cancer, Stroke, IHD and diabetes. The benefits on people's health have also been estimated to result in a reduction in respiratory and cardiovascular hospital admissions in the short-term.

The potential health benefits have been estimated to increase, on average, from scenarios 1 to 2, 3 and 4, which is because, typically, 'medium' pathways to achieve the air quality targets represent lower ambition and thus lower potential benefits than 'high' and 'speculative' pathways within these scenarios. These estimated health benefits are, of course, related to the estimated average reduction in air pollutant concentration (although this relationship is not necessarily linear).

The Table below provides two indicators that allow for a comparison of scenarios against the baseline in terms of 1) air quality improvements (in % difference); 2) gains in quality of life when compared to the baseline (in QALYs).

Table 4-2 Air pollutant concentration and health impact benefits across $PM_{2.5}$ scenarios when compared to the baseline

Scenarios	Average annual difference in air pollutant concentration against baseline, in % difference (***NB Negative sign means a reduction against the baseline***)	Average annual difference in QALYs against baseline, in additional LYs (*NB Positive sign means an increase against the baseline)*
1. 11 μg/m³ by 2030 ('medium')	-3.8%	+690
2. 11 μg/m³ by 2035 ('medium')	-3.9%	+712
3.1. 10 μg/m³ by 2035 ('medium')	-3.9%	+712
3.2. 10 μg/m³ by 2035 ('high')	-4.5%	+817
3.3. 10 μg/m³ by 2035 ('speculative')	-7.3%	+1,469
4.1. 10 μg/m³ by 2040 ('medium')	-3.9%	+712
4.2. 10 μg/m³ by 2040 ('high')	-4.5%	+822
4.3. 10 μg/m³ by 2040 ('speculative')	-7.4%	+1,476

The Table below presents a summary of the average annual health impacts, across a range of indicators and all Air Quality Target Scenarios in scope, to facilitate their comparison.

[15] See the UK NICE Glossary here: https://www.nice.org.uk/glossary?letter=q: "A measure of the state of health of a person or group in which the benefits, in terms of length of life, are adjusted to reflect the quality of life. One quality-adjusted life year (QALY) is equal to 1 year of life in perfect health. QALYs are calculated by estimating the years of life remaining for a patient following a particular treatment or intervention and weighting each year with a quality-of-life score (on a 0 to 1 scale). It is often measured in terms of the person's ability to carry out the activities of daily life, and freedom from pain and mental disturbance."

Table 4-3 Average annual health impacts across $PM_{2.5}$ scenarios over the period 2025-2040[16]

Impact	Indicators and units	Scenario 1: 11 µg/m3 by 2030 ('medium')	Scenario 2: 11 µg/m^3 by 2035 ('medium')	Scenario 3.1: 10 µg/m3 by 2035 ('medium')	Scenario 3.2: 10 µg/m3 by 2035 ('high')	Scenario 3.3: 10 µg/m3 by 2035 ('speculative')	Scenario 4.1: 10 µg/m3 by 2040 ('medium')	Scenario 4.2: 10 µg/m3 by 2040 ('high')	Scenario 4.3: 10 µg/m^3 by 2040 ('speculative')
Quality-Adjusted Life Years gained	LYs gained from deaths avoided	420	433	433	497	893	433	500	897
	QALY gained from morbidity avoided	271	279	279	320	576	279	322	579
	Total QALY gains	690	712	712	817	1,469	712	822	1,476
Deaths avoided (mortality)	Statistical deaths avoided	39	40	40	46	82	40	46	83
Illness prevented (morbidity)	Statistical cases avoided of asthma	12	12	12	14	25	12	14	25
	Statistical cases avoided of COPD	3	3	3	3	6	3	3	6
	Statistical cases avoided of Lung Cancer	4	4	4	5	9	4	5	9
	Statistical cases avoided of Stroke	8	9	9	10	18	9	10	18
	Statistical cases avoided of IHD	7	7	7	8	15	7	8	15
	Statistical cases avoided of Diabetes	33	34	34	39	70	34	39	70
Healthcare activity reduced	Respiratory and/or cardiovascular hospital admissions prevented	16	17	17	19	35	17	19	35

[16] Please note that Scenarios 2 and 3.1 showcase the same HIA results. This is because they follow the same pathway, and the difference in the policy scenario is the target and the likely levels of compliance that could be achieved across LSOAs. Under Scenario 2, it is estimated that 100% of LSOA's might meet the target, whereas it is estimated that 98.9% of LSOA's might be able to meet this target under Scenario 3.1.

4.2 ECONOMIC ASSESSMENT

This section details the methods and results of the economic appraisal of the Air Quality Target scenarios, including the estimated costs and benefits, capturing key economic, health and environmental impacts.

4.2.1 Methodological overview

The selected Air Quality Target Scenarios were characterised, drawing from the supporting evidence base.

This assessment was conducted in four steps, as follows:

- **Step 1: Air Quality Target Scenarios.** The Air Quality Target Scenarios and measures to achieve these were defined (see Section 3) by performing a screening and mapping of measures matched against each Air Quality Target Scenario.
- **Step 2: Identification and characterisation of costs and benefits based on supporting evidence**. Analysis of the economic costs of implementation were estimated at for each measure in previous research undertaken for the Welsh Government. Having mapped the measures against each Air Quality Target Scenario (see Appendix A), previous estimates of costs and benefits per measure were also re-organised and updated to 2025 prices using a pricing adjustment (GDP deflator). The cost and benefit categories considered, from implementing each measure, include:
    - Capital costs, which are upfront costs of installing or implementing an abatement measure (e.g., cost of new equipment or machinery).
    - Operating costs or benefits, which include estimates of the costs or savings associated with fuel consumption changes or ongoing costs or savings from non-fuel expenses (e.g., maintenance costs).
    - Time saving costs or benefits, which monetise the changes in travel time and associated costs or benefits the implementation of a measure (e.g., reduction of speed limit).
    - Greenhouse gas (GHG) benefits, which represent greenhouse gas emission savings as a result of implementing the measure, monetised using the social cost of carbon.[17]
    - Health benefits (non-market), which represent the benefits associated with Life Year and Quality-Adjusted Life Year gains from the prevention of statistical deaths and cases of ill health, monetised using evidence of the willingness-to-pay for Life Year[18] and/or QALY[19] gains.
    - Healthcare benefits (from reduction in NHS costs), which cover the costs avoided from a reduction in primary and secondary care activity and medicine costs due to improvements in people's health and lower demand for healthcare services.[20,21]
    - Productivity benefits (from reductions in sickness absence), which covers the economic costs avoided due to reductions in sickness absence from improvements in people's health, monetised by assuming a marginal productivity gain equivalent to hourly/daily average salaries and wages.
- **Step 3: Estimation of Net Present Value of costs and benefits (NPV)**. The total costs and benefits for each Air Quality Target Scenario were aggregated from the measure-level costs and benefits for the measures mapped to a scenario, for each year over the period 2025-2040. The NPV of these costs and benefits was estimated over this appraisal period, discounting to 2025 using the Green Book

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[17] UK DESNZ (2023). Green Book supplementary guidance: valuation of energy use and greenhouse gas emissions for appraisal. Available at: https://www.gov.uk/government/publications/valuation-of-energy-use-and-greenhouse-gas-emissions-for-appraisal

[18] Defra (2007). An Economic Analysis to inform the Air Quality Strategy. Available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/221088/pb12637-icgb.pdf

[19] UK HMT (2022). The Green Book – Central Government Guidance on Appraisal and Evaluation. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1063330/Green_Book_2022.pdf

[20] PHE (2018). "Estimation of costs to the NHS and social care due to the health impacts of air pollution". Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/836720/Estimation_of_costs_to_the_NHS_and_s ocial_care_due_to_the_health_impacts_of_air_pollution.pdf

[21] Defra (2007). An Economic Analysis to inform the Air Quality Strategy. Available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/221088/pb12637-icgb.pdf

social discount real rate of 3.5% (except for the health benefits, which were discounted using a 1.5% social discount real rate).[22] The NPV of the monetised cost and benefit values is calculated using the following formula:

$$NPV\ (r, N) = \sum_{t=0}^{N} \frac{V_t}{(1+r)^t}$$

Where:

t = time, 2025 to 2040, i.e., N=16

r = real discount rate = 3.5% or 1.5%

V_t= Value (monetary) of a specific cost or benefit category at time *t*

- **Step 4**: **Estimation of Net Benefit and Benefit Cost Ratio (BCR)**. The net benefits were calculated as the difference between total benefits and total costs associated with the scenario. The BCR was calculated as the absolute value of the ratio of the total benefits to the total costs for each scenario. A value greater than 1 means that benefits are higher than costs and, typically, larger BCR values suggest potential for higher social return on investment (albeit these estimates are affected by methodological choices, such as the appraisal period, etc.).

Finally, please note that costs and benefits for implementing $PM_{2.5}$ measures have been calculated separately. The outputs of the CBA for $PM_{2.5}$ scenarios should not be aggregated as there are substantial overlaps between the measures specified to address each pollutant. The figures should be considered as standalone values. The sensitivity analysis conducted is summarised in Appendix E.

4.2.2 Results for $PM_{2.5}$

This section presents the estimated costs and benefits, monetised in constant 2025 GBP, for each Air Quality $PM_{2.5}$ Target scenario.

4.2.2.1 Scenario 1: 11 µg/m³ by 2030 ('medium') and 20% reduction from 2019 concentrations

The Table below presents the Net Present Value of the core costs and benefits of a pathway to achieving the Air Quality Scenario Target for $PM_{2.5}$ under this scenario.

Table 4-4 Net Present Value of costs and benefits for Scenario 1: 11 µg/m³ by 2030 ('medium') and 20% reduction from 2019 concentrations (millions of GBP in 2025 prices, negative values representing costs)

Category	Specific cost or benefit	NPV (millions of £ 2025)
Costs	Capital costs	-£1,900
	Operating costs	-£1
	Other capital or operating costs	-£300
	Time saving costs	-£900
Benefits	Operational benefits (fuel and non-fuel)	£8,900
	Time saving benefits	£3,000
	GHG benefits	£3,200
	Health benefits (non-market)	£600
	Healthcare benefits (from lower demand for healthcare)	£10
	Productivity benefits (from reduction in sickness absence)	£50

The NPV of the total costs required to achieve Air Quality Scenario 1 is estimated at around £3 billion (in £ 2025), which includes capital investments with a NPV of around £2 billion (in £ 2025). However, these are

[22] UK HMT (2022). Green Book supplementary guidance: discounting. Available at: https://www.gov.uk/government/publications/green-book-supplementary-guidance-discounting

outweighed by the potential benefits, estimated at around £16 billion (in £ 2025). Overall, a net benefit of around £13 billion (in £ 2025) is expected and **a benefit-cost ratio of 5.1**. This means that benefits from achieving the scenario outweigh the costs that could be borne to achieve it.

4.2.2.2 Scenario 2: 11 µg/m³ by 2035 ('medium') and 25% reduction from 2019 concentrations

The Table below presents the Net Present Value of the core costs and benefits of a pathway to achieving the Air Quality Scenario Target for $PM_{2.5}$ under this scenario.

Table 4-5 Net Present Value of costs and benefits for Scenario 2: 11 µg/m³ by 2035 ('medium') and 25% reduction from 2019 concentrations (millions of GBP in 2025 prices, negative values representing costs)

Category	Specific cost or benefit	NPV (millions of £ 2025)
Costs	Capital costs	-£5,100
	Operating costs	-£25
	Other capital or operating costs	-£300
	Time saving costs	-£1,200
Benefits	Operational benefits (fuel and non-fuel)	£13,900
	Time saving benefits	£4,100
	GHG benefits	£5,400
	Health benefits (non-market)	£600
	Healthcare benefits (from lower demand for healthcare)	£10
	Productivity benefits (from reduction in sickness absence)	£50

The NPV of the total costs required to achieve Air Quality Scenario 2 is estimated at around £7 billion (in £ 2025), which includes capital investments with a NPV of around £5 billion (in £ 2025). However, these are outweighed by the potential benefits, estimated at around £24 billion (in £ 2025). Overall, a net benefit of around £17 billion (in £ 2025) is expected and **a benefit-cost ratio of 3.6**. This means that benefits from achieving the scenario outweigh the costs that could be borne to achieve it.

4.2.2.3 Scenario 3.1: 10 µg/m³ by 2035 ('medium') and 25% reduction from 2019 concentrations

The Table below presents the Net Present Value of the core costs and benefits of a pathway to achieving the Air Quality Scenario Target for $PM_{2.5}$ under this scenario.

Table 4-6 Net Present Value of costs and benefits for Scenario 3.1: 10 µg/m³ by 2035 ('medium') and 25% reduction from 2019 concentrations (millions of GBP in 2025 prices, negative values representing costs)

Category	Specific cost or benefit	NPV (millions of £ 2025)
Costs	Capital costs	-£5,100
	Operating costs	-£25
	Other capital or operating costs	-£300
	Time saving costs	-£1,200
Benefits	Operational benefits (fuel and non-fuel)	£13,900
	Time saving benefits	£4,100
	GHG benefits	£5,400
	Health benefits (non-market)	£600
	Healthcare benefits (from lower demand for healthcare)	£10
	Productivity benefits (from reduction in sickness absence)	£50

The NPV of the total costs required to achieve Air Quality Scenario 3.1 is estimated at around £7 billion (in £ 2025), which includes capital investments with a NPV of around £5 billion (in £ 2025). However, these are outweighed by the potential benefits, estimated at around £24 billion (in £ 2025). Overall, a net benefit of around £17 billion (in £ 2025) is expected and **a benefit-cost ratio of 3.6.** This means that benefits from achieving the scenario outweigh the costs that could be borne to achieve it.

4.2.2.4 Scenario 3.2: 10 µg/m³ by 2035 ('high') and 25% reduction from 2019 concentrations

The Table below presents the Net Present Value of the core costs and benefits of a pathway to achieving the Air Quality Scenario Target for $PM_{2.5}$ under this scenario.

Table 4-7 Net Present Value of costs and benefits for Scenario 3.2: 10 µg/m³ by 2035 ('high') and 25% reduction from 2019 concentrations (millions of GBP in 2025 prices, negative values representing costs)

Category	Specific cost or benefit	NPV (millions of £ 2025)
Costs	Capital costs	-£7,100
	Operating costs	-£25
	Other capital or operating costs	-£300
	Time saving costs	-£2,500
Benefits	Operational benefits (fuel and non-fuel)	£22,300
	Time saving benefits	£6,100
	GHG benefits	£8,400
	Health benefits (non-market)	£700
	Healthcare benefits (from lower demand for healthcare)	£10
	Productivity benefits (from reduction in sickness absence)	£60

The NPV of the total costs required to achieve Air Quality Scenario 3.2 is estimated at around £10 billion (in £ 2025), which includes capital investments with a NPV of around £7 billion (in £ 2025). However, these are outweighed by the potential benefits, estimated at around £38 billion (in £ 2025). Overall, a net benefit of around £28 billion (in £ 2025) is expected and **a benefit-cost ratio of 3.8.** This means that benefits from achieving the scenario outweigh the costs that could be borne to achieve it.

4.2.2.5 Scenario 3.3: 10 µg/m³ by 2035 ('speculative') and 25% reduction from 2019 concentrations

The Table below presents the Net Present Value of the core costs and benefits of a pathway to achieving the Air Quality Scenario Target for $PM_{2.5}$ under this scenario.

Table 4-8 Net Present Value of costs and benefits for Scenario 3.3: 10 µg/m³ by 2035 ('speculative') and 25% reduction from 2019 concentrations (millions of GBP in 2025 prices, negative values representing costs)

Category	Specific cost or benefit	NPV (millions of £ 2025)
Costs	Capital costs	-£9,800
	Operating costs	-£265
	Other capital or operating costs	-£300
	Time saving costs	-£5,700
Benefits	Operational benefits (fuel and non-fuel)	£34,200
	Time saving benefits	£8,100
	GHG benefits	£26,000
	Health benefits (non-market)	£1,300

Category	Specific cost or benefit	NPV (millions of £ 2025)
	Healthcare benefits (from lower demand for healthcare)	£20
	Productivity benefits (from reduction in sickness absence)	£110

The NPV of the total costs required to achieve Air Quality Scenario 3.3 is estimated at around £16 billion (in £ 2025), which includes capital investments with a NPV of around £10 billion (in £ 2025). However, these are outweighed by the potential benefits, estimated at around £70 billion (in £ 2025). Overall, a net benefit of around £54 billion (in £ 2025) is expected and **a benefit-cost ratio of 4.3**. This means that benefits from achieving the scenario outweigh the costs that could be borne to achieve it.

4.2.2.6 Scenario 4.1: 10 μg/m³ by 2040 ('medium') and 30% reduction from 2019 concentrations

The Table below presents the Net Present Value of the core costs and benefits of a pathway to achieving the Air Quality Scenario Target for $PM_{2.5}$ under this scenario.

Table 4-9 Net Present Value of costs and benefits for Scenario 4.1: 10 μg/m³ by 2040 ('medium') and 25% reduction from 2019 concentrations (millions of GBP in 2025 prices, negative values representing costs)

Category	Specific cost or benefit	NPV (millions of £ 2025)
Costs	Capital costs	-£10,000
	Operating costs	-£25
	Other capital or operating costs	-£300
	Time saving costs	-£1,400
Benefits	Operational benefits (fuel and non-fuel)	£15,800
	Time saving benefits	£4,500
	GHG benefits	£6,300
	Health benefits (non-market)	£600
	Healthcare benefits (from lower demand for healthcare)	£10
	Productivity benefits (from reduction in sickness absence)	£50

The NPV of the total costs required to achieve Air Quality Scenario 4.1 is estimated at around £12 billion (in £ 2025), which includes capital investments with a NPV of around £10 billion (in £ 2025). However, these are outweighed by the potential benefits, estimated at around £27 billion (in £ 2025). Overall, a net benefit of around £16 billion (in £ 2025) is expected and **a benefit-cost ratio of 2.3.** This means that benefits from achieving the scenario outweigh the costs that could be borne to achieve it.

4.2.2.7 Scenario 4.2: 10 μg/m³ by 2040 ('high') and 30% reduction from 2019 concentrations

The Table below presents the Net Present Value of the core costs and benefits of a pathway to achieving the Air Quality Scenario Target for $PM_{2.5}$ under this scenario.

Table 4-10 Net Present Value of costs and benefits for Scenario 4.2: 10 μg/m³ by 2040 ('high') and 25% reduction from 2019 concentrations (millions of GBP in 2025 prices, negative values representing costs)

Category	Specific cost or benefit	NPV (millions of £ 2025)
Costs	Capital costs	-£14,300
	Operating costs	-£25
	Other capital or operating costs	-£300
	Time saving costs	-£2,800
Benefits	Operational benefits (fuel and non-fuel)	£25,800
	Time saving benefits	£6,700

Category	Specific cost or benefit	NPV (millions of £ 2025)
	GHG benefits	£10,000
	Health benefits (non-market)	£700
	Healthcare benefits (from lower demand for healthcare)	£10
	Productivity benefits (from reduction in sickness absence)	£60

The NPV of the total costs required to achieve Air Quality Scenario 4.2 is estimated at around £17 billion (in £ 2025), which includes capital investments with a NPV of around £14 billion (in £ 2025). However, these are outweighed by the potential benefits, estimated at around £43 billion (in £ 2025). Overall, a net benefit of around £26 billion (in £ 2025) is expected and **a benefit-cost ratio of 2.5.** This means that benefits from achieving the scenario outweigh the costs that could be borne to achieve it.

4.2.2.8 Scenario 4.3: 10 µg/m³ by 2040 ('speculative') and 30% reduction from 2019 concentrations

The Table below presents the Net Present Value of the core costs and benefits of a pathway to achieving the Air Quality Scenario Target for $PM_{2.5}$ under this scenario.

Table 4-11 Net Present Value of costs and benefits for Scenario 4.3: 10 µg/m³ by 2040 ('speculative') and 30% reduction from 2019 concentrations (millions of GBP in 2025 prices, negative values representing costs)

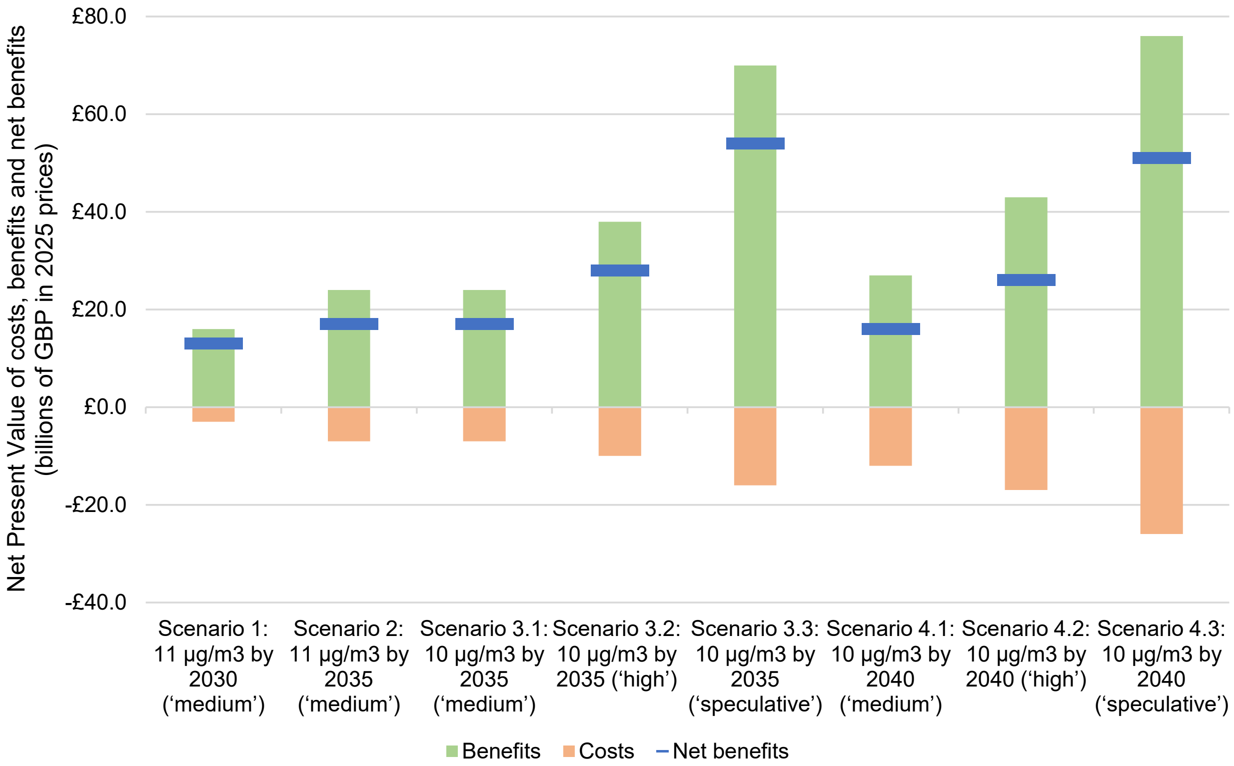
Category	Specific cost or benefit	NPV (millions of £ 2025)
Costs	Capital costs	-£18,800
	Operating costs	-£270
	Other capital or operating costs	-£300
	Time saving costs	-£6,200
Benefits	Operational benefits (fuel and non-fuel)	£38,100
	Time saving benefits	£8,900
	GHG benefits	£28,000
	Health benefits (non-market)	£1,300
	Healthcare benefits (from lower demand for healthcare)	£20
	Productivity benefits (from reduction in sickness absence)	£110

The NPV of the total costs required to achieve Air Quality Scenario 4.3 is estimated at around £26 billion (in £ 2025), which includes capital investments with a NPV of around £19 billion (in £ 2025). However, these are outweighed by the potential benefits, estimated at around £76 billion (in £ 2025). Overall, a net benefit of around £51 billion (in £ 2025) is expected and **a benefit-cost ratio of 3.0**. This means that benefits from achieving the scenario outweigh the costs that could be borne to achieve it.

