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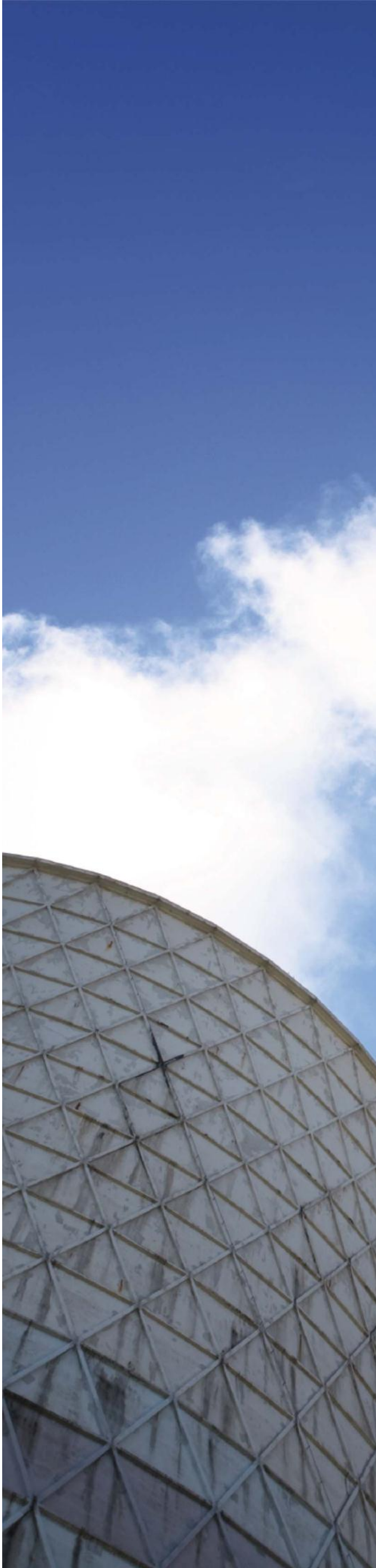

FINAL REPORT – VOLUME 1: MAIN REPORT

ECONOMIC ANALYSIS TO INFORM THE NATIONAL PLAN FOR CLEAN AIR (PARTICLES)

Prepared for:
NEPC Service Corporation

On behalf of:
Council of Australian Governments (COAG)
Standing Council on Environment and Water

August 2013

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EXECUTIVE SUMMARY

Introduction

Overview

This Report describes the work undertaken on the National Environment Protection Council (NEPC) project entitled *Economic Analysis to Inform the National Plan for Clean Air (Particles),* referred to hereafter as 'the economic analysis'. The overall objective of the project was to provide economic data to support an improved framework for managing airborne particulate matter (PM) in Australia. A cost-benefit analysis (CBA) approach was used to assess the implications of compliance with various hypothetical air quality standards for PM (including the current standards), as well as an exposure-reduction target. The project built upon an earlier CBA **(Wilson *et al.*, 2011a, 2011b)** and was informed by a number of other major Australian and overseas studies.

The project was complex and comprehensive; it brought together much of the information on emissions, air quality, air pollution abatement and health impacts in Australia. Each Australian jurisdiction was considered in the analysis and the best possible use was made of the available data. Significant advances were made in some areas to allow policymakers to pragmatically evaluate air quality management options.

Current national air quality standards

The current approach to air quality management in Australia focuses on reducing exceedances of air quality standards at specific locations. In 1998 Australia adopted a National Environment Protection (Ambient Air Quality) Measure (AAQ NEPM) that established standards for six criteria pollutants: carbon monoxide (CO), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), lead, ozone (O_3), and particulate matter with an aerodynamic diameter of less than 10 µm (PM_{10}). The goal of the AAQ NEPM was to ensure compliance with the standards, with a maximum allowable number of exceedances, within 10 years of commencement. The AAQ NEPM was extended in 2003 to include advisory reporting standards for PM with an aerodynamic diameter of less than 2.5 µm ($PM_{2.5}$).