4.2.3 Summary of economic assessment results

This section summarises the results of the economic assessment by highlighting the Net Present Value of the costs, benefits, net benefits and benefit-cost ratio across selected pathways to achieve the Air Quality Target Scenarios for $PM_{2.5}$. The results are presented as aggregates over the appraisal period 2025-2040 and discounted to 2025 in the following figures and tables. The outputs of the sensitivity analysis conducted are summarised in Appendix E.

Figure 4-2 Net Present Value of costs, benefits, net benefits by $PM_{2.5}$ scenario, discounted to 2025 (billions of GBP in 2025 prices, negative values representing costs)



The results of the economic assessment suggest that all $PM_{2.5}$ Air Quality Target Scenarios are likely to be beneficial to society. All scenarios are estimated to have positive NPV of net benefits, represented by the blue markers in the Figure 4-2 above.

On average, the scale of the costs and benefits increases as we move from Scenario 1 to Scenario 4, represented by the increasing height of the orange and green blocks from left to right in the Figure 4-2 above respectively (sub-scenarios of Scenario 3 and 4 can be compared against each other e.g., 3.1 to 4.1, 3.2 to 4.2 and 3.3 to 4.3).

Within the 'speculative' scenarios (3.3 and 4.3), changes in the steel making process at Port Talbot could have a relatively large positive effect on air pollutant emissions (PM_{10}, $PM_{2.5}$ and SO_2), as well as contributing to higher GHG benefits, comparatively to other scenarios, which would come at a large capital and operating cost.

The Net Present Value of costs, benefits, net benefits and benefit-cost ratio for all Air Quality Target Scenarios are also presented numerically in Table 4-12.

Table 4-12 Net Present Value of costs, benefits, net benefits and benefit-cost ratio by Air Quality Target Scenario for $PM_{2.5}$, discounted to 2025 (billions of GBP in 2025 prices, negative values representing costs)

Indicators	Scenario 1: 11 µg/m3 by 2030 (' medium')	Scenario 2: 11 µg/m³ by 2035 (' medium')	Scenario 3.1: 10 µg/m3 by 2035 (' medium')	Scenario 3.2: 10 µg/m3 by 2035 (' high')	Scenario 3.3: 10 µg/m3 by 2035 (' speculative')	Scenario 4.1: 10 µg/m3 by 2040 (' medium')	Scenario 4.2: 10 µg/m3 by 2040 (' high')	Scenario 4.3: 10 µg/m³ by 2040 (' speculative')
Costs (billions)	-£3.0	-£7.0	-£7.0	-£10.0	-£16.0	-£12.0	-£17.0	-£26.0
Benefits (billions)	£16.0	£24.0	£24.0	£38.0	£70.0	£27.0	£43.0	£76.0
Net benefits (billions)	**£13.0**	**£17.0**	**£17.0**	**£28.0**	**£54.0**	**£16.0**	**£26.0**	**£51.0**
Benefit Cost Ratio (BCR)	5.1	3.6	3.6	3.8	4.3	2.3	2.5	3.0

Overall, $PM_{2.5}$ Scenario 1 has the highest BCR, followed by Scenario 3 (average), Scenario 2 and Scenario 4 (average). However, the scale of benefits is higher across Scenarios 3 and 4. Scenarios 4 (Average) have lower BCR than Scenarios 3 (average) primarily due to the period of appraisal (2025-2040), which does not account for the additional and relatively higher benefits that could result from Scenario 4 (average) from 2040 onwards.

4.2.4 Discussion of where these costs might fall

The available evidence has been reviewed to identify the **stakeholders that might bear the costs** of implementing and achieving these Air Quality Target Scenarios. The distribution of costs will depend on the measures or actions that are finally taken to achieve each Target Scenario and the level of public and private sector cooperation. The following insights have been identified at this stage, by stakeholder group and measure sector group:

- **Public authorities in Wales** (and the UK more broadly) will have a role by investing in public awareness campaigns, providing financial incentives or subsidies for adopting cleaner technologies, and implementing regulations to limit emissions.
    - Domestic combustion: Public authorities have responsibilities to implement air quality improvement measures at the community level. This may include investing in public awareness campaigns, providing incentives or subsidies to households for adopting cleaner technologies, and implementing regulations to limit emissions from residential sources initiatives like enforcing restrictions on open burning and other high-emission activities.
    - Industry: Governments could play a critical role in supporting industries to transition to greener practices and may somewhat share the cost burden by providing financial incentives, subsidies, and regulatory frameworks. They may also invest in research and development for clean technologies and provide funding for large-scale infrastructure projects.
    - Energy: Public authorities, including state-owned enterprises, play a crucial role in financing network infrastructure and facilitating the transition to clean energy in emissions-intensive sectors.
    - Transport: Public authorities typically fund a range of initiatives like awareness campaigns to ensure businesses and industries are aware of any expected impact, investment in R&D to support technological improvements particularly concerning rail, aviation and shipping or additional support to ease the burden upon businesses and individuals (e.g., subsidies to reduce the costs to transition car, LGV and bus fleets to EVs).

- **Private sector companies** providing utilities such as electricity and natural gas may have a role in assisting households in adopting renewable and cleaner energy sources and technologies and might be affected by estimated changes in fuel consumption and associated revenues.
    - Domestic combustion: Utilities companies supplying electricity and natural gas may have a role in assisting households in adopting cleaner energy sources and technologies (e.g., through offering incentives for energy conservation) and will face an impact associated with changes in fuel consumption and associated revenues.
    - Industry: Manufacturing companies will need to invest in upgrading their infrastructure, adopting new technologies, and implementing energy-efficient practices to reduce their emissions and transition towards less polluting operations.
    - Energy: The expansion of renewable energy capacity for achieving decarbonisation objectives across the UK will require large capital investments from the private sector. Research indicates that approximately 70% of clean energy investments will likely come from private developers and financiers who respond to market signals and government policies[23].
    - Transport: The purchase of electric LGVs and HGVs, will require significant upfront investment from local businesses, particularly SMEs. Similarly, the requirement for taxis and PHVs to transition to EVs will also likely create economic challenges for smaller independent taxi firms.
- **Individual households** will likely bear a proportion of costs of meeting air quality targets through investment in cleaner technologies and appliances, directly or indirectly (e.g., through the impacts of public authority involvement).
    - Domestic combustion: Households may need to invest in energy-efficient heating and cooling systems, and low-emission cooking stoves. Additionally, households who switch to heat pumps could face higher bills because the costs of heating homes using electricity is currently estimated to be above the costs of using gas (not including any existing available subsidy[24]).
    - Industry: In some cases, consumers may also share the costs indirectly if industries pass on some of the expenses incurred to consumers through higher prices for products and services.
    - Energy: Considering the low price-elasticity of energy, it is possible that a sizeable portion of the costs of achieving decarbonisation could be pass-through to consumers via higher energy bills.
    - Transport: The road transport measures include requirements for the transition of passenger cars to EVs which could lead to a significant economic burden for individuals. There are also expected behavioural changes for individuals under certain measures. For example, lowering speed limits, working from home or transitioning with active travel will all impact the everyday lives of certain individuals.

4.2.5 Comparison of the Air Quality Target Scenarios

The economic assessment has concluded that all Air Quality Target Scenarios (and measures to achieve these) could be net beneficial to society, and, when compared against the baseline, their implementation could result in improvements to social welfare across Wales. Across stakeholders:

- All stakeholders residing or operating in Wales would benefit directly or indirectly from the Air Quality Target Scenarios, especially the citizens living in the most populous regions of Wales and people living in the most deprived areas (see Section 4.3).
- Public authorities, private companies and individuals and households would bear proportions of the estimated economic costs over the period of appraisal, including the upfront capital requirements (see Section 4.2.4). Measures to decarbonise and de-pollute the transport sector might require especially large capital investments.

Thus, another layer of analysis has been conducted to facilitate the comparison of the scenarios beyond the estimated net positive impacts that they could have on Wales if implemented. Each scenario was categorised against the following criteria:

[23] https://www.iea.org/reports/world-energy-outlook-2021/mobilising-investment-and-finance
[24] https://www.instituteforgovernment.org.uk/article/explainer/paying-net-zero

- The level of ambition (low, high and medium levels of ambition to improve air quality, when compared to baseline projections)
- The magnitude of upfront capital investment required (NPV of estimated capital requirements over the period of appraisal)
- Timing of investments (immediate, short-term and medium-term requirements)

Based on these categorisations, and all research and analysis conducted for the Welsh Government under this project, a qualitative conclusion was developed as to the extent to which a scenario might be deliverable or feasible.

The table below summarises the findings of this qualitative comparison of scenarios for $PM_{2.5}$.

Table 4-13 Qualitative comparison of scenarios across a set of criteria ($PM_{2.5}$)

Criteria	Scenario 1: 11 µg/m3 by 2030 ('medium')	Scenario 2: 11 µg/m³ by 2035 ('medium')	Scenario 3.1: 10 µg/m3 by 2035 ('medium')	Scenario 3.2: 10 µg/m3 by 2035 ('high')	Scenario 3.3: 10 µg/m3 by 2035 ('speculative')	Scenario 4.1: 10 µg/m3 by 2040 ('medium')	Scenario 4.2: 10 µg/m3 by 2040 ('high')	Scenario 4.3: 10 µg/m³ by 2040 ('speculative')
Level of ambition	Medium	Medium	Medium	Medium/ High	High	Medium	Medium/ High	High
Magnitude investment required	£1.8bn	£5.2bn	£5.2bn	£7.2bn	£9.8bn	£10.0bn	£14.3bn	£18.8bn
Timing of investment	Immediate	Short term	Short term	Short term	Short term	Medium term	Medium term	Medium term
Overall feasibility	Medium	High	High	Medium	Low	High	Medium	Low

This analysis suggests that the following three scenarios could be relatively more feasible, given the scale of ambition, upfront capital requirements and timetable for investment.

- Scenario 2: 11 µg/m3 by 2035 ('medium')
- Scenario 3.1: 10 µg/m3 by 2035 ('medium')
- Scenario 4.1: 10 µg/m3 by 2040 ('medium')

The difference between Scenarios 2 and 3.1 is primarily on the level of Target or Ambition that the Government wishes to set. The type and scale of actions taken forward have been assumed to be very similar or almost the same, and thus, the resulting upfront capital investment requirements and timetable for implementation. In comparison, Scenario 4.1 would set a timeline later, more in the medium-term, which would require double the upfront investments over the period and increase the risk of delayed implementation.

4.3 DISTRIBUTIONAL ANALYSIS

A distributional impact assessment of how the changes in $PM_{2.5}$ pollutant was shared across sensitive social groups was undertaken as part of previous studies commissioned by the Welsh Government. The analysis conducted investigated the relationship between the level of reduction in $PM_{2.5}$ pollutant across each Lower Layer Super Output Area (LSOA) and population demographics. The population demographics considered were:

- The level of income deprivation of each LSOA.
- The proportion of children within each LSOA.
- The proportion of elderly residents within each LSOA.

- The proportion of non-white residents within each LSOA.

The analysis found that although the level of action ('medium', 'high', 'speculative') impacts concentration levels of each pollutant across Wales, it had no significant effect on how the benefits of the changes were shared across the population. The following observations were made from the analysis:

- There is a good correlation between spatial reductions in $PM_{2.5}$ pollutant and the size of the human population of that region where the biggest reductions were shown to occur in the most populated regions (i.e., the biggest reductions were shown to occur in north and south Wales).
- There is a general trend that the biggest reduction in $PM_{2.5}$ pollutant concentrations tend to be greatest in areas with the highest level of income deprivation. The analysis also found that large reductions, comparable to those seen in the most deprived region, also occurred in the least deprived areas in the country.
- There is a general trend that the biggest reduction in $PM_{2.5}$ pollutant concentrations tended to occur in areas with the highest proportion of children. The analysis also found that these areas tended to be located in regions with high populations and a higher number of pollution sources.
- There is a general trend that the smallest reduction in $PM_{2.5}$ pollutant concentrations tended to occur in areas with the highest proportion of elderly citizens. The analysis found that these areas tended to be in regions of Wales with a more widely spatially dispersed populations and a lower density of pollution sources.
- There is a weak correlation between the concentration reduction of $PM_{2.5}$ pollutant and the proportion of BAME residents in the same spatial region, with the data showing that the level of pollutant reduction tends to increase as the proportion of BAME population increases. This was found to be true for each of the scenarios.

The updates to the proposed level of action suggests that concentrations of $PM_{2.5}$ are likely to remain consistent with the results reported in previous Ricardo work. Therefore, in summary:

- Each measure would benefit all citizens with the biggest reduction in $PM_{2.5}$ occurring in the most populous regions of Wales. This observation can be explained by these areas having the largest concentrations of each pollutant in the baseline scenario and are also the areas where actions are targeting. Therefore, the biggest reductions in these areas are expected.
- The implementation of any of the scenarios will tend to have the biggest reductions in $PM_{2.5}$ pollutants in the most deprived areas of Wales with those living in the least deprived areas also shown to have a greater benefit than those who live in areas with a more mixed level of income deprivation.
- The implementation of any of the scenarios will have the biggest reductions in $PM_{2.5}$ pollutant in areas with the highest proportions of children.

5. FINDINGS AND LIMITATIONS

5.1 FINDINGS

All Air Quality Target Scenarios and selected pathways of measures targeting $PM_{2.5}$ pollution across sectors to achieve these are net beneficial for society.

The Health Impact Assessment concludes that the resulting reductions in annual $PM_{2.5}$ population-weighted concentrations in air across Wales could improve people's health, achieving Quality-Adjusted Life Year gains over the period 2025-2040 in all scenarios. This would be predominantly driven by a reduction in preventable deaths and the prevention of disease onset across a range of health endpoints, including asthma, COPD, Lung Cancer, Stroke, IHD and diabetes. The benefits on people's health could also result in a reduction in respiratory and/or cardiovascular hospital admissions at least in the short-term.

Other estimated benefits could be even larger in monetary scale, such as positive impacts on business operations, especially concerning fuel savings and non-fuel operating efficiencies resulting from the implementation of measures (which are likely to be more than 10 times higher than the monetised health benefits). Similarly, large positive impacts are also estimated on travel time savings and GHG emission savings (around 4 times higher or more than monetised health benefits).

The pathways to achieve the Air Quality Scenarios would also require large upfront capital investments over the period of appraisal, ranging from £1.9 billion under Scenario 1 to £18.8 billion under Scenario 4.3 for $PM_{2.5}$.

The stakeholders that might bear these and other economic costs depend on the measures or actions that are finally taken to achieve each Target Scenario as well as the level of public and private sector cooperation. At this stage, it is considered that public authorities could bear a large proportion of these costs (e.g., costs of running awareness campaigns, providing incentives to facilitate transitions or investing in R&D to support technological improvements), followed by private companies (e.g., capital expenditures to support transition towards renewable and cleaner energy sources and technologies) and individual households (e.g., indirect costs passed on by companies through higher prices, cost of energy-efficient equipment and EVs).

The health impact assessment and cost-benefit analyses suggest that any of these pathways and Air Quality Scenarios to address $PM_{2.5}$ would result in improved social welfare, when compared to the baseline.

There are different advantages and disadvantages across the scenarios, such as the level of ambition and the timeframe for transformation that might be necessary to maximise the likelihood of target compliance.

On the one hand, Scenario 1 has a more immediate target and lower scale of ambition, the timescales might be tight to incentivise and/or undertake the necessary transformation. On the other, Scenario 4.3 has a delayed target with higher scale of ambition, the timescales are more relaxed, but the delay in the target may encourage stakeholders to leave action towards later in the 2030s, which could reduce short- and medium-term transformative action and reduce the likelihood of compliance.

The analysis conducted in Section 4.2 suggests that, whilst all scenarios could result in improved social welfare, the following three scenarios might be relatively more feasible, given the scale of ambition, upfront capital requirements and timetable for investment:

- Scenario 2: 11 $\mu g/m^3$ by 2035 (‘medium’)
- Scenario 3.1: 10 $\mu g/m^3$ by 2035 (‘medium’)
- Scenario 4.1: 10 $\mu g/m^3$ by 2040 (‘medium’)

5.2 LIMITATIONS

The existing modelling considered bundles of measures and their effect on multiple pollutants which limited the disaggregation of assessments per pollutant, requiring the application of expert judgement and approximation.

A APPENDICES

APPENDIX A EMISSIONS SCENARIO DEVELOPMENT

A.1 IDENTIFICATION OF POTENTIAL POLICY MEASURES

The assessment of identifying and appraising the potential for new air quality targets has been undertaken using a framework that has integrated the key principles within the Well-being for Future Generations (Wales) Act 2015. This includes the five ways of working within its sustainable development principles (Long-term, Prevention, Integration, Collaboration, Involvement) with respect to four key constituents to every-day life in Wales (Culture, Environment, Economy, Social).

Welsh government began consulting with a wide-ranging number of stakeholders during an early stage of the project. This included the hosting of a series of workshops where 150 people from different sectors and organisations with an interest in Welsh air quality were invited to steer the development of a long-list of actions that could help improve national air quality. Break-out sessions were held during these workshops under the four themes listed under the Clean Air Plan for Wales (People, Environment, Prosperity, Place). During these workshops, attendees were presented with a long-list of actions that Welsh Government had identified and had begun to consider in detail using the Air Quality Scenario Modelling Tool (SMT) that has been developed to help policy makers identify the feasibility of potential new actions and its potential returns. These workshops were complemented with follow up meetings with key stakeholders.

The outcome from this first phase of initial analysis and consultation was an estimate of the potential level of impact on emissions of $PM_{2.5}$ by four different suites of measures (baseline, medium, high, speculative). As the names suggest, each suite of measures contained a list of measures with varying degree of feasibility, with feasibility being determined with consideration to the measure's implementation cost, impact and practicality.

The second phase of analysis began with a review of the suite of measures derived from the first phase. The output of this analysis was that measures that had a significant impact on reducing either primary $PM_{2.5}$ or precursors to $PM_{2.5}$ i.e. NH_3 and VOC were considered further. The lists of measures were then ranked separately in order of largest contributors to emission reduction to the smallest. The Table below illustrates the number of measures that were screened in for each scenario for each pollutant.

Table A1.1 Number of measures screened into each scenario for each pollutant

Scenarios	$PM_{2.5}$	NH_3	VOC	Total number of measures	Total measures taken forward
1. 11 µg/m^3 by 2030 ('medium')	30	11	13	54	28
2. 11 µg/m^3 by 2035 ('medium')	30	11	13	54	26
3.1. 10 µg/m^3 by 2035 ('medium')	30	13	14	57	26
3.2. 10 µg/m^3 by 2035 ('high')	31	21	13	65	26
3.3. 10 µg/m^3 by 2035 ('speculative')	40	28	20	88	27
4.1. 10 µg/m^3 by 2040 ('medium')	30	14	14	58	36
4.4. 10 µg/m^3 by 2040 ('high')	32	28	16	76	28
4.5. 10 µg/m^3 by 2040 ('speculative')	41	29	22	92	36

To avoid artificially overestimating costs or benefits of implementing the pathways to achieving the $PM_{2.5}$ target scenarios, it was considered that only measures directly reducing primary $PM_{2.5}$ emissions should be included. In addition, these 'direct' measures included a small number of measures in the agricultural sector, which did not appear to contribute notably towards achieving the $PM_{2.5}$ Target Scenarios. Due to the complexities associated with the analysis undertaking these measures in previous phases of this work, these could not be easily mapped to the scenarios. Thus, it was decided that it would be most effective to exclude them from the

Cost-Benefit Analysis estimates, whilst acknowledging that, even if included, the conclusions of this assessment would likely remain unchanged.

A.1 Measures selected under each scenario

The Tables A1.3 and A1.4 below presents the lists of measures assumed to be implemented under each of the selected Air Quality Target Scenarios for $PM_{2.5}$.

A.2 Limitations

There were limitations in developing a single pollutant appraisal based on the overall multi-pollutant assessment. For example, equating % change of emissions to % change of concentration is only an approximation due to the impact of secondary pollutants including secondary inorganic aerosols (SIA, which include sulphate, nitrate, and ammonium), and secondary organic aerosols (SOA, formed from VOC precursors). Formation of these $PM_{2.5}$ components are accounted for in the detailed dispersion modelling process in CMAQ rather than in the emissions inventory (as these pollutants are formed by chemical reaction in the atmosphere from precursors). As a result, it is not possible to accurately account for the impact of emissions changes on the formation of these particles without detailed modelling work.

The proposed top-down screening methodology assumes that the effect of emissions changes on concentrations is linear, and independent of the spatial distribution and source characteristics of each source, i.e. that changes in concentration are proportional to the total changes in emissions across Wales. This is not true as some source types are typically located closer to receptors and therefore have a more significant impact on population weighted mean concentrations.

Table A1.3 Specific measures assumed to be implemented under each $PM_{2.5}$ Air Quality Target Scenario ('X' means included, and a blank excluded from a scenario)

Measures to address $PM_{2.5}$ air pollution, included under each Target Scenario	Scenario 1: 11 µg/m³ by 2030 ('medium')	Scenario 2: 11 µg/m³ by 2035 ('medium')	Scenario 3.1: 10 µg/m³ by 2035 ('medium')	Scenario 3.2: 10 µg/m³ by 2035 ('high')	Scenario 3.3: 10 µg/m3 by 2035 ('speculative')	Scenario 4.1: 10 µg/m³ by 2040 ('medium')	Scenario 4.2: 10 µg/m³ by 2040 ('high')	Scenario 4.3: 10 µg/m³ by 2040 ('speculative')
All taxis and private hire fleet to zero emissions					X		X	X
Ban on domestic combustion of coal	X	X	X	X	X	X	X	X
Bespoke solid fuel appliance approval/certification					X			X
CAA for Wales	X	X	X	X	X	X	X	X
Combined effect of cavity wall insulation					X			X
Communication - Clean Air Day, guidance for good practise to encourage behaviour change, including benefit for indoor AQ	X	X	X	X	X	X	X	X
Communication - outdoor burning - guidance for good practise to encourage behaviour change	X	X	X	X	X	X	X	X
Electrification of railway lines (i.e. Phase out diesel-only trains)	X	X	X	X	X	X	X	X
Modal shift to active travel: all passenger cars	X	X	X	X	X	X	X	X
National Speed Limit (from 30 to 20 mph)					X			X
New renewables (non-thermal) instead of CCGT					X			X
Reduced carbon steelmaking					X			X
Regulating the sale of wet wood	X	X	X	X	X	X	X	X
Retrofitting active open fires to Ecodesign appliances					X			X
Sector 1A2a reduction (Blast Furnaces, Sinter production, Iron and steel combustion plant)	X	X	X	X	X	X	X	X
Sector 1A2b-e/gviii reduction (Non ferrous metal combustion, vehicle manufacture combustion, ammonia production combustion, chemical combustion, methanol production combustion, pulp, paper and print combustion, other industrial	X	X	X	X	X	X	X	X

Measures to address $PM_{2.5}$ air pollution, included under each Target Scenario	**Scenario 1: 11 µg/m³ by 2030 ('medium')**	**Scenario 2: 11 µg/m³ by 2035 ('medium')**	**Scenario 3.1: 10 µg/m³ by 2035 ('medium')**	**Scenario 3.2: 10 µg/m³ by 2035 ('high')**	**Scenario 3.3: 10 µg/m3 by 2035 ('speculative')**	**Scenario 4.1: 10 µg/m³ by 2040 ('medium')**	**Scenario 4.2: 10 µg/m³ by 2040 ('high')**	**Scenario 4.3: 10 µg/m³ by 2040 ('speculative')**
combustion, Food and drink, tobacco combustion, auto generators, mechanical engineering combustion)								
Sector 1A2gvii reduction (Industrial off road mobile machinery, NRMM construction, NRMM generators, NRMM mining and quarrying, NRMM other industry, NRMM waste)	X	X	X	X	X	X	X	X
Sector 1A4a reduction (Miscellaneous industrial/ commercial combustion, public sector combustion, Railways stationary combustion, NRMM Forklifts)	X	X	X	X	X			X
Sector 1B1a reduction (Deep mined coal, open cast coal, coal storage and transport)	X	X	X	X	X	X	X	X
Sector 1B1b reduction (Coke production, Solid smokeless fuel production, iron and steel flaring, waste disposal benzole and tars, charcoal production)	X	X	X	X	X	X	X	X
Sector 2A3 reduction (Glass, general, lead crystal, glass wool, continuous filament glass fibre, frits, flat, container, domestic, special, ballotini)	X	X	X	X	X	X	X	X
Sector 2A5a reduction (Quarrying, dewatering of lead concentrates)	X	X	X	X	X	X	X	X
Sector 2A5b reduction (Construction of houses, apartment buildings, Roads and non-residential)	X	X	X	X	X	X	X	X
Sector 2B10a reduction (Chemical Industry)					X		X	X
Sector 2C7c reduction (Tin production, other non-ferrous metal processes, Foundries)	X	X	X	X	X	X	X	X
Sector 2D3b reduction (Road dressings, kerosene, bitumen, bitumen use, asphalt manufacture)				X	X	X	X	X
Sector 2H1 reduction (Paper production)	X	X	X	X	X	X	X	X
Sector 2H3 reduction (other industry – part B processes)	X	X	X	X	X	X	X	X

Measures to address $PM_{2.5}$ air pollution, included under each Target Scenario	**Scenario 1: 11 µg/m³ by 2030 ('medium')**	**Scenario 2: 11 µg/m³ by 2035 ('medium')**	**Scenario 3.1: 10 µg/m³ by 2035 ('medium')**	**Scenario 3.2: 10 µg/m³ by 2035 ('high')**	**Scenario 3.3: 10 µg/m3 by 2035 ('speculative')**	**Scenario 4.1: 10 µg/m³ by 2040 ('medium')**	**Scenario 4.2: 10 µg/m³ by 2040 ('high')**	**Scenario 4.3: 10 µg/m³ by 2040 ('speculative')**
Sector 2I reduction (wood impregnation, Creosote use, wood products manufacture)	X	X	X	X	X	X	X	X
Solid fuel ban in designated areas - wood fuels					X			X
Test standards for new manufactured solid fuels entering the market by 2024	X	X	X	X	X	X	X	X
Transition to electric/ULEV Cars	X	X	X	X	X	X	X	X
Transition to electric/ULEV HGVs	X	X	X	X	X	X	X	X
Transition to electric/ULEV LGVs	X	X	X	X	X	X	X	X
Uptake of cleaner NRMM (i.e. Stage V)	X	X	X	X	X	X	X	X
Working from home	X	X	X	X	X	X	X	X

APPENDIX B AIR QUALITY MODELLING METHODOLOGY

B.1 General approach

Emissions data from international and national inventories have been used as inputs to the air quality models. Concentrations have been modelled on an annual average basis for the three models, and the concentrations in a series of post-processing steps to obtain total $PM_{2.5}$ concentrations.

A nested approach to modelling has been used to utilise the most appropriate models and spatial resolution for different emissions sectors. The combination of a regional and near-field dispersion model has been demonstrated by Beevers *et al.* (2012) and we have used a similar method here. We have used the following models:

- WRF has been used to generate meteorological inputs to the air quality models at 50 km, 10 km and 2 km resolution, representing the EU, UK and Wales respectively.
- RapidAIR has been used for road transport sources in the near field for a grid covering Wales at 3 m in towns and cities, and 9m resolution in rural settings;
- AERMOD has been used to model for point and area sources from large industrial operators in the near field in the immediate vicinity of the sources at grid resolutions of <100 m;
- CMAQ has been used to calculate regional contributions and secondary chemistry effects using the same grid resolutions and coverage as the WRF model (50, 10, 2 km).

This allows the fine-scale outputs from the near-field dispersion models such as those used from road transport or industrial modelling, to be retained whilst including far field dispersion and associated chemistry from the regional model.

As well as the models themselves, we have used a series of in-house python programs to undertake the following main tasks:

- Generate CMAQ ready emission grids from the EMEP and NAEI format gridded inputs (including the SMT outputs), including spatial and temporal allocation, and chemical speciation. For the UK and Wales grids the routines also dealt with vertical allocation of emissions to represent air traffic emissions and those from tall point sources.
- Convert WRF 3D gridded outputs to AERMOD and RapidAIR ready 2D meteorological fields at relevant locations across Wales
- Prepare, control and post-process hundreds of AERMOD runs in a consistent manner for all the large point sources in Wales
- Prepare, control and process RapidAIR runs in 7 discrete domains covering Wales
- Post-process all model outputs to create concentration grids for Wales with the contributions of all models sensibly combined.
- Calibrate the total concentration models at Welsh Government monitoring stations
- Prepare final outputs (maps, figures etc) for presentation in this report

Much of the codebase comprising these tools existed already but significant work was required to repurpose them for this project.

The main advantage of this approach is reproducibility, by removing any potential for human error by using a completely programmatic workflow across the entire suite of systems. For such a complex project involving multiple meteorological and air quality models, this is a major benefit both in terms of being able to quality assure the results internally, and the confidence the Welsh Government can have in the results.

B.2 Input data sources

B.2.1 Emissions Inventories

All air pollutant dispersion models require inputs of the emission rates of the sources to be modelled. Accurate emissions inputs are crucial in order to be able to produce accurate and robust pollutant concentration estimates. A combination of UK (NAEI) and European (EMEP) inventories were used as the basis for the emissions inputs to the air quality modelling, these are discussed in more detail below.

B.2.2 NAEI

All emissions in Wales and the wider UK were obtained from the most recent iteration of the UK National Atmospheric Emissions Inventory (NAEI). The NAEI is produced for the Department of Environment, Food and Rural Affairs (Defra) and the Devolved Administrations by Ricardo, and it contains the official UK annual pollutant estimates since 1970. UK total emissions are published annually and although the latest release is the 2021 version, due to the timing of the data release it is the 2020 version used here – further information about the development of the NAEI is available in the latest annual DA report.[25]

Gridded outputs from the NAEI of emissions (total and split by sector) were available at 1 km resolution across the UK up to 2020. The gridded outputs from the NAEI were translated into appropriate input formats for the dispersion models – this involved the allocation of emissions following temporal, seasonal or activity-based profiles. Chemical speciation was also applied to some emission categories, for example VOCs, given the influence this has on particulate chemistry. We have conducted research to establish the most appropriate parameters to use in Wales, taking into consideration the parameters used within the UK Pollution Climate Mapping (PCM) model, the national model used for compliance assessment.[26]

There are cases where the emissions data should be spatially or physically refined e.g., road traffic sources should be refined to improve spatial resolution using emission factors from COPERT5, in accordance with the fleet allocation methods used in the NAEI. An enhancement of the parameters used to model large industrial facilities beyond what is done in the PCM model e.g., by using more representative stack parameters, and improving on the spatial resolution of the simulations (especially if they are large emitters of primary PM, providing the necessary input data is available) was also undertaken.

B.2.3 EMEP

Emissions from the European mainland were derived from the European Monitoring and Evaluation Programme (EMEP) model. EMEP is widely used in the air quality modelling community in the UK. By including European emissions in the modelling, any long-range transport of pollution impacting local air quality in Wales was captured. Gridded emissions are available from EMEP at 50 x 50 km grid for Europe to feed into the regional model and, as discussed for the NAEI emissions, processing was required to translate these into a suitable format for input to the air quality models, such as those described in reports to Defra.[27]

B.2.4 MEGAN

Biogenic emissions were taken from the Model of Emissions of Gases and Aerosols from Nature (MEGAN). Biogenic emission species such as isoprene, a key component of Volatile Organic compounds, can be simulated with MEGAN based in meteorology. MEGAN is used in the CMAQ-UK model to represent biogenic emissions.[27] In the new version of CMAQ as used in this project, MEGAN (version 3.2) is now incorporated as an online module.[28] Thus, the biogenic emissions are directly calculated at the same time as the air quality simulation.

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[25] Ricardo (2022), '*Air Pollutant Inventories for England, Scotland, Wales, and Northern Ireland: 2005 – 2020*', available from

[26] Ricardo (2020), 'Technical report on UK supplementary assessment under The Air Quality Directive (2008/50/EC), The Air Quality Framework Directive (96/62/EC) and Fourth Daughter Directive (2004/107/EC) for 2018', available from https://uk-air.defra.gov.uk/library/reports?report_id=993

[27] Ricardo-AEA. (2014). '*CMAQ Development for UK National Modelling*'. Retrieved from https://uk-air.defra.gov.uk/assets/documents/reports/cat20/1511251727_AQ0701_CMAQ-UK_Phase_2_Final_Report_20151120.pdf

[28] CMAQ Release Notes: Emissions Updates: Model of Emissions of Gases and Aerosols from Nature (MEGAN) Biogenic Emissions · USEPA/CMAQ Wiki (github.com)

B.2.5 Scenario Modelling Tool

The Scenario Modelling Toolkit (SMT) has been used to produce future year emissions estimates and emission reduction scenarios for $PM_{2.5}$. The SMT uses data from the Defra Multi Pollutant Measures Database (MPMD) and includes the latest available information on cost benefit of mitigation measures. The outputs from the SMT are emission totals for the model year/scenario in addition to 1km resolution gridded emission outputs showing the spatial locations of the emissions (total and by sector).

The SMT projections are based on national projections and do not account for the impact of the Covid-19 pandemic on future year emissions. Given the uncertainty regarding the long-term emission effects of the pandemic, we used future year estimates based on pre-Covid projections.

B.2.6 Global Forecasting System

The WRF model for the European 50 km domain is initialised by, and derives its boundary conditions from, the 6 hourly outputs from the National Centre for Environmental Prediction's GFS model. These data were acquired as 3D netCDF files at 6 hourly intervals covering the whole of 2019 and stored in our cloud archive.

B.3 Modelling emission scenarios

The second phase of the project used the emission outputs from the first phase to produce concentration outputs. The study aimed to provide a 'translation' of Welsh Government policy options for managing concentrations of air pollutants in the coming years. Outputs from the first phase of the project included details of the policy options included in the baseline and the changes in uptake rates for each of the three ambition scenarios for each of the policy measures. The output was disaggregated by the pollutant emission and by sector (agricultural, residential, transport, energy supply and industrial). In this section we describe the main features of the emission modelling that was undertaken for this work.

B.3.1 2019 Baseline

At the commencement of the project the 2020 NAEI was the most recently available version. The 2019 CMAQ model is based on a combination of publicly available emissions data (NAEI and EMEP) and emissions data produced for other government programmes, but which is not published (MAAQ). These additional datasets were obtained by agreement between Welsh Government and Defra and were used in AERMOD and RapidAIR.

The emission data for the 2019 base case was based on the following:

- EMEP - we used the 0.1 x 0.1 degree resolution data from EMEP to populate our EU50 domain in CMAQ. We retained the same sectoral splits defined by the providers so that we could temporally allocate the emissions by sector and apply the speciation profiles required by CMAQ.
- NAEI - we used the 1 km^2 spatially disaggregated maps published by the NAEI for 2019. We retained the sector splits defined in the datasets which allowed us to apply the relevant temporal variation and speciation to the emissions. The 1 km^2 grids were post-processed into 10 x 10 km and 2 x 2 km grids for use in the UK10 and WG02 CMAQ models. We also used the 2019 large point source emission inventory to populate the AERMOD point source model and to vertically allocate the emissions in the CMAQ grid.
- MAAQ - we used the road traffic emission inventory from the MAAQ project (data provided by personal communication) which was spatially allocated to the major road network for 2020. The data was made available by agreement between WG and Defra. These data were gridded at either 9 m^2 or 81 m^2 depending on the location and passed through the RapidAIR dispersion model.

The 2019 data is largely based on inventories which are in turn supported by existing national and international reporting frameworks, which utilise observed emissions in many cases. Thus, it is likely that the 2019 baseline emission model has the least uncertainty of all the cases.

B.3.2 Spatially disaggregated emissions

Spatially disaggregated emissions data from the SMT was exported at UK wide level for each source/activity combination. For use in modelling, this needed disaggregating to high resolution, such as points, lines and grids. The method of disaggregation followed the method and principles used in the NAEI and PCM (MAAQ project).

The emissions and activity data are split into three types: point sources, area sources and roads:

- Industrial localised (**'point' source**) emissions are compiled from detailed official sources prepared by the EA, SEPA, NRW, DAERA, DESNZ OPRED and Local Authorities. These provide both the geographical location and the magnitude of the emission.
- The national total minus these point sources provides an **'area' source**. For these smaller and more widely distributed sources, less detailed information on the location and magnitude of emissions is available. Subsequently, a set of the distribution of emissions is generated using appropriate surrogate statistics at a sector level.
- The data from **roads** were generated at DfT traffic count point level where detailed breakdown of traffic and emissions were estimated and allocated to specific high resolution road links (OS Open Roads).

The method used for each source and sector varies according to the data available, and a detailed description of these can be found in the UK Spatial Emissions Methodology report.[29]

For this project, the above emission datasets were projected to future years. The projected national totals for the baseline and for each of the scenarios were generated in the SMT. The projected emissions for the individual point sources, the gridded area sources and the major roads were scaled forward outside the main SMT, but in line with the baseline and the scenarios SMT's national totals.

This is an improvement from the previous modelling process, as there is better harmonisation between the baseline/scenarios and the disaggregated emissions data for all the types mentioned above.

All the outputs, generated from this new process, are fully consistent with the released NAEI spatial emissions outputs, in terms of breakdown, format and methodology.

[29] https://uk-air.defra.gov.uk/assets/documents/reports/cat09/2307061053_UK_Spatial_Emissions_Methodology_for_NAEI_2021_v1.pdf

B.4 Meteorological modelling

Numerical weather prediction (NWP) models are commonly used to provide the meteorological inputs to air quality dispersion models. These systems model the dynamics of the atmosphere and the physical processes that occur, such as the formation of clouds, and the other processes in the Earth system that influence the weather such as atmospheric composition, the marine environment and land processes. We used the Weather Research and Forecast (WRF) model (v4.5), one of the most utilised NWP models in the world, to produce all meteorology inputs for the air quality models.

B.4.1 Weather Research and Forecasting Model

The WRF model[30] is an open-source mesoscale numerical weather prediction model developed by a number of organisations including the US National Centre for Atmospheric Research (NCAR), the Forecast Systems Laboratory and the National Centres for Environmental Prediction of the National Oceanic and Atmospheric Administration (FSL, NCEP/NOAA), with a large active community of scientists and agency users. Dynamic solvers, including the Advanced Research WRF, are used to simulate advection, pressure-gradient, Coriolis, diffusion, and time-stepping effects on weather conditions within the WRF domain. The model serves a wide range of meteorological applications across scales from tens of meters to thousands of kilometres.

The use of WRF has been reported in the UK e.g. coupled with CMAQ to produce the Scottish Government's ongoing air quality forecast, with CMAQ-ADMS or with the EMEP4UK model which is used to support European policy development by UNECE.

B.4.2 Methods

Global scale meteorological data is required as input to the WRF simulations; mainly as a means of introducing initial and boundary conditions to the model, which WRF then 'localizes' to the domain of interest. We used the published model configurations optimized for the UK.[31]

B.4.3 Outputs

The WRF modelling has yielded a complete one-year dataset for 2019. This comprises hourly grids for each of the three nested domains, at 50, 10 and 2km resolution respectively. For each grid we post-processed the data to separate netCDF files containing a single day of hourly outputs. Hence there are 365 files for each of the 3 grids.

B.4.4 Meteorological model performance

Full details of the WRF model setup and validation are available in the WRF optimisation report.[69] To confirm model performance in the 2km domain, hourly meteorological data was extracted at the locations of 5 meteorological observation within the domain. The locations of the stations used are provided in Table B4-1.

Table B4-1: Meteorological stations

Site	Longitude	Latitude	Setting
Hawarden	-2.978	53.178	Suburban
Sennybridge	-3.617	52.067	Rural
Valley	-4.535	53.348	Rural
Pembry	-4.367	51.717	Rural
Cardiff	-3.343	51.397	Suburban

The statistics used to evaluate the WRF model performance for each variable are described below, where M_i is the modelled value, O_i is the observed value, and N is the number of values analysed:

Mean Absolute Error (MAE): The lower the value the smaller the error in the model predictions.

[30] https://www.mmm.ucar.edu/models/wrf

[31] Defra. (2013). '*CMAQ Development for UK National Modelling: WRF Optimisation*'. Retrieved from https://uk-air.defra.gov.uk/assets/documents/reports/cat20/1511260908_AQ0701_DevelopmentWRFOptimisation_Objective5_Final.pdf

$$MAE = \sum_{i=1}^{N} \frac{|M_i - O_i|}{N}$$

Root Mean Square Error (RMSE): The lower the value the smaller the error in the model predictions.

$$RMSE = \sqrt{\sum_{i=1}^{N} \frac{(M_i - O_i)^2}{N}}$$

Bias (BIAS): The lower the value the smaller the error in the model predictions.

$$BIAS = \sum_{i=1}^{N} \frac{(M_i - O_i)}{N}$$

Table B4-2 shows the evaluation statistics for temperature at each measurement station. The model slightly overpredicts temperatures in the winter months, and underpredicts temperatures in the summer months across all sites.

Table B4-2: Temperature evaluation

Site	MAE	RMSE	BIAS
Cardiff	2.91	3.65	0.71
Hawarden	2.81	3.42	1.92
Pembry	3.10	3.84	0.92
Sennybridge	2.59	3.24	1.31
Valley	2.59	3.24	1.89

The evaluation statistics for the modelled wind speed are provided in Table B4-3. Wind roses showing observed and modelled wind direction and speed at the 5 sites are presented in Figure B4-1.

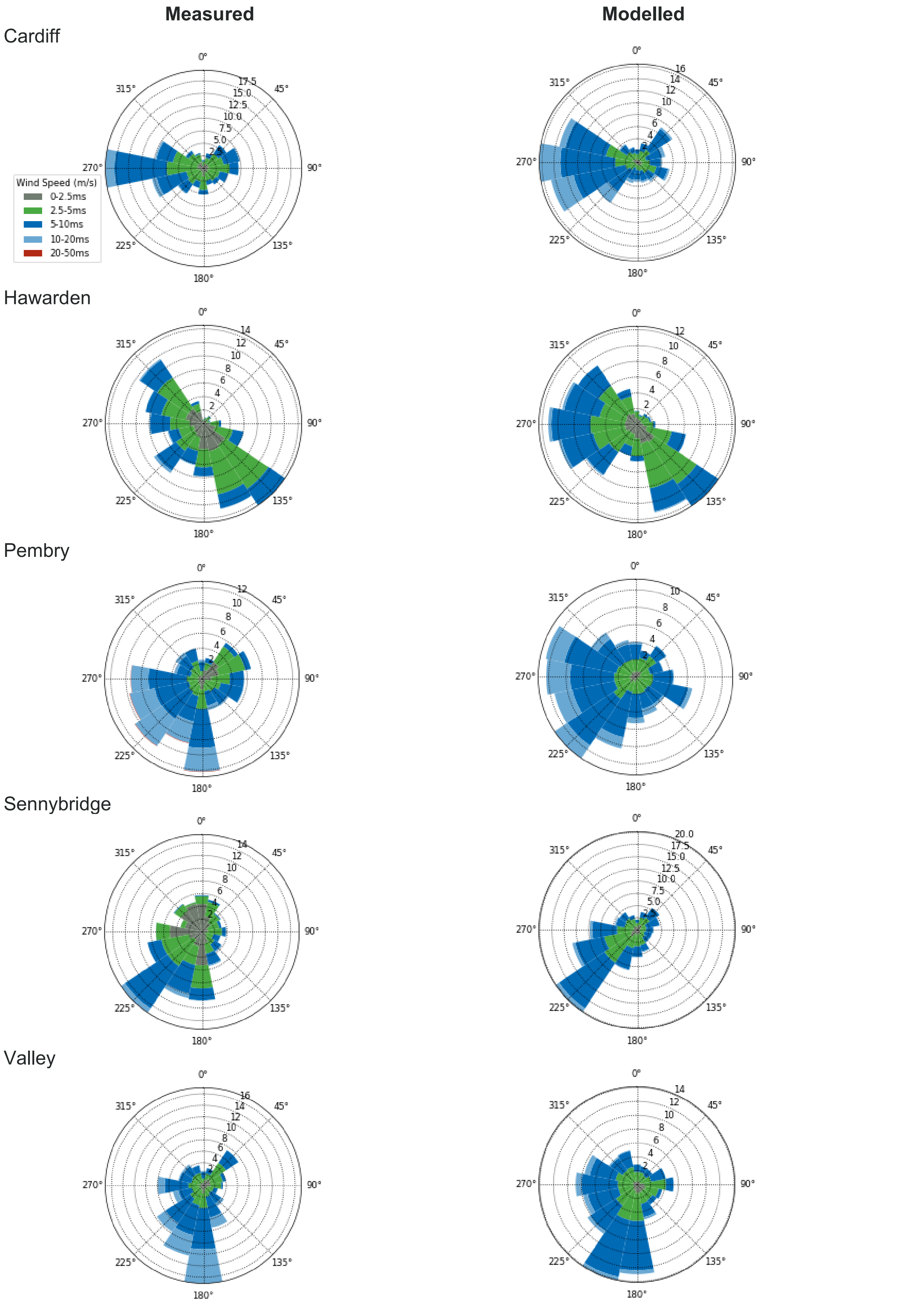
The wind rose plots show the direction and magnitude of the winds predicted by the WRF model are similar to those measured at the meteorological stations. The wind roses broadly agree at all sites, indicating that the model is performing well at the majority of locations across the domain.

The model predicts a larger spread of wind directions than is observed at the Pembry station, indicating that predicted concentrations at coastal locations may be subject to greater uncertainty in the model.

Table B4-3: Model evaluation statistics for wind speed

Site	MAE	RMSE	BIAS
Cardiff	2.67	3.40	-1.75
Hawarden	1.80	2.32	-0.58
Pembry	2.64	3.46	-0.03
Sennybridge	2.53	3.13	-1.64
Valley	2.45	3.26	0.96

Figure B4-1: Wind roses of measured and modelled meteorological data at sites in Wales, 2019



B.4.5 Use of modelled meteorology in the air quality models

The CMAQ model requires several meteorological input files which needed to be processed before to be used by the model[32]- most commonly the outputs of the WRF model. The Meteorology-Chemistry Interface Processor (MCIP) is provided with the CMAQ source code and is used to processes the meteorological fields from WRF into files that are compatible with CMAQ. MCIP retains the nested grid structure used in the WRF model.

The output files generated by MCIP are also used to create the initial and boundary conditions for CMAQ. MCIP was run for each of the three regional modelling domains to derive the meteorology for CMAQ.

[32] https://github.com/USEPA/CMAQ/blob/main/DOCS/Users_Guide/CMAQ_UG_ch04_model_inputs.md

B.5 Regional air quality modelling

B.5.1 Community Multiscale Air Quality Model (CMAQ)

The Community Multiscale Air Quality (CMAQ) model,[33] has been developed and distributed by the USEPA over many years, in which time it has become a state-of-the-science and widely applied modelling suite. It is used by regulatory agencies and forecasting groups in many countries around the world, including the US, China and the UK.

CMAQ is a 3D Eulerian model, incorporating the effects of meteorology, emissions, land use, chemistry and aerosol processes on modelled air pollution. It has been developed to represent the emission, transport, formation, destruction, and deposition of many air pollutants, including nitrogen dioxide (NO_2), ozone (O_3) and particulate matter with an aerodynamic diameter lower than 2.5 µm ($PM_{2.5}$). The version used in this project is 5.4.

This chemical-transport model requires input from the weather model, emissions and the background atmospheric composition. For our work, the CMAQ model is driven by meteorological fields from the WRF model v4.5.

B.5.2 Methods

The downscaling model system is based on three domains shown in Figure B5-1, namely:

- EU50, representing the European domain at 50 km horizontal resolution,
- UK10, covering the UK domain at 10 km horizontal resolution,
- WG02, representing the Welsh domain at 2 km horizontal resolution.

The CMAQ calculations for the three domains have been carried out for the year 2019, representing the baseline conditions for the project. It is recommended to initialise the first relevant timestep of interest (i.e. January 1st, 00:00 hrs) with a fully evolved 3D concentration grid which accounts for the propagation of distant emission sources through the whole domain- this is known as 'spin-up'. An initial spin-up of 15 days has been conducted for the EU50 domain (16-31 December 2018), while the initial conditions for the two other domains have been taken from the larger domain (e.g. from EU50 for the UK10 run), as shown in Figure B5-1.

In addition, the calculated concentrations for each larger domain have been used as chemical boundary conditions for each subsequent smaller domain, as shown in Figure B5-2. For example, the CMAQ concentrations calculated within the EU50 domain have been used as boundary conditions for the UK10 domain, and the UK10 provides the boundaries to the WG02 domain. Only the EU50 simulation has used prescribed concentrations as boundary conditions. These prescribed concentrations are representative to annual background conditions provided by the US EPA.[34] Our use of a large EU50 domain, extending as far south as North Africa, means that all relevant emission sources are modelled discretely in CMAQ in this project, so there is less reliance on global boundary conditions.

In this developed system, the CMAQ calculations in each domain use the WRF meteorological data for the corresponding domain.

[33] Appel, K et al. (2021). '*The Community Multiscale Air Quality (CMAQ) model versions 5.3 and 5.3.1: system updates and evaluation*'. Geosci. Model Dev., 14, 2867–2897. doi: https://doi.org/10.5194/gmd-14-2867-2021

[34] https://github.com/USEPA/CMAQ/tree/main/PREP/bcon

Figure B5-1. Illustration of the three modelled domains within WRF/CMAQ

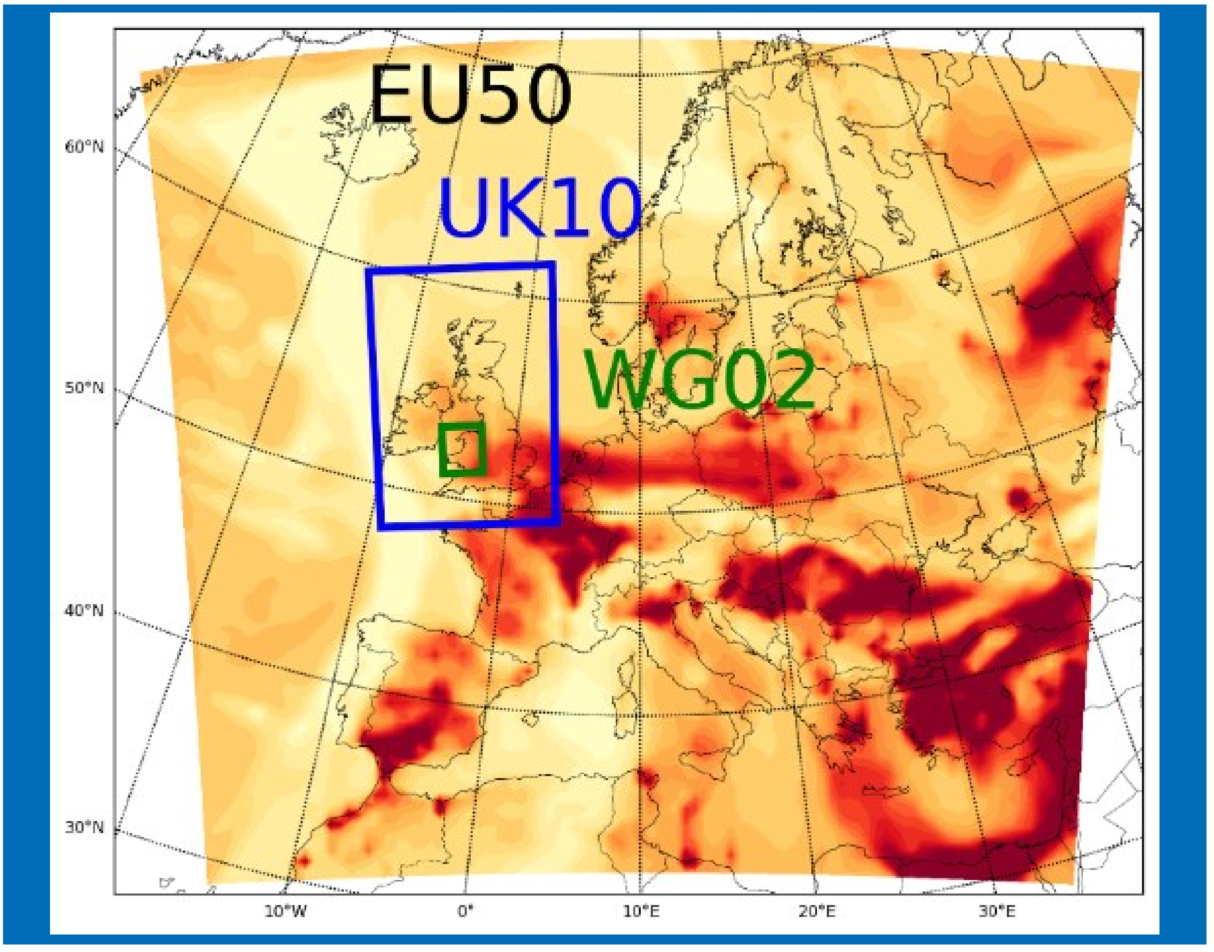
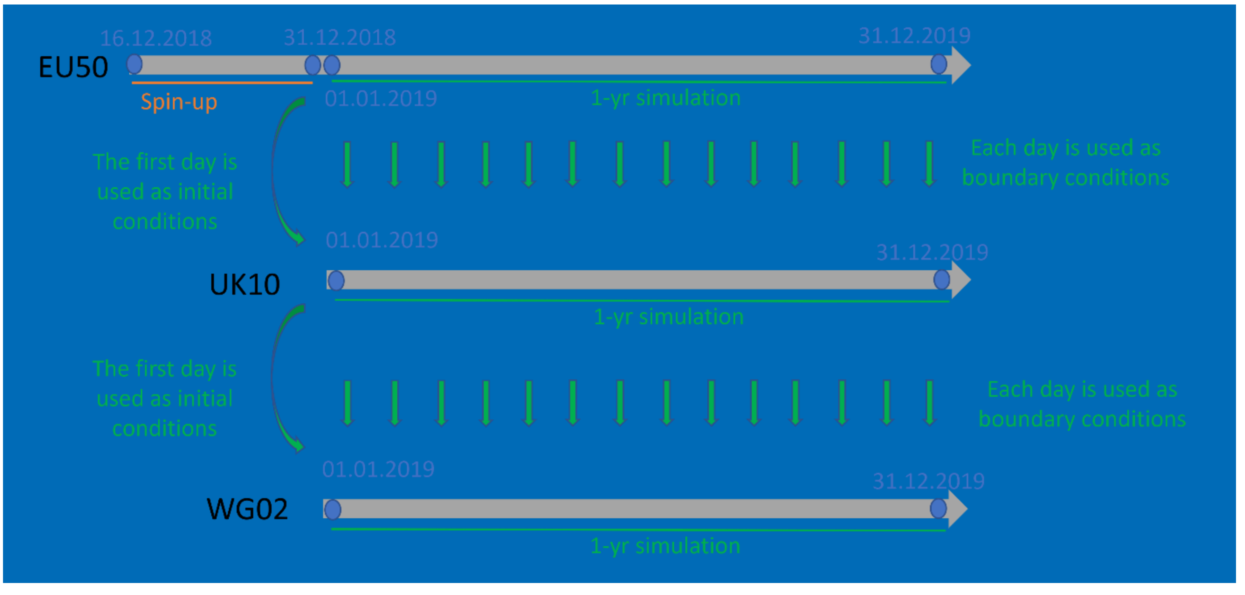


Figure B5-2. Downscaling modelling system: from the European regional-scale (EU50) to the British subregional (UK10) and Wales (WG02). The spin-up period for the EU50 run is shown with the orange horizontal bar. The green horizontal bars show the 2019 simulation. The green arrows represent the data flow between the different domains.



B.5.3 Derived data products

B.5.3.1 Pollutant coverage

CMAQ calculates a range of air quality parameters including a range of gaseous species and particulate matter concentrations, and deposition (wet and dry) to land. This results in a list of more than 200 variables calculated by the model. These variables are output in file formats that retain the hourly timesteps in each of the three grids, so they must be postprocessed in order to get usable values (e.g., annual mean values for comparison with standards). CMAQ ships with a series of tools for the purposes of post-processing its outputs.

B.5.3.2 Gridded data

The CMAQ outputs correspond to 3D gridded values following the resolution of the corresponding domain, for example 2 km × 2 km for the WG02 domain. These data contain hourly concentration and deposition values for all the variables.

As aforementioned, CMAQ calculates hourly gridded concentrations for the whole studied domain. This allows calculation of the timeseries of concentrations for each grid cell of each domain.

B.5.3.3 PM speciation

Concentrations of $PM_{2.5}$ in the model are derived from a post-processing stage where a list of recommended PM components are summed to yield hourly $PM_{2.5}$ concentrations. This means that as well as the aggregated $PM_{2.5}$ values, it is possible to retain the hourly concentrations of some $PM_{2.5}$ components.

Indeed, the $PM_{2.5}$ are composed of primary components such as organic matter (OM), elemental carbon (EC), fine crustal dusts, and other compounds. CMAQ accounts for the formation of the secondary components of $PM_{2.5}$ which are formed by chemical reactions in the atmosphere from gas-phase precursors. The most important of these (in terms of their share of the final $PM_{2.5}$ mass), are Secondary Inorganic Aerosols (SIA) nitrate (NO_3^-), ammonium (NH_4^+), sulphate (SO_4^{2-}), and a large range of secondary organic aerosol (SOA) compounds. The SOA component of secondary $PM_{2.5}$ is much smaller than the SIA component and as the projected concentrations are small [35][36] and the effect of SOA is expected to be limited.

B.5.3.4 Source apportionment

The source apportionment in this project will focus on two aspects: the geographical source apportionment and the sectoral source apportionment. Both calculations follow a separate approach.

B.5.3.5 Geographical source apportionment

The geographical source apportionment will be based on a set of sensitivity simulations where the region of interest is characterized by reduced emissions and then compare to the reference, where no reductions is applied. The difference between the two simulations is then assumed to be attributed to the removed source region. This approach is useful for analysing the concentration changes due to emission reductions, but one simulation per source region is needed to calculate the impact of the corresponding source.

This approach is also named “brute force” and is commonly used in the determination of the transboundary pollution in European countries within the EMEP programme[37], in the Policy support tool in calculating the country contribution to urban concentrations developed by the Copernicus programme[38] [39] or used as input of a tool developed by the European Commission[40] to cite a few examples.

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[35] Ricardo, (2025), *Atmosphere, Volume 16, Issue 4 (April 2025)*. The Impact of Farming Mitigation Measures on Ammonia Concentrations and Nitrogen Deposition in the UK. Available at: https://www.mdpi.com/2073-4433/16/4/353

[36] Pastorino, S et al (2024), *Health Impact of Policies to reduce agriculture-related air pollutants in the UK: The relative contribution change in $PM_{2.5}$ exposure and diets to morbidity and mortality'*, Environmental Research, Volume 262, Part 1, 1 December 2024, available from https://www.sciencedirect.com/science/article/abs/pii/S0013935124018280

[37] EMEP Status Report 1/2023, '*Transboundary particulate matter, photo-oxidants, acidifying and eutrophying components'*, Joint MSC-W & CCC & CEIP & CIAM Report

[38] https://policy.atmosphere.copernicus.eu/

[39] https://gmd.copernicus.org/articles/13/1787/2020/

[40] E. Pisoni, P. Thunis, A. Clappier, “*Application of the SHERPA source-receptor relationships, based on the EMEP MSC-W model, for the assessment of air quality policy scenarios*”, Atmospheric Environment: X, Volume 4, 2019, https://doi.org/10.1016/j.aeaoa.2019.100047 .

B.5.3.6 Sectoral source apportionment

As part of the new developments of the CMAQ model, the Integrated Source Apportionment Method (ISAM) calculates source attribution information for user specified ozone and particulate matter precursors within the model.[41][42] In other words, by tracking the corresponding species by sector, this module calculates source attribution of sectors directly in one simulation (per scenario). The same sectoral split as the NAEI/SMT will be used. It is worth noting this module creates heavy files (larger than the usual CMAQ simulation files) so only a limited number of sectors was selected and for a limited number of species (e.g. $PM_{2.5}$).

B.6 Road source air quality modelling

The major roads in Wales (those included in the UK Pollution Climate Mapping (PCM) model) have been discretely modelled as part of this work. This section discusses the road transport air quality modelling for the baseline scenarios of 2019, 2025, 2030, 2035 and 2040.

Emission rates for each road link in the domain were calculated using Ricardo's RapidEMS® model. The RapidEMS model is an implementation of the COPERT 5.3 vehicle specific emission coefficients, localised to UK conditions using NAEI fleet data. The emission model is used to generate speed-emissions curves, which are then coupled to the activity data to calculate the appropriate total emissions rates for each vehicle category based on the speed on the road link.

B.6.1 Road Transport Emissions

B.6.1.1 Road geometry data

Road geometry was taken from the NAEI/PCM model. This dataset collapses dual carriageways into single lines in all cases; this is the same data used in the 2019 NAEI emissions. Lane width was calculated based on the road classification as described in Table B6-1. The RapidAir road modelling only modelled A Roads and Motorways, emissions from all roads were included within the CMAQ modelling.

Table B6-1: Modelled road widths

Road class	Form	Modelled lanes
A Road	Single Carriageway	2
A Road	Roundabout	2
A Road	Dual Carriageway	4
A Road	Slip Road	2
Motorway	Dual Carriageway	4
Motorway	Slip Road	2

Gradient-effects on emissions have been accounted for following guidance outlined in the Local Air Quality Management Technical Guidance (LAQM.TG 2016)[43] that was current at the commencement of the project.

The elevation of the start and end node of each road link was sampled from the OS Terrain 50[44] data sets. The terrain data is presented in Figure B6-1.

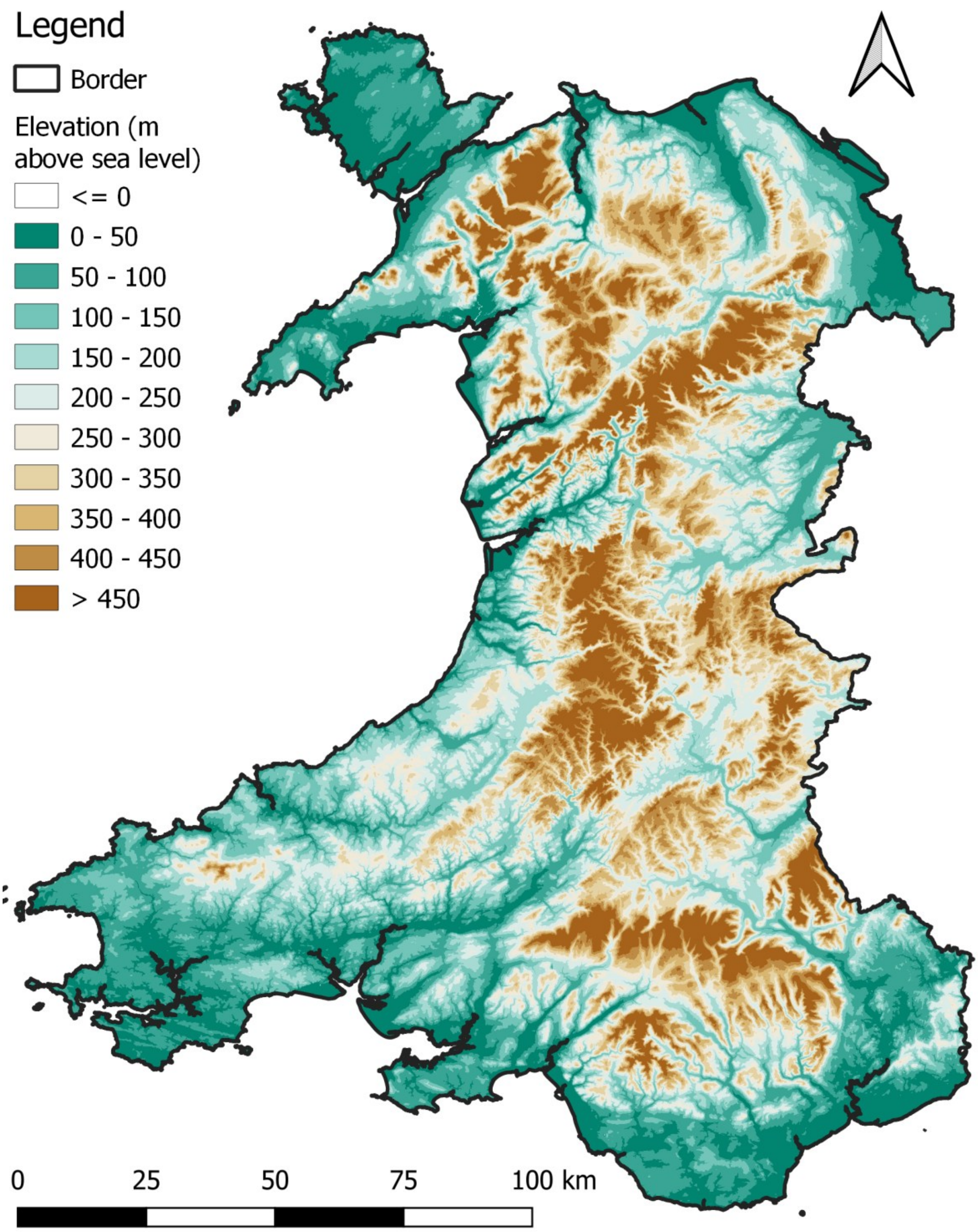
[41] https://github.com/USEPA/CMAQ/blob/main/DOCS/Users_Guide/CMAQ_UG_ch11_ISAM.md

[42] Yasmin Kaore et al., Source apportionment modelling of PM2.5 using CMAQ-ISAM over a tropical coastal-urban area, Atmospheric Pollution Research, Volume 12, Issue 12, 2021, https://doi.org/10.1016/j.apr.2021.101250.

[43] https://laqm.defra.gov.uk/guidance/ (obtained in January 2021)

[44] https://www.ordnancesurvey.co.uk/business-government/products/terrain-50

Figure B6-1: Modelled terrain data



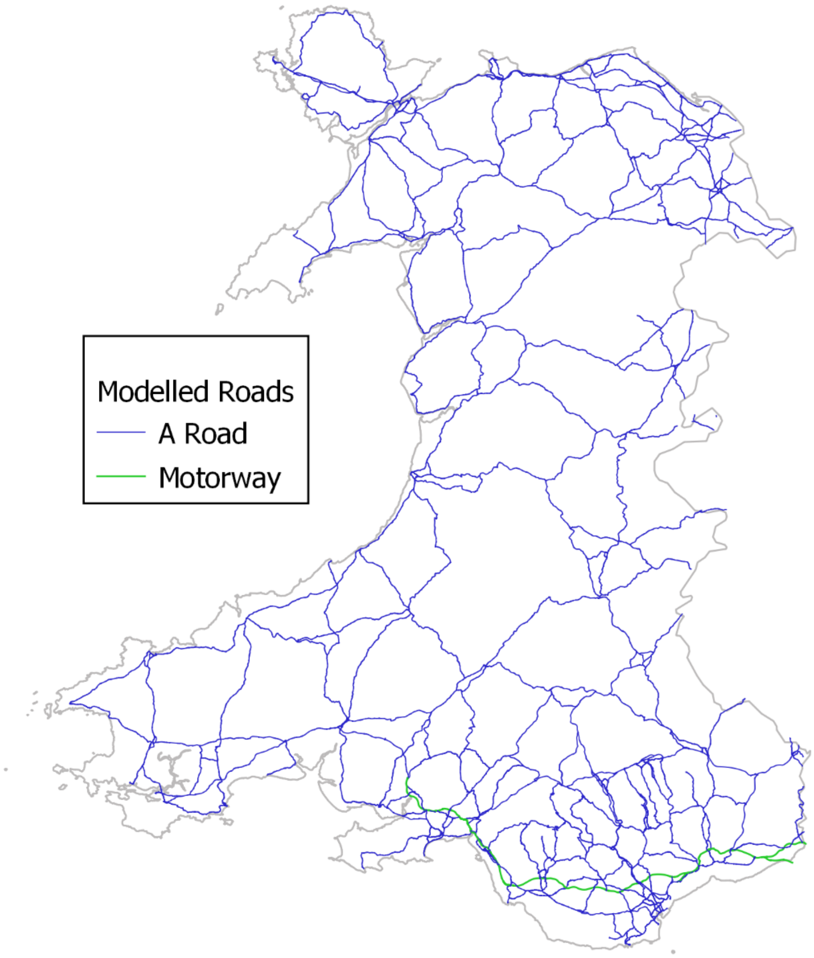
B.6.1.2 Activity data

Traffic flows

Traffic flows were derived from the data used in the PCM model. This is the data used in the 2019 NAEI emissions i.e., the emissions data being used in the CMAQ regional modelling. The activity data is mainly derived from the network of counting stations run by the Department for Transport, which measures traffic flows and basic fleet composition on the trunk road network in the UK.

This data was provided as a shapefile of road links with attributes describing the total flow and car, bus, LGV, rigid HGV and artic HGVs flows respectively, as well as the number of lanes and length of each road link. Following discussions with the PCM team it was decided to remove any roads categorised as slip roads from the analysis due to uncertainties associated with the activity data on these links. The final road network used in the modelling is shown in Figure B6-2.

Figure B6-2: Modelled roads



The PCM data, whilst being very useful for this application, remains quite a simple representation of the complexities of road traffic activity in Wales. The road activity data does not include factors such as idling/queuing, stop and start, acceleration, and deceleration around junctions and other obstacles. For example, the PCM has a single traffic speed for sometimes quite long stretches of road (several km in some cases), and this is treated as a constant over time. Thus, it should be kept in mind that when we describe the high-resolution outputs from RapidAIR, the emissions feeding the model still retain some features more associated with national scale emission models.

For future years, traffic flows were derived from the emissions inventory presented in the Phase1 report.

Traffic speeds

Speed data was also provided from the PCM model, which is based firstly on mapped speed limit data, which is amended to reflect the type of road and its setting, as used in the 2019 NAEI. For example, urban roads with the same speed limit as rural roads will be assigned a slower average speed to provide a basic reflection of congestion and increased journey times. Speed data for each vehicle category was provided for each road link – a weighted average calculation was used to produce a single average daily speed on each link for use in the emissions calculations.

No future year speed data was available therefore 2019 speeds have been used in the 2025, 2030, 2035 and 2040 models.

Time-varying emission factors

The final data point in the model is the temporal variation in the emissions- which is intended to match the diurnal flux to the appropriate meteorological conditions. This is normally done using road type specific traffic activity profiles from the DfT, with the simplifying assumption that traffic emissions scale hourly by the volume of vehicles (disregarding the influence of speed). We used this method, assuming the default traffic diurnal profile outlined in DfT TRA0307.[45]

B.6.1.3 Emission factors

Emissions from all modelled road traffic sources were calculated using speed-dependent vehicle emission factors for NOx, primary NO_2, particulates, carbon monoxide, and ammonia from COPERT v5.[46] COPERT is a European database of emission factors which is recommended for the quantification of road-transport emissions. These factors provide emission factors categorised by vehicle size, age, and Euro classification, taking into account average vehicle mileage and engine degradation.

B.6.1.4 Vehicle fleet age and technology

The Euro compositions and fuel use for the Welsh transport fleet in 2019, 2025, 2030, 2035 and 2040 was derived from NAEI datasets. The derived vehicle fleet, in terms of Euro standard, is presented in B6-2.

The general trend shows a decrease in diesel light vehicles to a mix of petrol and electric. There is also a technology shift to almost all Euro 6 light vehicles (and hybrids) and Euro 6 heavy vehicles. From such shifts, a dramatic reduction in NOx from road vehicles would be expected, from BAU 2019 to 2040. A lesser reduction would be expected for PM for several reasons. Non-exhaust PM emissions are unlikely to change with Euro standards and the framing of the emission limits for successive Euro standards has stricter NOx standards from Euro 5 to 6, but they do not have a stricter PM standard.[47]

Table B6-2: Euro composition of Welsh transport fleet in 2019, 2025, 2030, 2035 and 2040.

Vehicle	Euro Standard	2019 (%)	2025 (%)	2030 (%)	2035 (%)	2040 (%)
Car	Pre Euro 1	-	-	-	-	-
(petrol)	Euro 1	-	-	-	-	-
	Euro 2	1%	-	-	-	-
	Euro 3	12%	-	-	-	-
	Euro 4	21%	4%	-	-	-
	Euro 5	25%	16%	4%	-	-
	Euro 6_1	29%	25%	13%	3%	-
	Euro 6_2	9%	13%	10%	4%	-
	Euro 6_3	-	30%	56%	83%	73%
	Euro 3 PEV	-	-	-	-	-
	Euro 4 PEV	-	-	-	-	-
	Euro 5 PEV	1%	-	-	-	-
	Euro 6_1 PEV	1%	1%	-	-	-
	Euro 6_2 PEV	-	1%	1%	-	-
	Euro 6_3 PEV	-	3%	7%	10%	9%
	Euro 4 PHEV	-	-	-	-	-
	Euro 5 PHEV	-	-	-	-	-
	Euro 6_1 PHEV	1%	1%	-	-	-
	Euro 6_2 PHEV	-	-	-	-	-
	Euro 6_3 PHEV	-	4%	10%	-	17%
Car	Pre Euro 1	-	-	-	-	-
(Diesel)	Euro 1	-	-	-	-	-
	Euro 2	-	-	-	-	-
	Euro 3	6%	-	-	-	-
	Euro 4	18%	5%	-	-	-
	Euro 5	34%	28%	9%	-	-
	Euro 6_1	36%	36%	26%	5%	-

[45] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/981987/tra0307.ods

[46] http://www.emisia.com/utilities/copert/

[47] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A02007R0715-20200901

Vehicle	Euro Standard	2019 (%)	2025 (%)	2030 (%)	2035 (%)	2040 (%)
	Euro 6_2	6%	10%	9%	4%	-
	Euro 6_3	-	17%	49%	83%	92%
	Euro 3 DEV	-	-	-	-	-
	Euro 4 DEV	-	-	-	-	-
	Euro 5 DEV	-	-	-	-	-
	Euro 6_1 DEV	-	-	-	-	-
	Euro 6_2 DEV	-	1%	1%	-	-
	Euro 6_3 DEV	-	2%	5%	8%	8%
Car (Electric)	Electric	100%	100%	100%	100%	100%
LGV	Pre Euro 1	0%	0%	0%	0%	0%
(Petrol)	Euro 1	0%	0%	0%	0%	0%
	Euro 2	0%	0%	0%	0%	0%
	Euro 3	0%	0%	0%	0%	0%
	Euro 4	1%	0%	0%	0%	0%
	Euro 5	1%	0%	0%	0%	0%
	Euro 6_1	1%	0%	0%	0%	0%
	Euro 6_2	1%	0%	0%	0%	0%
	Euro 6_3	0%	2%	2%	2%	2%
LGV	Pre Euro 1	0%	0%	0%	0%	0%
(Diesel)	Euro 1	0%	0%	0%	0%	0%
	Euro 2	1%	0%	0%	0%	0%
	Euro 3	5%	0%	0%	0%	0%
	Euro 4	15%	3%	0%	0%	0%
	Euro 5	31%	13%	3%	0%	0%
	Euro 6_1	20%	9%	4%	1%	0%
	Euro 6_2	25%	19%	9%	2%	0%
	Euro 6_3	0%	53%	78%	87%	86%
LGV (Electric)	Electric	0%	2%	4%	8%	12%
HGV	Pre Euro 1	-	-	-	-	-
(Artic)	Euro 1	0%	-	-	-	-
	Euro 2	0%	0%	-	-	-
	Euro 3	1%	0%	0%	-	-
	Euro 4	2%	0%	0%	-	-
	Euro 5 EGR	3%	0%	0%	0%	-
	Euro 5 SCR	10%	1%	0%	0%	-
	Euro 6	83%	98%	100%	100%	100%
HGV	Pre Euro 1	-	-	-	-	-
(Rigid)	Euro 1	1%	-	-	-	-
	Euro 2	3%	0%	-	-	-
	Euro 3	8%	2%	0%	-	-
	Euro 4	7%	1%	1%	-	-
	Euro 5 EGR	5%	1%	0%	0%	-
	Euro 5 SCR	16%	4%	1%	0%	-
	Euro 6	60%	91%	98%	100%	100%
Bus	Pre Euro 1	-	-	-	-	-
	Euro 1	0%	-	-	-	-
	Euro 2	1%	0%	-	-	-
	Euro 3	11%	1%	0%	-	-
	Euro 4	10%	2%	0%	-	-

Vehicle	Euro Standard	2019 (%)	2025 (%)	2030 (%)	2035 (%)	2040 (%)
	Euro 5 EGR	6%	3%	1%	0%	-
	Euro 5 SCR	19%	10%	2%	0%	-
	Euro 6	52%	83%	97%	100%	100%
Coach	Pre Euro 1	-	-	-	-	-
	Euro 1	0%	-	-	-	-
	Euro 2	1%	0%	-	-	-
	Euro 3	11%	1%	0%	-	-
	Euro 4	10%	2%	0%	-	-
	Euro 5 EGR	6%	3%	1%	0%	-
	Euro 5 SCR	19%	10%	2%	0%	-
	Euro 6	52%	83%	97%	100%	100%

B.6.2 Modelling methodology

B.6.2.1 Model description

Ricardo's RapidAir model has been used to model gridded road transport $PM_{2.5}$ concentrations. RapidAIR uses the USEPA's AERMOD system to derive a 2D concentration field comprising >250,000 discrete locations around a single idealised area source of unit emissions

The resulting concentration field is used as a dispersion kernel to convolve a national grid of emissions, resulting in a continuous national scale concentration field. Each cell in the national concentration field will be influenced by road emissions at a distance broadly equal to the size of the kernel times the model resolution- in practice this usually equates to several km which is enough to capture the effects of relevant roads within that distance to each receptor location. To capture any minor effects from more distant roads, we additionally run RapidAIR in urban background mode, which multiplies the coverage distance of the kernel by a factor of 5. The urban background component is superimposed on the local component of concentrations to provide a total for each single cell in the domain. In the end, each receptor cell in the whole of Wales will have a concentration that is influenced to varying degrees by emissions from the road network surrounding their location.

RapidAir has been used to support many air quality studies in the UK, including the Clean Air Zone assessments in Southampton, Bradford and Cardiff, and has been peer-reviewed and described in the literature.[48]

B.6.2.2 Meteorology

RapidAir uses a range of hourly sequential meteorological data to calculate atmospheric conditions and therefore atmospheric dispersion. The meteorology for RapidAIR is usually sourced either from surface monitoring stations, or from modelled wind fields. The meteorological variables required by the model include wind speed and direction, cloud cover. In a typical case, a set of additional variables such as convective and mechanical boundary layer height are derived from these using the USEPA AERMET system.

In this study, the modelled meteorological data used to drive the CMAQ simulations were used.

The WRF data is gridded, so 'virtual' meteorological stations were extracted from the grid at representative locations. The USEPA provide a processor to carry out this process[49] the Mesoscale Model Interface (MMIF), which we obtained for use in this study. MMIF converts prognostic meteorological model output fields to the parameters and formats required for direct input into dispersion models.

MMIF has been used to extract ground level meteorology from the WRF model grid from three virtual meteorology stations in Wales. The three virtual meteorology stations have been selected in each of North, Mid and South Wales to ensure any broad differences in meteorology across the country were captured. The

[48] Masey, Nicola, Scott Hamilton, and Iain J. Beverland. "Development and evaluation of the RapidAir® dispersion model, including the use of geospatial surrogates to represent street canyon effects.", *Environmental Modelling & Software* 108 (2018): 253-263.

[49] https://www.epa.gov/scram/air-quality-dispersion-modeling-related-model-support-programs

location of each of these sites is intended to represent the broad surrounding area, whilst minimising the impact of any local features such as mountains which could unduly influence the meteorology.

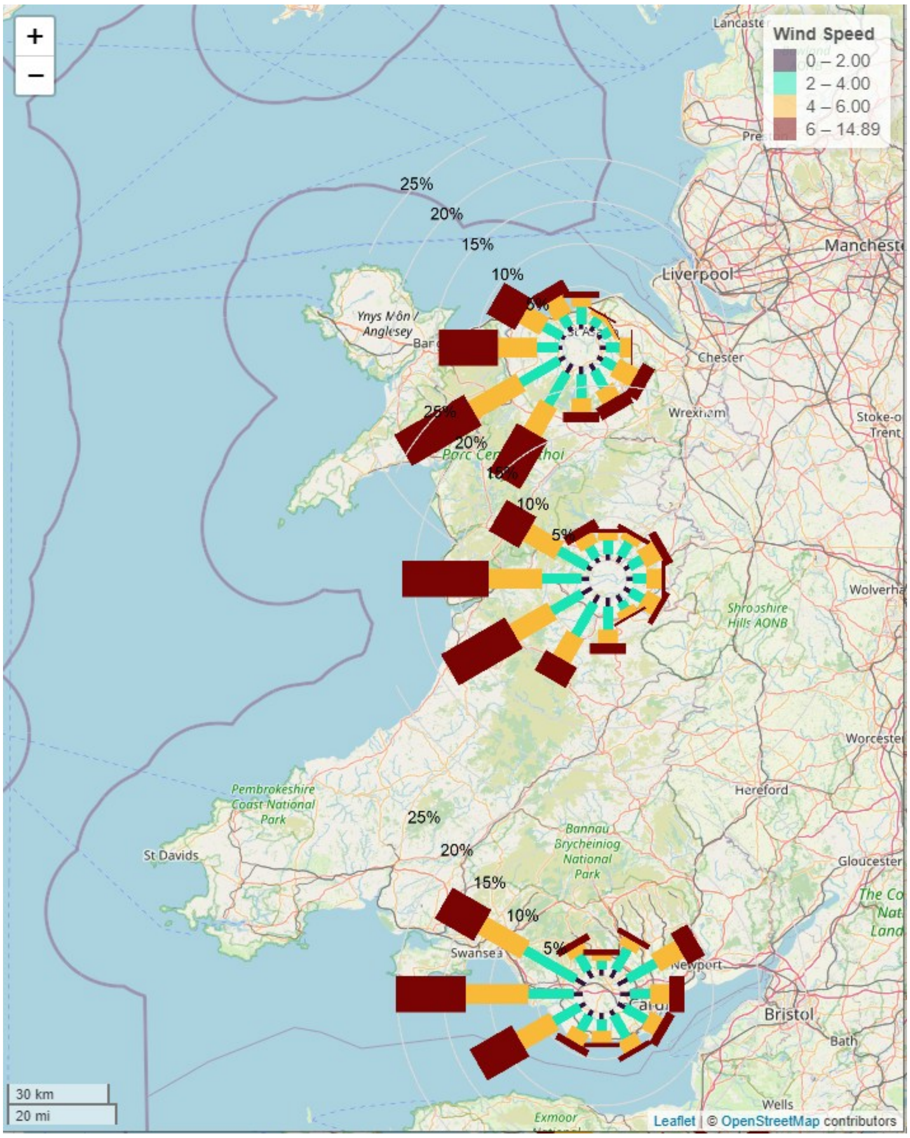
The coordinates of the virtual meteorology stations are provided in Table B6-3.

Table B6-3: Location of virtual meteorology stations used in the RapidAir model

Virtual Station	Latitude	Longitude
North Wales	53.199	-3.519
Mid Wales	52.596	-3.405
South Wales	51.490	-3.435

Wind roses for the meteorological data used in the study are presented in the figure below. The wind rose shows the frequency of winds blowing from each direction over the year. The length of each spoke around the circle is the frequency that the wind blows from that direction.

Figure B6-3: Wind roses as the three virtual meteorological stations used in the study



B.6.2.3 Kernels

The model domain was subdivided into seven zones based on meteorological and topographical characteristics. Dispersion was run separately in each zone to best capture the variations in meteorological conditions across Wales.

As well as integrating different meteorology for different locations, RapidAIR requires estimates of surface roughness and population to ensure the geophysical representativeness of the generated kernel. These variables broadly account for the prevalence of ground level obstacles in the domain (which increases mechanical turbulence), and the scale of convective turbulence generated by the urban heat island effect (which sets a lower limit on atmospheric stability near to ground level in towns and cities due to waste heat).

Each zone uses the meteorology from the virtual station located closest to the zone. The various model inputs used in each zone are shown below.

The population bands selected for each zone are based on those used in the PCM modelling.[50] All kernels have been generated for a model grid height of 1.5m (effectively setting the receptor height in all the model results).

Table B6-4: Kernel parameters used in the RapidAir model.

Zone	Meteorology Station	Surface Roughness (m)	Population	Resolution (m)
Rural North	North Wales	0.5	100	9
Rural Mid	Mid Wales	0.5	100	9
Rural South	South Wales	0.5	100	9
Urban North	North Wales	0.8	25,000	3
Urban South (25,000)	South Wales	0.8	25,000	3
Urban South (100,000)	South Wales	1.0	100,000	3
Urban South (250,000)	South Wales	1.0	250,000	3

B.6.2.4 Street canyons

Building height data for Wales was provided by Ricardo's PCM team, by licence from the Ordnance Survey, and by agreement with Defra.

RapidAIR includes an algorithm which iteratively 'searches' for the presence of street canyons (defined by the aspect ratio of the road width and adjacent building heights). These are represented as polygon geometries which define boundaries where a street canyon contribution to total concentrations is applied to represent recirculation of air when winds are perpendicular to the geometry.

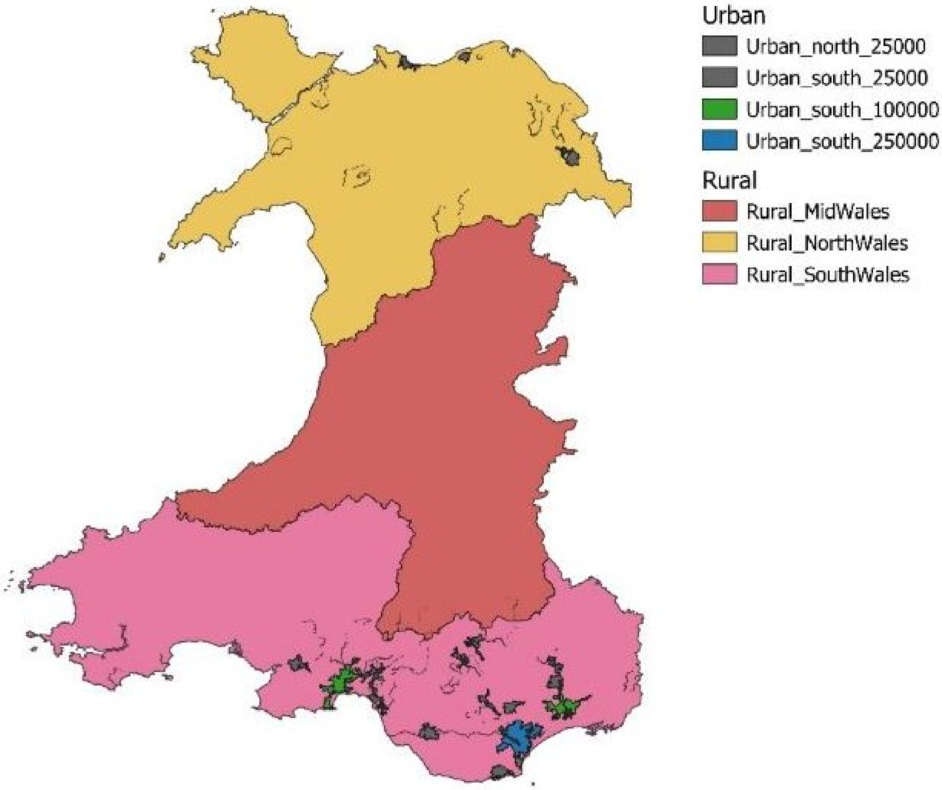
For each of the urban areas, street canyons have been automatically allocated. The locations and geometries of each canyon were checked using satellite imagery and Google Street View.

Inside each of the final canyon geometries, RapidAIR applies the same algorithms as the well-known AEOLIUS street canyon model to calculate the recirculation concentrations within the canyon, which are then added to the RapidAir estimated concentrations.

[50] https://uk-air.defra.gov.uk/assets/documents/reports/cat09/2102111100_2019_PCM_technical_report.pdf

The AEOLIUS model was developed by the UK Meteorological Office, who presented the scientific basis for the model is presented in a series of papers [51, 52, 53, 54)]. The AEOLIUS model shares many common features with the Operational Street Pollution Model (OSPM) which underpins street canyon models included in other road source dispersion models. There are three principal contributions to concentrations estimated by the AEOLIUS model: a direct contribution from the source to the receptor; a recirculating component within a vortex caused by winds flowing across the top of the canyon; and the urban background concentration. The RapidAir model only takes the recirculating component from the canyon model and sums this with the kernel derived concentrations.

Figure B6-5: Zones used in RapidAir modelling



[51] Buckland, A. T., and D. R. Middleton (1999). '*Nomograms for calculating pollution within street canyons*.' Atmospheric Environment 33.7 (1999): 1017-1036.

[52] Middleton, D.R., (1999), '*Development of AEOLIUS for street canyon screening*'. Clean Air 29, 155–161.

[53] Middleton, D.R., (1998), '*Dispersion Modelling: A Guide for Local Authorities, Met Office Turbulence and Diffusion Note number 241*'. The Meteorologcal Office, Bracknell, Bercks.

[54] Middleton, D.R., (1998), '*A New Box Model to Forecast Urban Air Quality: Boxurb*'. Environ. Monit. Assess. 52, 315–335. doi :10.1023/A:1005817202196

B.7 Industrial source air quality modelling

B.7.1 Method

Local scale modelling of emissions from large industrial point sources has been conducted using the USEPA AERMOD dispersion model.[55] AERMOD is the regulatory model in the US, as defined in Appendix W of the Federal Register for dispersion modelling of multiple source types, including point sources which are the focus of this part of the work. The model has been used widely in the UK for environmental permitting, environmental impact assessments, and for local air quality management studies.

Multiple (41) sources at various sites across Wales were modelled in this work. As with many models of this type, the AERMOD system (and its pre-processors like AERMAP) are set up and controlled by text files which contain variables which are read by the model on execution. Manipulating these across multiple different simulations in a documented, reproducible way can be difficult, and QA of the outcomes can be compromised.

To counter this, all model input and control files were created using an automated process programmed in python. This removes much of the manual effort in creating and running AERMAP and AERMOD by building the required input/control text files from a standardised csv input data format containing emission parameters for each source. In this way we can conveniently regenerate all AERMOD runs in a few minutes. This means that changes in emissions (say from the SMT scenarios) across the one or multiple sources in the Welsh domain are applied in a single csv file, which is read to make and run the models. The QA process is very straightforward as the source csv is the single 'point of entry' for all source data, whereas a manually built set of model runs would have multiple sets of files to QA.

In essence, the programmatic workflow was designed from first principles to make the modelling more convenient but also make it completely reproducible and human error is much less likely.

B.7.2 Model description

The AERMOD model is an open-source steady-state Gaussian air quality dispersion model developed for regulatory purposes in the USA. It is by far the most widely used air quality model in the world and comes with a very high level of provenance given its authors are themselves environmental regulators. The model includes physics representing planetary boundary later, plume rise/buoyancy, and handling of complex terrain. The PCM model uses ADMS to model large industrial sources which comprises the same fundamental physics driving the dispersion estimates as AERMOD. We chose AERMOD for this work due to its open-source distribution, its applicability to this use case, well understood incorporation of WRF data, and its ability to produce the gridded outputs we required.

B.7.3 Source and emission data

B.7.3.1 PCM large points sources

NAEI 'Large' Point sources emissions of $PM_{2.5}$ have been modelled explicitly at the local scale using AERMOD.

Emissions release parameters from the Pollution Climate Mapping model (PCM) provided the input data required to model each source using AERMOD. The emission parameters are provided on a per 'PlantID' basis and are equivalent to those used in the PCM2019 model. Mass emissions were derived from the NAEI2020.

The stack parameters provided are the most current set that have been used to model the contribution from stationary point sources in the UK national air quality compliance assessment undertaken for the Defra Modelling Ambient Air Quality programme. Parameters include stack heights, diameters, discharge temperatures, flow rates and pollutant mass emission rates.

These parameters are derived from a mixture of information from permits, authorisations, and data requests compiled over a long period; and where required included Ricardo's (PCM team) own assumptions where data is missing.

A summary of the large point source inventory sites and sources modelled is presented in Table B7-1.

[55] https://www.epa.gov/scram/air-quality-dispersion-modeling-preferred-and-recommended-models#aermod

Table B7-1: Welsh Large Point source inventory sites modelled explicitly using AERMOD.

AERMOD abbreviated Site ID	PCM PlantID	PCM Site name	PCM StackId	NAEI Snap Sector
Aberthaw	6490	Aberthaw	646	30
	8239	Aberthaw B	83	10
Bridgend	7059	Bridgend	1121	30
Chirk	2675	Chirk	467	40
	7137	Chirk	1136a	40
	8364	Chirk	1136b	30
Clydach	6578	Clydach	707a	30
	6578	Clydach	707b	30
	6578	Clydach	708a	30
	6578	Clydach	708b	30
Connahs Quay	14452	Connahs Quay Power Station	1179	10
	14452	Connahs Quay Power Station	1292	10
	14452	Connahs Quay Power Station	1293	10
	14452	Connahs Quay Power Station	1294	10
Ebbw_Vale	10198	Ebbw Vale	864	30
Felinfach	9606	Felinfach	1263a	30
	9606	Felinfach	1263b	30
Llanwern	7055	LLlanwern	49	30
Milford_Haven	9982	Milford Haven	62	30
	9982	Milford Haven	63	30
	9982	Milford Haven	64	30
Padeswood	7013	Padeswood	25	30
Pembroke_Plt	10604	Pembroke Plant	113	10
	10604	Pembroke Plant	114	10
	10604	Pembroke Plant	115	10
	10604	Pembroke Plant	116	10
	10604	Pembroke Plant	117	10
Pembroke_PS	11068	Pembroke Power Station	1064	10
	11068	Pembroke Power Station	1065	10
	11068	Pembroke Power Station	1066	10
	11068	Pembroke Power Station	1067	10
	11068	Pembroke Power Station	1068	10
Port_Talbot	40545	Port Talbot BFG Flaring	1278	40
	40545	Port Talbot BFG Flaring	1300	40
	40538	Port Talbot Blast Furnaces	55	30
	40540	Port Talbot Morfa Coke Ovens	51	10
	40539	Port Talbot Oxygen Furnaces	632	40
	40542	Port Talbot Power Station	1276	30
	40543	Port Talbot Rolling Mill Furnaces	1277	30

AERMOD abbreviated Site ID	PCM PlantID	PCM Site name	PCM StackId	NAEI Snap Sector
	40537	Port Talbot Sinter	56	30
Shotton	8614	Shotton	1137	30
	8614	Shotton	1138	30
	6700	Shotton	1139a	30
	6700	Shotton	1140a	30
	8614	Shotton	1139b	30
	8614	Shotton	1140b	30
Tremorfa	9949	Tremorfa 2	1288	40
Uskmouth_B	8865	Uskmouth B	4	10
Uskmouth_PS	11064	Uskmouth Power Station	1033	10
	11064	Uskmouth Power Station	1034	10

B.7.3.2 Temporal emission profiles

Temporal/time varying emission profiles were applied to each source in AERMOD using relevant SNAP sector specific temporal profiles for each source. The temporal profiles for each sector type were identical to those used in the CMAQ modelling.

B.7.3.3 Unit emissions approach

The model automation process uses a unit emissions approach, whereby each source emission rate is set to 1 $g.sec^{-1}$ and run in isolation from other sources in the dispersion model. Gridded AERMOD outputs are then scaled using actual source emission rates (say, to reflect a scenario driven change) in a post-processing step.

This allows very efficient modelling of test option scenarios where only the emission rate changes (i.e., no re-run of the dispersion model is required which saves considerable computational time). If any other source parameters change or a different meteorological year is required, the dispersion model set up should be amended accordingly and re-run. Once the initial unit emission dispersion simulations have been run, the emission changes to represent a scenario shift across all sources can be applied fairly quickly.

B.7.4 Meteorology

AERMOD utilised hourly sequential surface and upper air profile meteorological data from virtual met station data extracted from the Weather Research and Forecasting (WRF) modelling. The Mesoscale Model Interface Program (MMIF) converts prognostic meteorological model output fields to the parameters and formats required for direct input into dispersion models. The virtual met stations in this case we located at the centre of each industrial site providing a site specific AERMOD ready met datasets.

B.7.5 Terrain and land use

The OS Terrain 50 dataset[56] was used to characterise terrain in the model domain surrounding each dispersion site. The AERMAP terrain pre-processer was then run for each site to extract receptor elevations, source base elevations and hill height scale data.

When modelling with AERMOD, land-use characteristics are usually applied to measured/observed weather data during the meteorological pre-processing step (AERMET). In this case however, all met processing was handled by WRF then converted using MMIF. These modelling processes will have accounted for land use/cover in those calculations; hence land-use was not a required parameter when modelling using AERMOD.

[56] Ordnance Survey (2021) https://www.ordnancesurvey.co.uk/business-government/products/terrain-50

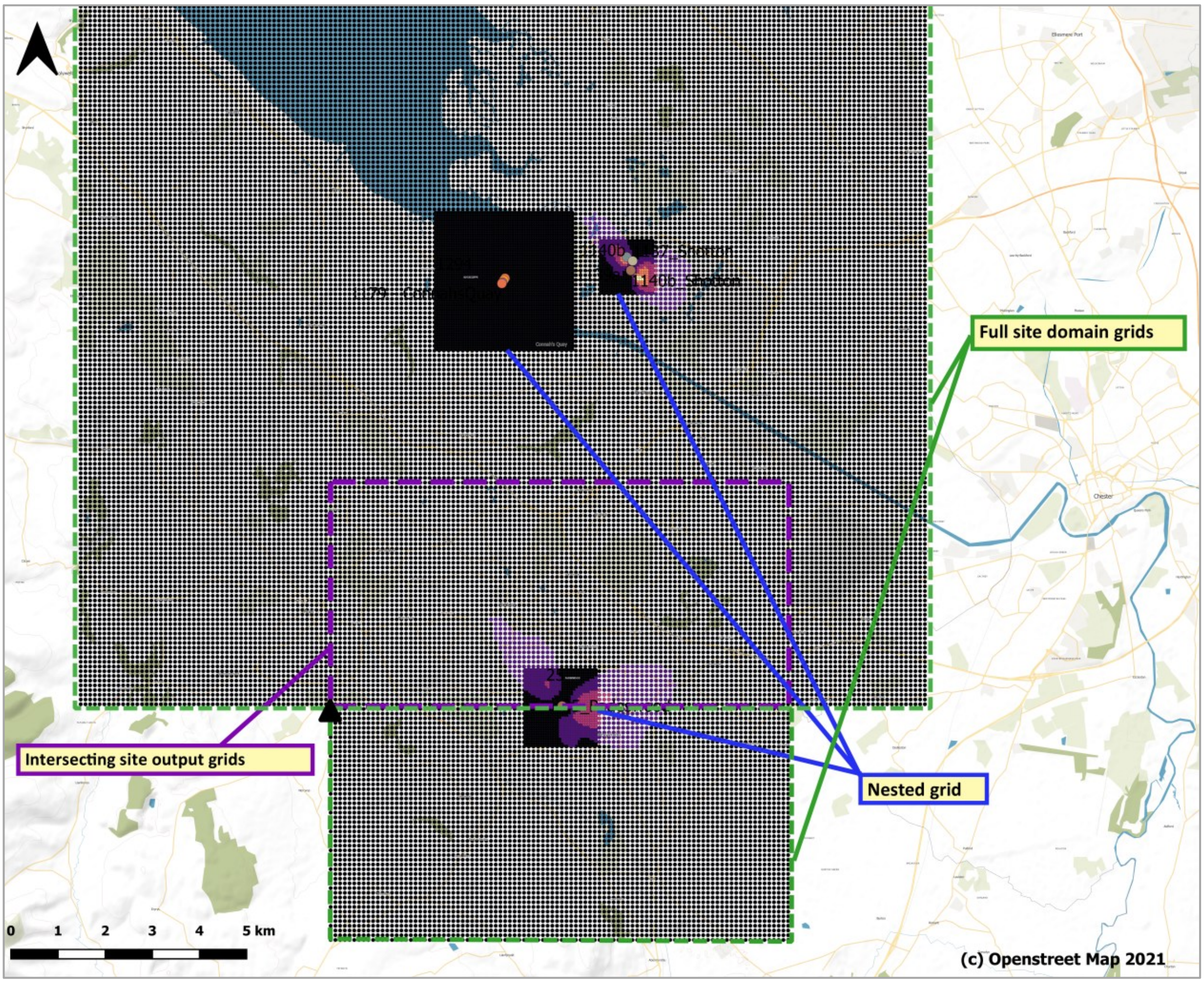
B.7.5.1 Source locations, Model domain and receptor grid resolution

Source location grid references were provided in the PCM large point source dataset. In many cases the grid references in the PCM dataset are representative of the general site/installation location and do not accurately represent the actual stack release point locations. To remedy this, we have refined all the stack location grid references using manual checking of aerial photography and amending the source grid references prior to any further processing.

All grid references were re-projected from the OSGB1936 coordinate reference system (CRS) to WGS82 UTM 30N for modelling using AERMAP and AERMOD. Gridded model outputs were then re-projected back to OSGB1936 as the final step in the post-processing routine.

Model domain centroids were calculated as the central point of all sources at that site. The domain size for each site specific AERMOD model was allocated based on a multiple of the tallest emission source at each site. Model resolution was standardised across all sites (100 m main grid, 50 m nested grid) and grid origins all set to the multiples of 100m to facilitate summing of modelled concentrations during post-processing where there are intersecting output grids. A map aiming to demonstrate this intersection of output grids at the Connahs Quay, Shotton and Padeswood sites is presented in the figure below.

Figure B7-1: Example of intersecting AERMOD output grids at Connahs Quay, Shotton & Padeswood



The constants applied when assigning receptor grid parameters are summarised in the table below.

Table B7-1: AERMOD/AERMAP receptor grid assignment constants

Parameter	Main/full grid	Nested grid
Domain size (from site centre)	120 x max flue height	20 x max flue height
Cartesian grid resolution	100m	50m
Receptor height from ground	1.5m (flagpole receptor)	1.5m (flagpole receptor)

In total, for the current dataset of large point source emitters, pollutant concentrations were modelled at approximately 950,000 gridded receptor points surrounding the various sites modelled. Once intersecting grids were combined this reduced to ~725,000 gridded receptor points. A map showing the AERMOD receptor grid locations relative to the whole of Wales is shown in the figure below.

QA checks were derived in a python program to ensure that the allocated receptor grid sizes were appropriate i.e., to ensure that all predicted process contributions > 1% of the pollutant objective being assessed were built into the post-processing routines. This ensures that there is not an unacceptable drop in modelled concentrations at the edge of each of the domains. A small extract example from the output of this QA test is shown in Figure B7-2.

Figure B7-2: Welsh large point sources - AERMOD output grid locations

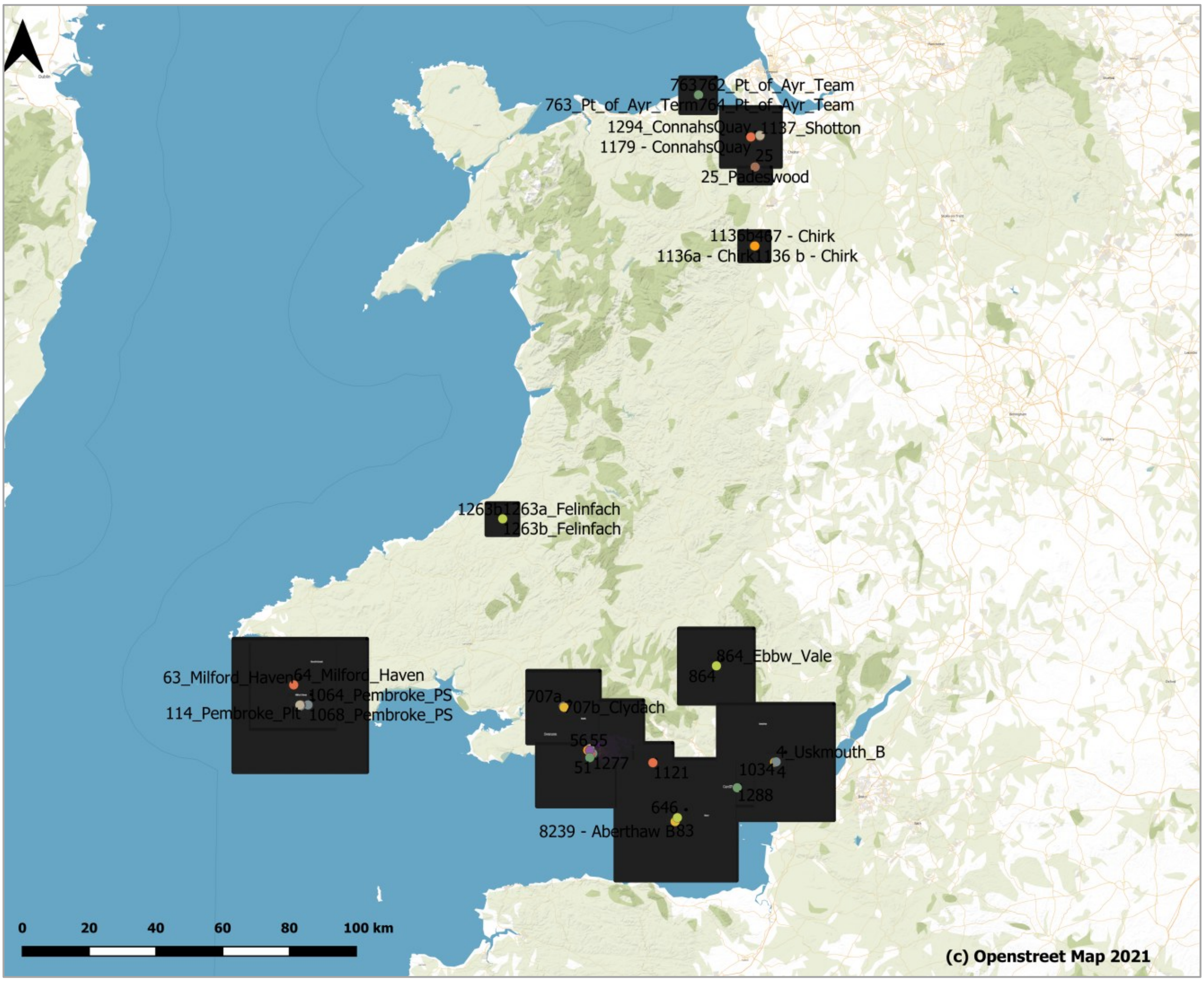


Figure B7-3: AERMOD output grid size QA check – 2019 baseline

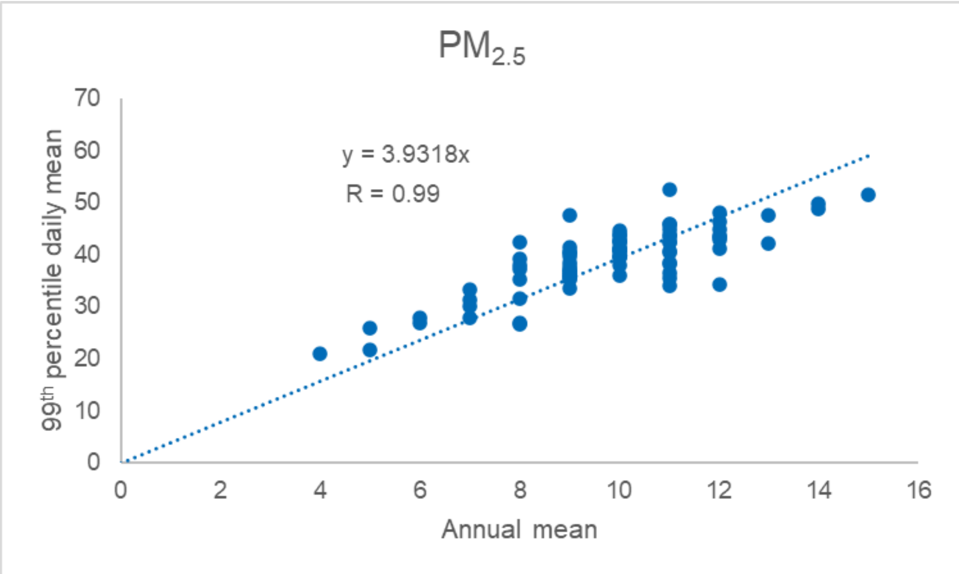
```
Site name:  Aberthaw Source ID:  646 Pollutant emission field name: Scenario_0_2019_PM2p5_emiss
Source emission rate = 0.20277 g/sec
max conc across domain =  0.0345
eastern edge of domain max conc (ug.m-3) =  0.0023
western edge of domain max conc (ug.m-3) =  0.001
North edge of domain max conc (ug.m-3) =  0.0013
South edge of domain max conc (ug.m-3) =  0.0007


Site name:  Aberthaw Source ID:  83 Pollutant emission field name: Scenario_0_2019_PM2p5_emiss
Source emission rate = 0.45718 g/sec
max conc across domain =  0.0045
eastern edge of domain max conc (ug.m-3) =  0.0026
western edge of domain max conc (ug.m-3) =  0.0006
North edge of domain max conc (ug.m-3) =  0.0006
South edge of domain max conc (ug.m-3) =  0.0009


Site name:  Bridgend Source ID:  1121 Pollutant emission field name: Scenario_0_2019_PM2p5_emiss
Source emission rate = 0.70065 g/sec
max conc across domain =  0.0711
eastern edge of domain max conc (ug.m-3) =  0.0227
western edge of domain max conc (ug.m-3) =  0.0097
North edge of domain max conc (ug.m-3) =  0.0088
South edge of domain max conc (ug.m-3) =  0.0026


Site name:  Chirk Source ID:  467 Pollutant emission field name: Scenario_0_2019_PM2p5_emiss
Source emission rate = 2.18671 g/sec
max conc across domain =  0.3397
eastern edge of domain max conc (ug.m-3) =  0.0798
western edge of domain max conc (ug.m-3) =  0.0448
North edge of domain max conc (ug.m-3) =  0.0756
South edge of domain max conc (ug.m-3) =  0.0582
```

B.8 Calculation of Daily Means

The 99th percentile daily mean concentrations were derived for $PM_{2.5}$. Regression equations between annual mean and 99th percentile daily mean measurements were used to predict daily mean concentrations from modelled annual mean results.

2019 measurements from across the UK (data capture of at least 75%) were used in the regression analysis to include all valid, available measurements. Regression statistics indicated strong correlations in ambient measurements, and this method was deemed to be the most reliable way to determine 99th percentile daily mean concentrations. Although it was possible to extract 99th percentile daily mean results from each model's results, combining the model results would be very uncertain, as the 99th percentile was not likely to occur on the same day for each of the models.

Figure B8-1: $PM_{2.5}$ regression equation between annual mean and 99th percentile daily mean concentrations ($\mu g.m^{-3}$)



APPENDIX C MODEL ENSEMBLE VERIFICATION

Model uncertainty in the 2019 base year has been quantified through model verification, comparing measured concentrations of key pollutants at automatic analysers in the Automatic Urban and Rural Network and Welsh Air Quality Network with the total modelled concentrations from the model ensemble for 2019. These automatic sites have robust QA/QC procedures adhering to the requirements of the Air Quality Directive.[57]

The model ensemble verification approach follows the Pollution Climate Mapping (PCM) model[58], as the PCM model is a (UK) regional scale model utilising chemistry models in combination with local modelling. This approach is very similar to the modelling approach used in this study, in which local modelling results have been combined with explicitly modelled background sources including chemistry.

Some sites were excluded from the verification for the following reasons:

- Insufficient data capture (<75%).
- Particulate matter measurements collected using reference equivalent instruments.
- Sites classified as traffic sites which do not have a modelled road within a 50 m radius and kerbside sites.
- Roadside sites in areas that were modelled at 9m resolution, which is not sufficiently fine for verification. The other roadside sites have been verified at 3m resolution, which more precisely reflects how pollutant concentrations change at different distances from the road centre.

The concentrations from the regional (CMAQ), industrial (AERMOD) and roads (RapidAir) models have been combined to produce total concentrations of $PM_{2.5}$.

$PM_{2.5}$ concentrations from the CMAQ results have been adjusted for bound water and metal dust, following the same methodology and input data presented in the previous modelling project for the Welsh Government.

To minimise double counting of the roads and industrial sources in CMAQ and the respective local scale models, the modelled concentrations have been combined using the brute force method described by Isakov et al.[59] To summarise the combination method used, the average concentration in the local model grid within each of the CMAQ cells is deducted from the concentrations within the local model. The following equation describes the combination, where $\overline{RapidAir}$ and $\overline{AERMOD}$ are the average concentrations of these models in the CMAQ grid cell respectively:

$$Total\ concentration = CMAQ + \left(RapidAir - \overline{RapidAir}\right) + (AERMOD - \overline{AERMOD})$$

Following best practice guidance (LAQM.TG22), the relationship between measured and modelled concentrations has been identified. After iteratively reviewing and making changes to the model to improve agreement with measured concentrations, a linear adjustment factor based on this relationship has been derived for each pollutant. This adjustment factor has been applied to all modelled scenarios

Additionally, statistics evaluating the modelled concentrations against the measurements have been presented. As no measurements are available for total VOC, the VOC modelled concentrations have not been adjusted.

The units of all pollutants, except for VOC, are in $\mu g.m^{-3}$. VOC units are in ppb; the modelled concentrations from RapidAir and AERMOD have been converted from $\mu g.m^{-3}$ to ppb to combine them with the concentrations from CMAQ. Average conversion factors were calculated for industrial (0.255) and road (0.289) sectors from VOC speciation data in DUKEMS.

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[57] DEFRA, UK Regions (2016), Improving air quality in the UK: Tackling nitrogen dioxide in our towns and cities: Technical report, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/492901/aq-plan-2015-technical-report.pdf

[58] Ricardo (2024), Technical report on UK supplementary modelling assessment under the Air Quality Standards Regulations 2010 for 2022, Technical report on UK supplementary modelling assessment under the Air Quality Standards Regulations 2010 for 2022 (defra.gov.uk)

[59] Isakov, V., Irwin, J. S., & Ching, J. (2006). '*Using CMAQ for Exposure Modelling and Characterizing the Subgrid Variability for Exposure Estimates*'. Journal of Applied Meteorology and Climatology Volume 46, 1354-1371.

$$VOC\ ppb = VOC\ \mu g.m^{-3} * conversion\ factor$$

C.1 Verification statistics description

Statistics have been presented to describe the agreement between the modelled and measured pollutant concentrations. A description of the statistics[60], along with how to interpret these, are described below:

- Fraction of prediction within a factor of 2 (FAC2)

The FAC2 value of a model ranges from 0 to 1, where a value of 1 represents a model in which all of the modelled data points fall within a factor of two of the measurements.

- Mean Bias (MB)

The MB represents the error in the model and has units the same as the modelled data. A model that perfectly represents the measurements would have a MB value of 0 µg.m^{-3}. The mean bias is represented by the equation below, where M is the modelled concentrations, O is the observed measured concentrations and n is the number of measurement points.

$$\text{Mean Bias} = \frac{1}{n}\sum_{1}^{n}(M - O)$$

- Normalised Mean Bias (NMB)

The normalised mean bias is the mean bias value divided by the average measurement concentrations. The lower this error value the better agreement between the modelled and measured concentrations, and this also has the same units as the measurement data.

$$\text{Normalized Mean Bias} = \frac{\sum_{1}^{n}(M - O)}{\sum_{1}^{n}(O)}$$

- Root Mean Square Error (RMSE)

The RMSE of a model explains the deviation of variance between the measured and modelled concentrations. The RMSE has units the same as the measurement data, and consequently a lower RMSE shows a model with less variation compared to the measurement data.

$$\text{Root Mean Square Error} = \sqrt{\frac{\sum_{1}^{n}(M - O)^2}{n}}$$

- Pearson Correlation Coefficient (r)

The Pearson coefficient measures the linear relationship between the measured and modelled concentrations. This unitless value ranges from 0 to 1, with r values of 1 representing perfectly linear relationships.

$$r = \frac{\sum(M_i - \bar{M})(O_i - \bar{O})}{\sqrt{\sum(M_i - \bar{M})^2 \sum(O_i - \bar{O})^2}}$$

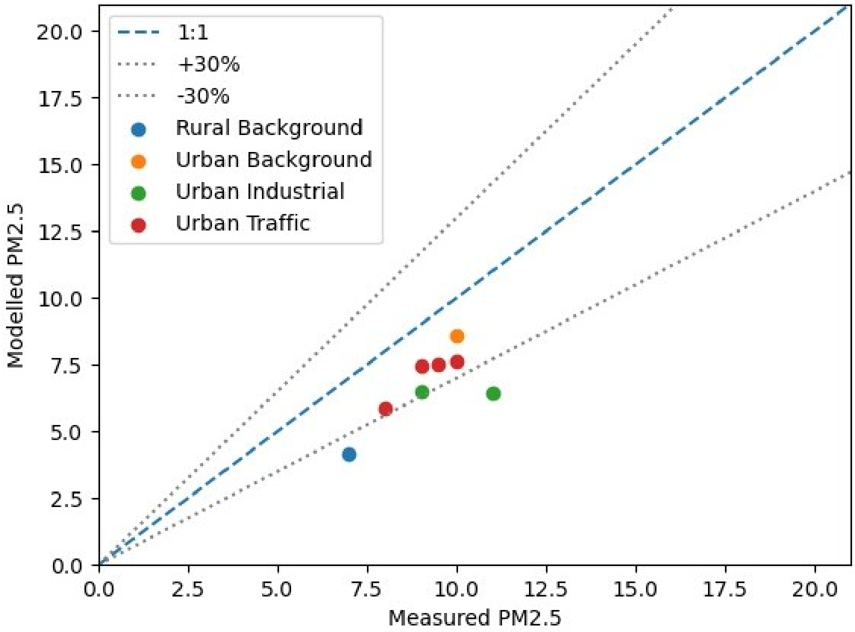
[60] Chang, J. C.; Hanna, S. R, (2004), '*Air quality model performance evaluation*', Meteorology and Atmospheric Physics Volume 87 p167 - 196

C.2 $PM_{2.5}$

The below figure shows the measured and modelled $PM_{2.5}$ concentrations – the model underestimates the $PM_{2.5}$ concentrations. The regression equation between the measured and modelled $PM_{2.5}$ concentrations is as follows.

$$Measured\ PM2.5 = 1.3563 * Modelled\ PM2.5$$

Figure C2-1: Measured vs Modelled annual $PM_{2.5}$ ($\mu g.m^{-3}$) pre-model adjustment



The above adjustment equation was applied, and the plots below show the adjusted modelled concentrations. Table C2-1 shows the measured and modelled $PM_{2.5}$ concentrations pre and post adjustment. After linear adjustment, the modelled and measured concentrations are similar, with the model having a Root Mean Square Error (RMSE) of 1.2 $\mu g.m^{-3}$.

Figure C2-2: Measured vs Modelled $PM_{2.5}$ ($\mu g.m^{-3}$) following linear adjustment of modelled concentrations

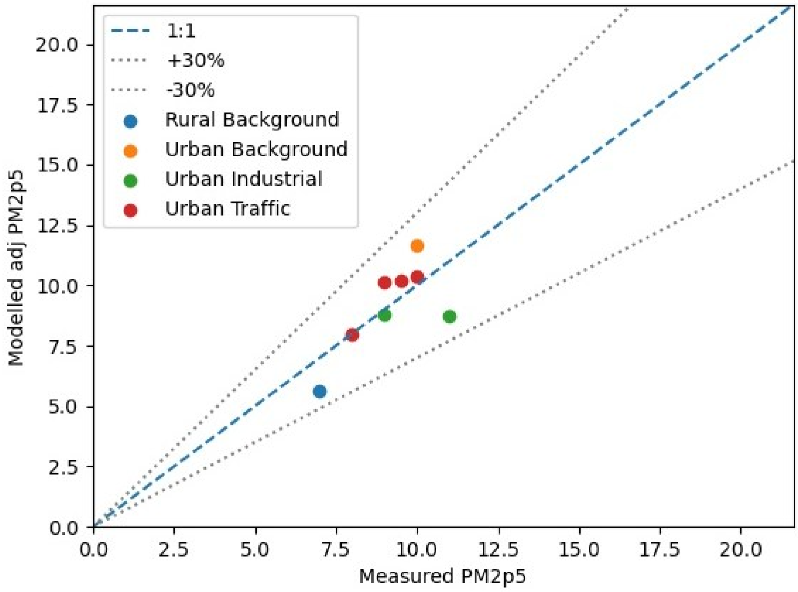


Figure C2-3: Box plot showing measured and modelled $PM_{2.5}$ concentrations for the three different site types

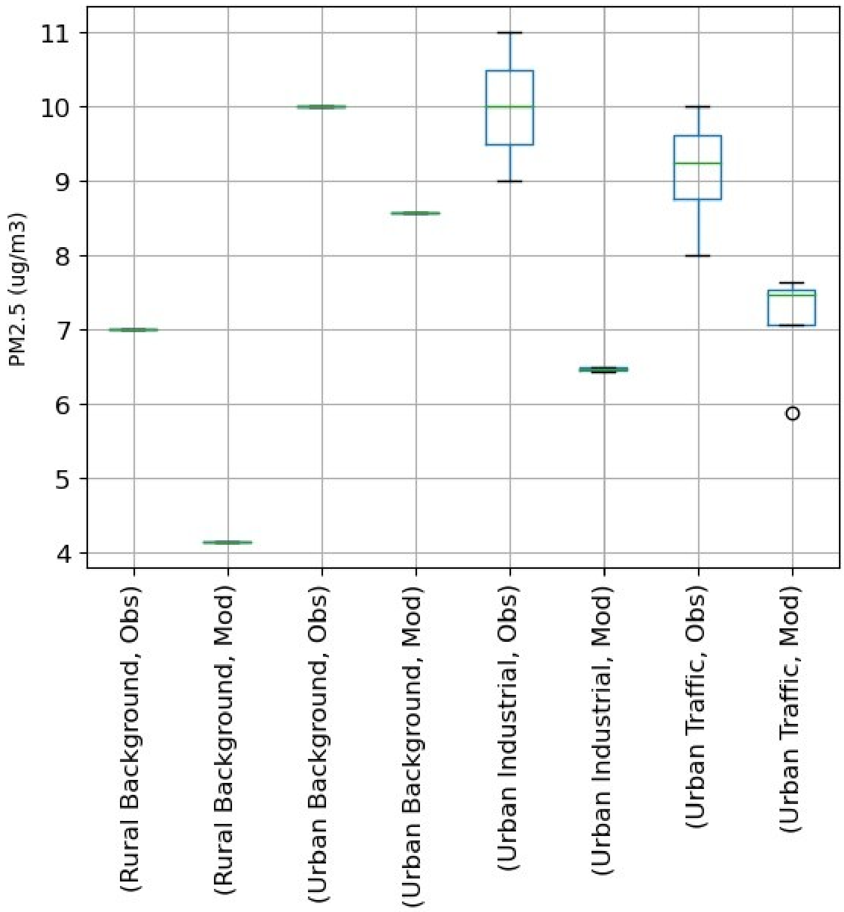


Table C2-1: Measured and modelled $PM_{2.5}$ concentrations pre- and post- model adjustment

Site name	Site type	Measured $PM_{2.5}$ (µg.m^{-3})	Modelled $PM_{2.5}$ raw (µg.m^{-3})	Modelled $PM_{2.5}$ adjusted (µg.m^{-3})
Narberth	Rural Background	7.0	4.1	5.6
Swansea Roadside	Urban Traffic	10.0	7.6	10.4
Swansea Port Tennant Roadside	Urban Traffic	9.5	7.5	10.2
Swansea Morriston Roadside	Urban Traffic	9.0	7.5	10.1
Port Talbot Margam	Urban Industrial	11.0	6.4	8.7
Port Talbot Prince Street 2	Urban Industrial	9.0	6.5	8.8
Wrexham	Urban Traffic	8.0	5.9	8.0
Newport	Urban Background	10.0	8.6	11.6

Table C2-2: $PM_{2.5}$ model evaluation statistics

	No. Sites	Observed Mean (µg.m^{-3})	Modelled Mean (µg.m^{-3})	FAC2	MB (µg.m^{-3})	NMB (µg.m^{-3})	RMSE (µg.m^{-3})	r
Pre	8	9.2	6.8	1.0	2.4	0.6	2.6	0.7
Post	8	9.2	9.2	1.0	0.0	0.0	1.2	0.7

C.3 Uncertainty analysis

C.3.1 Emissions inventory uncertainty

Uncertainties in the UK inventory are associated with the availability and quality of the activity data, the quality of the emission factors and estimation methodologies used in emissions calculations throughout the time series.

Since emission estimates for Wales are intimately linked to those for the UK, areas of high uncertainty are often shared. Sources for which emission estimates are uncertain at the UK level, will also be uncertain for Wales. Sources that are lower uncertainty at the UK level may also be lower uncertainty at the Welsh level, but some will be more uncertain at the Welsh level than at UK level because of uncertainty in estimating the Welsh component of the UK emission. Thus, uncertainty in the Welsh emission estimates for many sources reflects:

1. Uncertainty in the activity data available at the UK, which underpins the UK estimate
2. Uncertainty in the factors and methods used to derive UK emission estimates from the UK activity
3. Uncertainty in estimating what share of the UK emission occurs in Wales

An uncertainty analysis for national estimates of NAEI pollutants has been undertaken using the Tier 1 uncertainty aggregation method as part of the UK inventory submission and are shown below.

Table C3-1: Uncertainty of the NAEI for a sample of key air quality pollutants61

Pollutant	Emissions (kt)	Uncertainty (%)
$PM_{2.5}$	80.1	52%

C.3.2 Interannual variability

In addition to long-term trends resulting from changes in emissions, concentrations are subject to interannual variability as a result of changes in meteorological data.

To quantify this variability, annual mean monitoring data from 2000 to 2023 at monitoring stations in the Welsh Air Quality Network was analysed to provide an indicative analysis. In order to separate interannual variability from long-term trends, annual mean monitored concentrations were detrended following an approach broadly following that taken in Lee et al (2020).[62]

In Lee et al (2020) data was detrended assuming an underlying linear trend; however, in practice long-term trends in concentrations are frequently non-linear over longer time series, being driven by policy and technology changes. To account for this non-linearity, data was detrended through application of a Generalized Additive Model (GAM) using the *mgcv* package in R, following the approach outlined in the OpenAir manual.[63]

The RMSE of residuals from the model was calculated for each site and pollutant. The average RMSE across all relevant sites for each pollutant was then calculated to provide an indication of the average deviation of annual monitored concentrations from the long-term trend.

Table C3-2: Mean monitored concentration, and average RMSE of monitored concentrations from 2000 to 2023 detrended using a Generalized Additive Model

Pollutant	Sites	Annual mean concentration, $\mu g.m^{-3}$		RMSE	RMSE as % of mean
		Mean	Maximum		
$PM_{2.5}$	10	9	12	1.1	12%

The data shows that the average deviation from the long-term trend as estimated using the GAM approach is approximately 10% of the average concentration across the period.

There are inherent uncertainties in this approach, primarily resulting from uncertainties in the fitness of the GAM in describing concentrations discounting the impacts of interannual variability. It should also be noted that this analysis will include uncertainty in measurements.

As such, it is recommended that these results are used as an indicator of average interannual variability in monitored concentrations in Wales rather than being directly applied to the targets.

[61] Ricardo (2021), '*UK Informative Inventory Report (1990 to 2020)*', available at https://uk-air.defra.gov.uk/assets/documents/reports/cat09/2203151456_GB_IIR_2022_Submission_v1.pdf

[62] Lee, J. D., Drysdale, W. S., Finch, D. P., Wilde, S. E., and Palmer, P. I. (2020), '*UK surface NO2 levels dropped by 42 % during the COVID-19 lockdown: impact on surface O3*', Atmos. Chem. Phys., 20, 15743–15759, available from https://doi.org/10.5194/acp-20-15743-2020

[63] Carslaw, D.C. (2019). '*The openair manual — open-source tools for analysing air pollution data. Manual for version 2.6-6*', University of York

APPENDIX D MODEL RESULTS AT MONITORING STATIONS

The appendix below presents annual mean concentrations of $PM_{2.5}$ at monitoring stations for all modelled years and scenarios. These modelled concentrations show no exceedances of the Welsh National Air Quality Objective 25 µg.m^{-3} at monitoring stations for each scenario modelled.

Table D1-1 Predicted annual mean $PM_{2.5}$ concentrations at monitoring stations for all modelled years, baseline (B), medium (M), high (H) and speculative (S) scenarios, µg.m^{-3}

Site Name	2025				2030				2035				2040			
	B	M	H	S	B	M	H	S	B	M	H	S	B	M	H	S
Cwmystwyth	4.2	4.2	4.2	4.1	3.9	3.9	3.9	3.8	3.8	3.7	3.7	3.6	3.7	3.6	3.6	3.6
Cardigan	4.9	4.8	4.8	4.8	4.6	4.5	4.5	4.4	4.4	4.3	4.3	4.2	4.3	4.2	4.2	4.1
Narberth	5.1	5.1	5.1	5.0	4.8	4.7	4.7	4.6	4.6	4.5	4.5	4.4	4.5	4.4	4.4	4.3
Anglesey Llynfaes	4.6	4.6	4.6	4.5	4.3	4.3	4.3	4.2	4.2	4.1	4.1	4.1	4.1	4.1	4.0	4.0
Anglesey Brynteg	4.7	4.6	4.6	4.6	4.4	4.3	4.3	4.3	4.2	4.1	4.1	4.1	4.2	4.1	4.0	4.0
Anglesey Penhesgyn 3	4.9	4.8	4.8	4.8	4.6	4.5	4.5	4.4	4.4	4.3	4.3	4.2	4.3	4.2	4.2	4.1
Anglesey Felin Cafnan	4.7	4.6	4.6	4.6	4.4	4.3	4.3	4.3	4.2	4.1	4.1	4.1	4.2	4.1	4.0	4.0
Swansea Hafod	8.3	8.2	8.2	8.1	7.8	7.4	7.3	7.1	7.4	6.9	6.9	6.7	7.2	6.8	6.7	6.5
Swansea Roadside	9.1	9.0	9.0	8.9	8.5	8.1	8.1	7.9	8.1	7.7	7.6	7.4	8.0	7.5	7.5	7.2
Swansea Cwm Level Park	7.7	7.6	7.6	7.4	7.2	6.8	6.8	6.6	6.8	6.4	6.4	6.1	6.7	6.3	6.2	6.0
Swansea St Thomas	8.6	8.5	8.5	8.4	8.0	7.7	7.7	7.5	7.7	7.3	7.3	7.1	7.5	7.2	7.1	6.9
Swansea Station Court High St	8.3	8.3	8.2	8.1	7.8	7.4	7.4	7.2	7.4	7.0	6.9	6.7	7.3	6.8	6.8	6.5
Swansea Morfa Road	9.3	9.2	9.2	9.0	8.7	8.3	8.2	8.0	8.3	7.8	7.8	7.5	8.1	7.7	7.6	7.3
Swansea Port Tennant Rdside	9.8	9.7	9.7	9.5	9.2	8.9	8.8	8.6	8.8	8.5	8.4	8.2	8.6	8.3	8.2	8.0
Swansea Morriston Rdside	8.9	8.7	8.7	8.5	8.3	7.9	7.9	7.6	7.9	7.5	7.4	7.2	7.8	7.4	7.3	7.0
Marchlyn Mawr	4.3	4.3	4.3	4.3	4.1	4.1	4.1	4.0	4.0	3.9	3.9	3.9	3.9	3.9	3.8	3.8
Port Talbot Margam	7.9	7.8	7.8	7.4	7.4	7.1	7.1	6.7	7.1	6.7	6.7	6.3	6.9	6.6	6.5	6.1
Port Talbot Dyffryn School	8.6	8.4	8.4	7.5	8.1	7.7	7.6	6.8	7.7	7.3	7.2	6.4	7.6	7.1	7.0	6.2
Port Talbot Twll-yn-y-Wal Park	8.6	8.5	8.4	7.7	8.1	7.7	7.7	7.0	7.8	7.3	7.2	6.6	7.6	7.2	7.0	6.4
Port Talbot Little Warren	7.4	7.4	7.3	7.0	6.9	6.7	6.7	6.3	6.6	6.3	6.3	6.0	6.4	6.2	6.1	5.8
Port Talbot Prince Street 2	8.0	7.9	7.9	7.3	7.5	7.2	7.1	6.6	7.1	6.8	6.7	6.2	6.9	6.6	6.5	6.0
Cimla Rd / Victoria Gardens	7.1	7.1	7.0	6.7	6.6	6.4	6.3	6.0	6.3	6.0	6.0	5.7	6.2	5.9	5.8	5.5
Rhondda-Cynon-Taf Broadway	8.9	8.8	8.8	8.6	8.1	7.7	7.6	7.4	7.5	7.1	7.0	6.8	7.2	6.8	6.8	6.5
Rhondda Pontypridd Gelliwastad Rd	8.9	8.8	8.8	8.5	8.1	7.7	7.6	7.4	7.5	7.1	7.0	6.8	7.2	6.8	6.8	6.5
Rhondda Glyncoch Garth Ave	9.3	9.1	9.1	8.9	8.3	7.9	7.8	7.6	7.6	7.2	7.1	6.9	7.4	6.9	6.8	6.6
Twynyrodyn	6.9	6.8	6.8	6.6	6.3	6.1	6.1	5.9	6.0	5.7	5.7	5.5	5.8	5.6	5.5	5.3
Rhondda Mountain Ash	7.7	7.6	7.6	7.4	7.1	6.8	6.8	6.6	6.6	6.3	6.3	6.1	6.4	6.1	6.1	5.9
Cardiff Centre	9.9	9.8	9.7	9.5	9.1	8.6	8.6	8.3	8.6	8.1	8.0	7.7	8.4	7.9	7.8	7.4
Caerphilly White Street	8.5	8.4	8.4	8.1	7.8	7.4	7.3	7.1	7.3	6.9	6.8	6.5	7.1	6.7	6.6	6.3
Nantgarw Road	8.8	8.7	8.7	8.5	8.1	7.7	7.6	7.3	7.6	7.1	7.0	6.7	7.4	6.9	6.8	6.5
Cardiff Newport Road	10.6	10.5	10.4	10.2	9.8	9.4	9.3	9.0	9.3	8.8	8.7	8.4	9.1	8.6	8.5	8.2
Caerphilly Blackwood High St	8.2	8.1	8.0	7.9	7.5	7.1	7.0	6.8	6.9	6.5	6.5	6.2	6.7	6.3	6.2	6.0
Caerphilly Fochriw	6.0	5.9	5.9	5.8	5.5	5.3	5.3	5.2	5.1	5.0	4.9	4.8	5.0	4.8	4.8	4.7

Site Name	2025				2030				2035				2040			
	B	M	H	S	B	M	H	S	B	M	H	S	B	M	H	S
Caerphilly Islwyn Rd Wattsville	6.9	6.9	6.8	6.7	6.3	6.1	6.0	5.9	6.0	5.7	5.6	5.4	5.8	5.5	5.5	5.3
Aston Hill	5.1	5.0	5.0	5.0	4.7	4.6	4.6	4.5	4.4	4.3	4.3	4.3	4.3	4.3	4.2	4.2
Newport M4 Junction 25	12.4	12.3	12.3	12.1	11.7	11.2	11.2	10.9	11.3	10.7	10.7	10.4	11.1	10.6	10.5	10.2
Wrexham	6.9	6.8	6.8	6.7	6.3	6.2	6.1	6.1	6.1	5.9	5.8	5.7	5.9	5.7	5.7	5.6
Chepstow A48	8.2	8.1	8.1	8.0	7.5	7.4	7.3	7.2	7.2	7.0	6.9	6.8	7.1	6.8	6.8	6.7
Hafod-yr-ynys Roadside	7.8	7.7	7.7	7.6	7.2	7.0	6.9	6.8	6.8	6.6	6.5	6.4	6.7	6.4	6.4	6.2
Cwmbran	7.8	7.7	7.7	7.5	7.1	6.8	6.8	6.6	6.7	6.4	6.3	6.1	6.5	6.2	6.1	5.9
Newport	10.1	10.0	10.0	9.8	9.4	8.9	8.9	8.6	8.9	8.4	8.3	8.0	8.7	8.2	8.1	7.8
V Glamorgan Windsor Rd	9.1	9.0	9.0	8.7	8.4	8.1	8.0	7.7	7.9	7.6	7.5	7.2	7.8	7.4	7.3	7.0

APPENDIX E HEALTH IMPACT AND ECONOMIC ASSESSMENT METHODOLOGIES

Previous work commissioned by the Welsh Government presents a detailed outline of the methodologies undertaken to assess health impacts, and costs and benefits of the different air quality scenarios in Wales. The analysis and outputs presented in this report build on this work as follows.

Methods

We have built on the previous work by taking the following steps.

- **Step 1**: Mapping and screening of relevant measures and developing new scenario-based bundles or packages.
- **Step 2:** Update of the analysis of costs, which will include costs, cost savings and monetised greenhouse gas emission impacts disaggregated if possible.
- **Step 3:** Update of the benefit analysis, focussing on non-market health and wellbeing benefits (that is, monetised Quality-Adjusted Life Year gains and preventable deaths), as well as potential health care (or NHS) savings and productivity costs avoided (or gains) due to reductions in sickness absence.
- **Step 4:** Qualitative analysis and considerations concerning the stakeholders affected, especially concerning those that may be affected by the costs.
- **Step 5:** Updating the 2030, 2035, and 2040 comparison of costs and benefits and calculation of Net Present Values over the period of assessment (2025-2040).

These steps are further specified below. Section 1.3.2 sets out the limitations and assumptions associated with this proposed methodology.

Step 1: Mapping and screening of relevant measures

The list of measures considered in previous stages of work have been reviewed and matched against the Air Quality Target Scenarios to develop new scenario-based bundles of measures tackling $PM_{2.5}$ pollution. The selection of measures presents a reasonable pathway to work towards and/or achieve each of the **Air Quality Target Scenarios** identified and under consideration.

The table below contains the key assumptions associated with the air pollutant concentrations that might be achieved across these Air Quality Target Scenarios for $PM_{2.5}$.

Table E1.1 Change (i.e., decrease when compared to the baseline) in air pollutant concentration across scenarios (µg/m^3) for $PM_{2.5}$

Scenarios	2030	2035	2040
1. 11 µg/m^3 by 2030 (‘medium’)	0.23	0.23	0.23
2. 11 µg/m^3 by 2035 (‘medium’)	0.23	0.25	0.25
3.1. 10 µg/m^3 by 2035 (‘medium’)	0.23	0.25	0.25
3.2. 10 µg/m^3 by 2035 (‘high’)	0.26	0.29	0.29
3.3. 10 µg/m^3 by 2035 (‘speculative’)	0.43	0.46	0.46
4.1. 10 µg/m^3 by 2040 (‘medium’)	0.23	0.25	0.25
4.2. 10 µg/m^3 by 2040 (‘high’)	0.26	0.29	0.31
4.3. 10 µg/m^3 by 2040 (‘speculative’)	0.43	0.46	0.49

Step 2: Updating the analysis of costs

We have reorganised and update the evidence to estimate the costs of the implementation of measures under these Air Quality Target Scenarios for $PM_{2.5}$ by mapping, screening and reorganising the costing analysis shown in studies supporting the development of the Air Quality Targets.

An in-depth assessment of the potential cost of implementing each policy measure in terms of capex, opex (fuel and non-fuel) and monetised greenhouse gas (GHG) emission impacts was undertaken in supporting the studies. The results show social cost savings that capture some of the environmental benefits of the measures considered.

The analysis separates the capex and opex impacts (costs and cost-savings) from the monetised GHG emission impacts for each measure under consideration; and aggregated the impacts across each cost category and for the relevant bundle of measures matched against each Air Quality Target Scenario, to develop updated total costs for each Scenario.

Step 3: Updating the analysis of benefits

Non-market health and wellbeing benefits have been estimated from the population-weighted mean concentration changes generated by the detailed dispersion modelling (see tables A2.1 and A2.2). For clarification, new dispersion modelling has not been conducted; instead, the change in population-weighted mean concentration between the baseline scenario and Target Scenarios for $PM_{2.5}$.

The estimated population-weighted mean concentration changes resulting from the implementation of the new bundles or packages of measures by Scenario have been used to update our health impact modelling and the resulting monetised health benefits. The focus will be to capture the benefits associated with reducing the air concentration of the target pollutant (thus limiting the analysis and capture of co-benefits).

With regards to the impacts on environmental health, this assessment has not included monetised benefits to ecosystem services as previous research has found that only small net benefits are expected as a result of the impact upon ecosystem services. However, it should be acknowledged that there will be additional benefits for ecosystems from reduced levels of secondary inorganic aerosols (e.g. via emissions of Nox, SO_2 and NH_3).

Moreover, additional benefits have been estimated. These include healthcare cost savings (i.e., NHS savings) and productivity benefits through a reduction in sickness absence.

- For NHS budgetary savings (or costs), we drew on Public Health England's 2018 study "Estimation of costs to the NHS and social care due to the health impacts of air pollution"[64] to develop evidence-based assumptions of the healthcare costs (including the sum of primary, secondary and medicine costs) attributable to a typical case of ill health across the endpoints in scope. These costs were uplifted to account for price inflation. Healthcare costs per case were then multiplied by number of statistical cases avoided from improved air quality to estimate potential NHS budgetary savings.
- For productivity impacts (or benefits in this case, from reducing sickness absence), we conducted this analysis in three steps. Firstly, we developed evidence-based assumptions of the typical sickness absence for a worker that is diagnosed with a case of illness in scope of this study (e.g., IHD). Secondly, we monetised marginal worker productivity, by assuming this to be equivalent to average hourly wages and salaries in Wales. In this case, we did not include non-market impacts, as those are primarily captured and could overlap with estimates of willingness to pay to avoid illness (see non-market health benefits above). Finally, sickness absence per case (days/case), marginal productivity (GBP/day), and number of cases avoided are multiplied to estimate the scale of total productivity costs avoided, that is, the productivity benefits resulting from improved air pollution.

Step 4: Qualitative analysis of the affected stakeholders

In addition, we have provided a brief, qualitative assessment of the stakeholders that could be most affected by the estimated impacts, especially the costs (public versus private organisations across sectors). The evidence available is limited, and thus, a quantitative disaggregation has not been possible.

Step 5: Comparison of costs and benefits and calculating the Net Present Value

Finally, the costs and benefits have been compared over the appraisal period and discounted in line with the UK Green Book[65] guidance and as set out supporting studies to produce the Net Present Social Value of Costs, Benefits and Net Benefits, as well as the Benefit-Cost Ratio for each Scenario for comparison.

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[64] PHE (2018). "Estimation of costs to the NHS and social care due to the health impacts of air pollution". Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/836720/Estimation_of_costs_to_the_NHS_and_s ocial_care_due_to_the_health_impacts_of_air_pollution.pdf

[65] https://www.gov.uk/government/publications/the-green-book-appraisal-and-evaluation-in-central-government/the-green-book-2020

Limitations

The detailed multi-pollutant emissions scenario assessments for Wales provided the basis for single pollutant cost-benefit assessments in relation to $PM_{2.5}$. There are recognised constraints associated with this approach, for example, bundles of measures affecting a range of pollutants were modelled to provide robust projections of concentration upon measure implementation, considering the influence of external factors such as weather, terrain and external sources from the UK and rest of the world. Ideally, the emissions inventory estimates and dispersion models for specific bundles of measures targeted at single pollutants would be updated to align with these new scenario definitions.

Tasks considered in this specification would expand upon this and cover additional categories of impact, strengthening the CBA. For example, when considering $PM_{2.5}$ targets and associated measures, our existing modelling work does not produce an assessment of co-benefits e.g., associated NO_2 emission savings. It has not been possible to quantify these, however, we have pointed out that additional benefits might be delivered qualitatively. The methodology does not consider the effects of secondary pollutant interactions (for example, as an illustration, such as the effect of ammonia emissions on $PM_{2.5}$ concentrations).

Sensitivity analysis outputs

This section presents the results of sensitivity analysis on the HIA and the CBA outputs. HIA sensitivities are primarily based on the quantification of uncertainties associated with concentration response functions. Assumptions embedded in other costs and benefits of Air Quality Targets were tested within +/- 20% of the central estimates.

The following tables explore the sensitivities to assumptions for the human health impacts (e.g., QALYs gained, deaths avoided, illness prevented, and healthcare activity reduced) and the benefit cost-ratios across scenarios for $PM_{2.5}$.

Table E1.2 Sensitivity analysis of average annual health impacts across $PM_{2.5}$ scenarios over the period 2025-2040[66] (central [low-high] sensitivities)

Impact	Indicators and units	Scenario 1: 11 µg/m3 by 2030 ('medium')	Scenario 2: 11 µg/m³ by 2035 ('medium')	Scenario 3.1: 10 µg/m3 by 2035 ('medium')	Scenario 3.2: 10 µg/m3 by 2035 ('high')	Scenario 3.3: 10 µg/m3 by 2035 ('speculative')	Scenario 4.1: 10 µg/m3 by 2040 ('medium')	Scenario 4.2: 10 µg/m3 by 2040 ('high')	Scenario 4.3: 10 µg/m³ by 2040 ('speculative')
Quality-Adjusted Life Years gained	LYs gained from deaths avoided	420 [315-472]	433 [325-487]	433 [325-487]	497 [373-559]	893 [670-1005]	433 [325-487]	500 [375-562]	897 [673-1010]
	QALY gained from morbidity avoided	271 [83-498]	279 [86-514]	279 [86-514]	320 [99-589]	576 [178-1,060]	279 [86-514]	322 [99-593]	579 [179-1,065]
	Total QALY gains	690 [398-970]	712 [411-1,001]	712 [411-1,001]	817 [471-1,148]	1469 [847-2,064]	713 [411-1,001]	822 [474-1,155]	1476 [852-2,074]
Deaths avoided (mortality)	Statistical deaths avoided	39 [29-43]	40 [30-45]	40 [30-45]	46 [34-51]	82 [62-92]	40 [30-45]	46 [35-52]	83 [62-93]
Illness prevented (morbidity)	Statistical cases avoided of asthma	12 [6-20]	12 [6-21]	12 [6-21]	14 [7-24]	25 [13-42]	12 [6-21]	14 [7-24]	25 [13-43]
	Statistical cases avoided of COPD	3 [3-3]	3 [3-3]	3 [3-3]	3 [3-4]	6 [6-6]	3 [3-3]	3 [3-4]	6 [6-6]
	Statistical cases avoided of Lung Cancer	4 [2-6]	4 [2-6]	4 [2-6]	5 [2-7]	9 [4-13]	4 [2-6]	5 [2-7]	9 [4-13]
	Statistical cases avoided of Stroke	8 [0-19]	9 [0-20]	9 [0-20]	10 [0-23]	18 [0-41]	9 [0-20]	10 [0-23]	18 [0-41]
	Statistical cases avoided of IHD	7 [0-16]	7 [0-16]	7 [0-16]	8 [0-19]	15 [0-33]	7 [0-16]	8 [0-19]	15 [0-33]
	Statistical cases avoided of Diabetes	33 [7-59]	34 [7-61]	34 [7-61]	39 [8-70]	70 [14-125]	34 [7-61]	39 [8-70]	70 [14-126]
Healthcare activity reduced	Respiratory and/or cardiovascular hospital admissions prevented	16 [2-38]	17 [2-40]	17 [2-40]	19 [2-46]	35 [3-82]	17 [2-40]	19 [2-46]	35 [3-82]

[66] Please note that Scenarios 2 and 3.1 showcase the same HIA results. This is because they follow the same pathway, and the difference in the policy scenario is the target and the likely levels of compliance that could be achieved across LSOAs. Under Scenario 2, it is estimated that 100% of LSOA's might meet the target, whereas it is estimated that 98.9% of LSOA's might be able to meet this target under Scenario 3.1.

The sensitivity of assumptions underpinning the NPV of costs, benefits, net benefits and the benefit cost-ratios across scenarios for $PM_{2.5}$ were also explored. These results are presented in the table below.

Table E1.3 Sensitivity analysis of Net Present Value of costs, benefits, net benefits and benefit-cost ratio by Air Quality Target Scenario for $PM_{2.5}$, discounted to 2025 (billions of GBP in 2025 prices, negative values representing costs) (central [low-high] sensitivities)

Indicators	Scenario 1: 11 µg/m3 by 2030 (‘ medium’)	Scenario 2: 11 µg/m³ by 2035 (‘ medium’)	Scenario 3.1: 10 µg/m3 by 2035 (‘ medium’)	Scenario 3.2: 10 µg/m3 by 2035 (‘ high’)	Scenario 3.3: 10 µg/m3 by 2035 (‘ speculative’)	Scenario 4.1: 10 µg/m3 by 2040 (‘ medium’)	Scenario 4.2: 10 µg/m3 by 2040 (‘ high’)	Scenario 4.3: 10 µg/m³ by 2040 (‘ speculative’)
Costs (billions)	-3 [-4 - -2]	-7 [-8 - -5]	-7 [-8 - -5]	-10 [-12 - -8]	-16 [-19 - -13]	-12 [-14 - -9]	-17 [-21 - -14]	-26 [-31 - -20]
Benefits (billions)	16 [12 - 19]	24 [19 - 29]	24 [19 - 29]	38 [30 - 46]	70 [55 - 85]	27 [22 - 33]	43 [34 - 52]	76 [61 - 93]
Net benefits (billions)	13 [9 - 17]	17 [11 - 24]	17 [11 - 24]	28 [18 - 38]	54 [36 - 72]	16 [7 - 24]	26 [13 - 39]	51 [30 - 72]
Benefit Cost Ratio (BCR)	5.1 [3.3 - 7.9]	3.6 [2.3 - 5.4]	3.6 [2.3 - 5.4]	3.8 [2.5 - 5.7]	4.3 [2.9 - 6.6]	2.3 [1.5 - 3.5]	2.5 [1.6 - 3.8]	3.0 [2.0 - 4.5]

All $PM_{2.5}$ Air Quality Target Scenarios have a benefit-cost ratio that is greater than 1, that is, estimated benefits are estimated to surpass the costs even when sensitivities to key assumptions are tested (and despite the short appraisal period 2025-2040). This suggests that any of these Air Quality Target Scenarios and pathways to achieving them will likely benefit Welsh society. The BCR remains highest for Scenario 1 across all sensitivities, followed by Scenario 3 (average), Scenario 2 and Scenario 4 (average). However, the scale of benefits is higher across Scenarios 3 and 4. Scenarios 4 (Average) have lower BCR than Scenarios 3 (average) primarily due to the period of appraisal (2025-2040), which does not account for the additional and relatively higher benefits that could result from Scenario 4 (average) from 2040 onwards.

APPENDIX F DISTRIBUTIONAL ANALYSIS

This section presents distributional analysis of health impacts. Distributional analysis estimates how the impacts of policy scenarios are shared across areas with a low/high proportion of different demographics which are most sensitive to prolonged exposure to an air pollutant. While the cost-benefit analysis includes the health impacts of the policy scenarios on society as a whole. This section provides a summary of the approach and findings.

This section explores if the scenarios have a disproportionate impact on different society groups, namely the elderly, young children, or areas of deprivation.

F.1 Summary of approach

The distributional analysis has been performed based on the methodology set out in the Department for Transports (DfT) TAG unit A4-2 guidance document.[67] The distributional analysis has evaluated the share of benefits of targeted action to reduce exposure to $PM_{2.5}$ pollutant. The DfT methodology consists of three steps: Screening, Assessment and Appraisal which relate to the distributional impacts of air quality.

The distributional analysis has not undertaken a screening assessment which is designed to evaluate whether a full assessment would be required. The screening step was not undertaken as it is already known that the evaluated policies will have a significant impact on air quality across Wales.

The distributional analysis has included a full assessment of the distribution of the impacts on air quality. This stage included the following three components:

1. Understanding how concentrations $PM_{2.5}$ change spatially across Wales by each scenario.
2. Understanding the relationship between changes in the concentration of an air pollutant and the population demographics residing within these spatial regions.
3. Review of demographics living in LSOA's where air quality exceeds the WHO 2030 threshold ambitions.

Component 1 was completed by aggregating the air pollutant maps produced through the air quality modelling component of the study. These maps were overlayered by Lower Super Output Area (LSOA) spatial maps. LSOA's are spatial zones that are defined by population size (typically between 1000 – 3000 residents) which are commonly used in national datasets which aggregated demographic data.[68] A data table was produced to detail the average concentration of each air pollutant for each LSOA in Wales for each scenario. The change in pollutant concentration for each scenario was calculated by deducting the average concentration for each implementation scenario from the baseline scenario for the same year (e.g. Medium 2030 scenario – baseline 2030 scenario). Maps showing the spatial changes for each air pollutant for each scenario was produced from this exercise. These maps show how each scenario changes the concentration of an air pollutant across Wales.

Component 2 was undertaken by combining the tabulated output from component 1 with demographic data. As recommended by DfT TAG guidance, an evaluation of how the concentration of each pollutant changes in areas with a low/high level of income distribution and low/high proportion of children (under the age of 16) was undertaken. Additionally, an analysis on the impacts in areas with a low/high proportion of elderly citizen (those over the age of 65) was also undertaken in recognition of the potential health impacts caused by any deterioration in air quality on these citizens. The analysis also included an assessment of how changes in each type of air pollutant corresponds to areas with a low/high proportion of BAME citizens, this analysis was undertaken using Medium Super Output Areas (MSOAs) as statistics on the proportion of BAME residents living in the higher resolution LSOAs was not available. Each LSOA/MSOA within the database was assigned a quintile grouping value for each demographic type and a high-level analysis was undertaken to understand the relationship between changes in the concentration of an air pollutant and spatial areas with a low/high proportion of each demographic.

[67] Document can be downloaded from: https://www.gov.uk/government/publications/tag-unit-a4-2-distributional-impact-appraisal

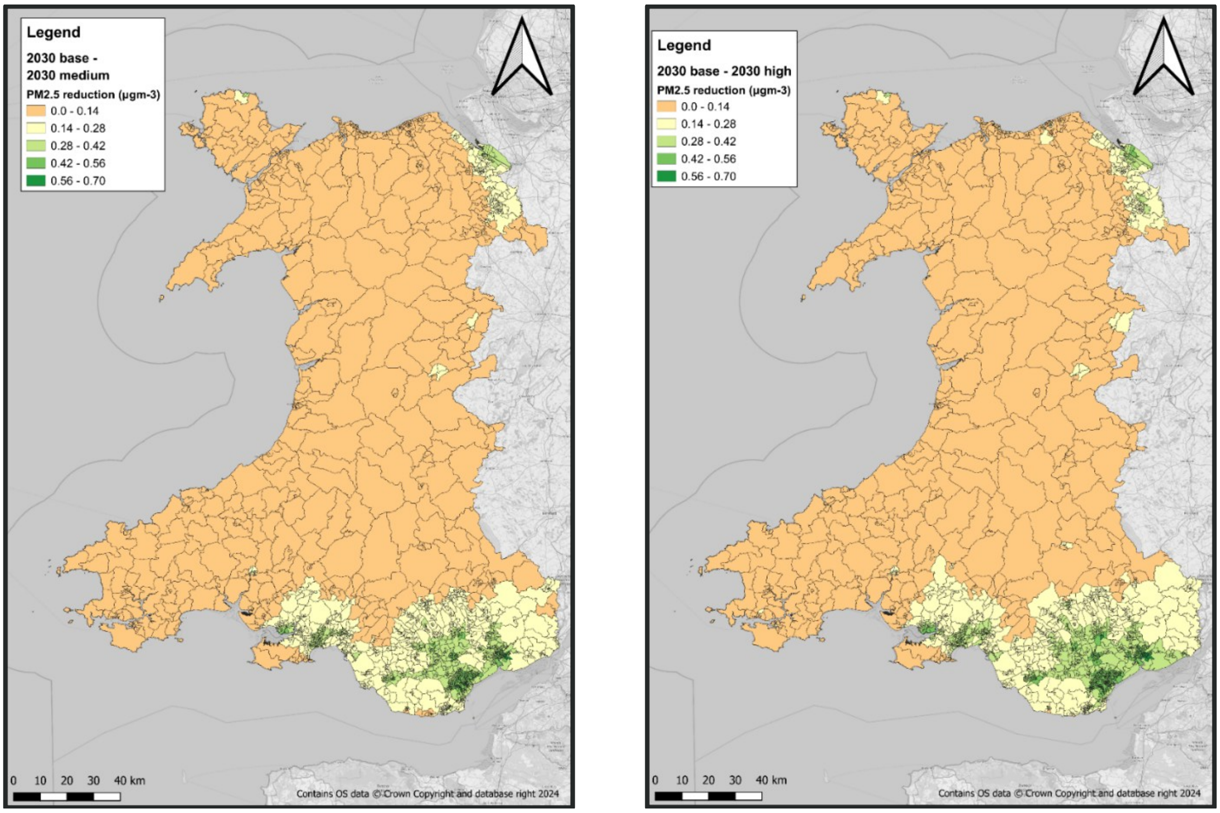
[68] More information on LSOAs is available from: https://www.ons.gov.uk/methodology/geography/ukgeographies/censusgeographies/census2021geographies

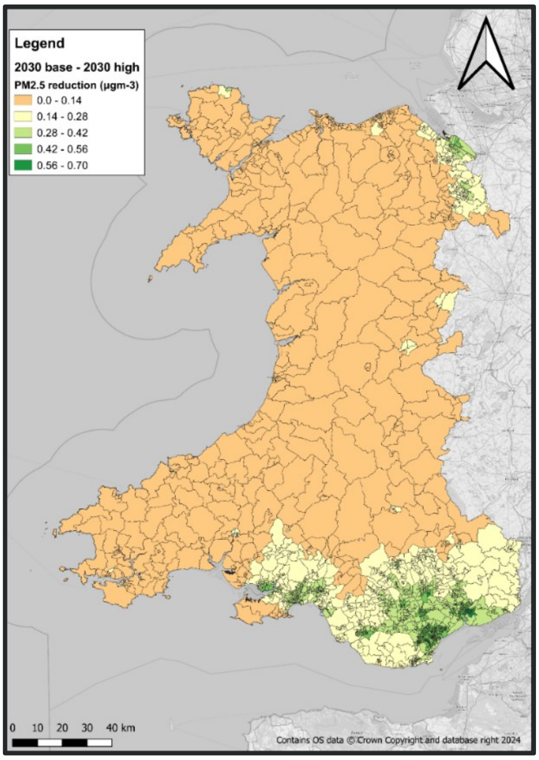
Component 3 is an assessment that is not detailed in the DfT TAG guidance documents. The aim of this analysis is to understand whether there is a pattern between the LSOAS which have been identified to be in non-compliance with the WHO pollutant threshold limit and the same demographics considered in component 2. This component was achieved by extracting the highest predicted value of each pollutant from the air quality modelling for each LSOA and comparing this value against the WHO 2030 targets. The process for component 2 was then repeated for LSOAs that were identified to be non-compliant with the 2030 targets for each scenario.

F.2 Summary of results

The results from component 1 are shown in the map below. The maps show that in areas with higher population densities the concentration reductions realised are higher. This is the case for all scenarios in 2030.

Figure F2-1 Spatial representation of pollutant concentrations reductions across Wales per scenario





With regards to component 2; Table F2-4 shows a summary of the findings from the distributional impact assessment. In this analysis Quintile groups 1 to 5 represent a most deprived (1) to least deprived (5) range of citizens in the IMD (income deprivation) group. In the case of the children and elderly groups the Quintile groups 1 to 5 represent the LSOAs with the lowest (1) to highest (5) proportion of each demographic.

Table F2-4 Summary of the relative change in pollutant concentration (%) by each scenario from the 2030 BAU baseline

Scenario	Social indicator	Quintile 1	Quintile 2	Quintile 3	Quintile 4	Quintile 5	Spearman rank correlation coefficient
Medium	IMD	4.4	3.2	3.3	3.4	3.1	-0.1
High	IMD	4.4	4.8	3.3	3.4	4.6	-0.1
Speculative	IMD	7.4	6.3	6.7	6.8	6.2	-0.1
Medium	Children	3.3	3.4	3.2	3.1	4.3	0.3
High	Children	3.3	3.4	4.8	4.6	4.3	0.3
Speculative	Children	6.7	6.8	6.3	7.7	7.2	0.3
Medium	Elderly	4.0	4.6	3.2	3.4	3.6	-0.5
High	Elderly	5.3	4.6	4.8	3.4	3.6	-0.5
Speculative	Elderly	8.0	7.7	6.3	6.9	5.5	-0.4
Medium	Ethnicity	2.1	3.0	3.1	3.6	4.6	0.61
High	Ethnicity	2.4	3.4	3.5	4.0	5.2	0.61
Speculative	Ethnicity	4.3	5.8	6.0	6.6	8.2	0.52

The distributional assessment has found that:

- There is not an overall linear trend showing a relationship between the level of pollutant reduction and quintile groups in the Medium or High scenarios with consideration to the distribution of impacts across areas with a low to high proportion of income deprived citizens or children.
- There is a linear trend which shows a relationship between the level of pollutant reduction and elderly quintile groups in the Medium and High scenarios. The data shows that the level of pollutant reduction tends to reduce as the proportion of elderly citizens increases. This observation is likely to as elderly residents tended to live in the more rural areas of Wales where averaged pollutant concentrations were lowest. The measures introduced by each scenario would therefore have the lowest impact in these areas and therefore the lowest percentage reduction of each pollutant.
- The analysis also found that there is a correlational relationship between the level of $PM_{2.5}$ pollutant and the proportion of BAME citizens in an MSOA. The data shows that the level of reduction tends to increase as the proportion of BAME citizens increases.

The analysis undertaken for component 3 found that:

- 85% of all LSOAs present within Wales are predicted to have at least one location which exceeds the WHO standard for $PM_{2.5}$ in 2030 in the baseline scenario, this value falls to 79% should the speculative scenario be implemented.
- The modelling shows that the impact of each scenario is not predicted to alter the proportional share of the number of LSOAs with an exceedance of the WHO standard for each quintile group shown in the baseline. This finding was repeated for all three demographic types with respect to the reduction of $PM_{2.5}$ pollutant. This means that:
    - LSOAs with the either the highest (quintile 1) or lowest (quintile 5) proportion of income deprived citizens are likely to have the greatest number of LSOAs with a location that exceeds the WHO standard for $PM_{2.5}$.
    - LSOAs with the highest proportion of children (quintile 5) are likely to have the greatest number of LSOAs with a location that exceeds the WHO standard for $PM_{2.5}$.
    - LSOAs with the highest proportion of elderly citizens (quintile 5) are likely to have the least number of LSOAs with a location that exceeds the WHO standard for $PM_{2.5}$.

5.3 OVERALL CONCLUSION

Component 1 has identified that annual mean baseline concentrations of $PM_{2.5}$ across LSOAs tend to be proportional to the size of the human population within the LSOA. The analysis also showed that the level of reduction of each pollutant concentration is proportional to the baseline concentration level (i.e. the scenarios are expected to successfully reduce pollutant concentrations in areas where the concentrations are highest).

Component 2 (The distributional impact assessment) has found that:

- Each scenario has reduced concentrations of $PM_{2.5}$ across Wales. The biggest reductions have been shown to occur in the most populated regions of the country (i.e. across the south and also the northeast regions).
- There is not a linear relationship between the concentration reductions of $PM_{2.5}$ and a LSOAs level of income deprivation. Generally, the biggest average reduction of each pollutant is likely to occur in the two most deprived quintile groups (quintiles 1 and 2). Whilst the level of reduction is smaller in the lesser deprived quintile groups (3 and 4), those living in the least deprived (quintile 5) are also likely to enjoy a level of reduction comparable to that predicted for the quintile 1 and 2 groupings. This general observation was observed for all scenarios and all pollutants.
- There is not a linear relationship between the concentration reductions of any of the pollutants and the proportion of a LSOA's population classified as a child. The analysis has found that LSOAs with a higher proportion of children (quintiles 4 and 5) tend to have the highest average level of reduction of $PM_{2.5}$. The average level of reduction is otherwise relatively similar in all other quintile groups with those living in the quintile group with the highest reduction only experiencing a marginal greater benefit to the other quintiles. This general observation was observed for all scenarios and pollutants.
- The analysis found that the quintile 5 LSOAs are likely to the lowest reduction in $PM_{2.5}$ pollutant. The level of reduction did not correlate in a linear scale with the other quintile groups (quintiles 1 to 4). The analysis has identified that quintile 4 and 5 LSOA's tend to be located in rural locations where the concentration of pollutant is lowest and where actions included in each scenario have least effect.

- There is a reasonable relationship between the concentration reduction of $PM_{2.5}$ pollutant and the proportion of BAME residents in the same spatial region, with the data showing that the level of pollutant reduction tends to increase as the proportion of BAME population increases. This was found to be true for each of the scenarios.

Component 3 (Distribution of compliance with WHO air quality targets) has identified that the implementation of any of the considered scenarios are not likely to alter the status quo with respect to the share of the number of LSOAs with a location where resident is likely to be exposed to a concentration of $PM_{2.5}$ pollutant that exceeds the WHO target standard.