Reducing exposure to PM

There is no evidence of a threshold PM concentration below which adverse health effects are not observed **(Pope and Dockery, 2006; COMPEAP, 2009; Brook *et al.*, 2010)**. Long-term exposure to PM is the most important determinant of pollution-related health effects, and the benefits of reducing PM are independent of the absolute concentration. Therefore, in situations where PM concentrations are below the AAQ NEPM standards for most of the time there is still a health benefit to be gained by reducing them further, especially in areas of high population density. However, whilst air quality standards have an important role to play in driving down concentrations where exceedances are observed, localised remedial actions are unlikely to lead to large-scale reductions in population exposure.

National Plan for Clean Air

In 2010 the Environment Protection and Heritage Council (EPHC) recommended that a strategic approach to air quality management should be adopted in Australia. In 2011 a number of further steps were taken, including a review of the AAQ NEPM which recommended updating the standards **(NEPC, 2011a)**, and the publication of a methodology for the setting of air quality standards **(NEPC, 2011b)**. In 2012 the Council of Australian Governments (COAG) identified air quality as an issue of national priority **(COAG, 2012)** and agreed that its Standing Council on Environment and Water (SCEW) would implement a National Plan for Clean Air (NPCA). SCEW established an Air Thematic Oversight Group (Air TOG) to develop the NPCA. The hypothetical air quality standards for PM_{10} and $PM_{2.5}$ adapted from air quality scenarios developed by a Working Group of the Air TOG are shown in **Table ES1**.

Table ES1: Hypothetical air quality standards

Pollutant	Averaging period	Concentration ($\mu g/m^3$)[(a)]
PM_{10}	1 year	20.0
		16.0
		12.0
$PM_{2.5}$	1 year	10.0
		8.0
		6.0
PM_{10}	24 hours (5 exceedances allowed)	**50.0**
		40.0
		30.0
$PM_{2.5}$	24 hours (98th percentile)[(b)]	**25.0**
		20.0
		15.0

(a) Current Australian standards and advisory reporting levels are shown in bold
(b) The advisory NEPM standard allows no exceedances. For practicality we adopted the 98th percentile.

Where relevant, the economic analysis has applied the existing AAQ NEPM criteria covering natural events (*i.e.* five allowable exceedances or the 98th percentile concentration as a proxy) so that the economic analysis compares hypothetical and business-as-usual (BAU) standards based on similar assumptions.

Consideration of an exposure-reduction framework for $PM_{2.5}$ was another important recommendation of the AAQ NEPM review, and the options for developing such a framework in Australia were investigated by **Bawden *et al.* (2012)**. As part of this analysis a hypothetical target of a 10% reduction in the measured long-term mean $PM_{2.5}$ concentration between 2015 and 2025 has been considered.

The role of cost-benefit analysis

CBA is a widely-used economic tool for evaluating environmental policy options. Its main strength is that it permits decision-makers to develop pollution-control strategies in an objective manner, and allows the economics of environmental protection to be framed in a wider context. In the economic analysis the costs and benefits of compliance with the hypothetical standards in **Table ES1** were determined relative to a BAU case.

Project objectives

The implications of the hypothetical air quality standards and 10% exposure-reduction target were addressed in the economic analysis. The project was designed to answer specific questions, including the following:

- What total reductions in PM emissions would be required to meet the hypothetical air quality standards?
- What are the abatement measures that are feasible at the national level?
- What would be the effects on emissions and air quality of introducing all feasible abatement measures?
- What would be the net economic benefit of compliance with the hypothetical air quality standards?
- What would be the net economic benefit of implementing all feasible national abatement measures?
- What would be the net economic benefit of implementing all economic national abatement measures?

- What reductions in PM emissions would be required to meet the exposure-reduction target?
- What would be the monetised health benefit of implementing a new exposure-reduction framework for PM?

The base year for the assessment was 2011, with costs and benefits mainly being evaluated to 2036 (the end date of most abatement programmes, and the assumed target year for achieving the air quality standards for the purpose of the economic analysis). Residual cost and benefits out to 2055 were also taken into account.

Methodology

Focussing on primary anthropogenic PM

Airborne PM is a complex mixture of particles from different sources, and the contributions of the different sources vary considerably both temporally and spatially. The components of PM can be categorised in a number of different ways, but it is usually essential to distinguish between the following:

- Primary natural PM
- Primary anthropogenic PM
- Secondary natural PM
- Secondary anthropogenic PM

Primary natural PM is emitted directly into the atmosphere as a result of processes such as wind erosion (mineral dust) and the production of marine aerosol (sea salt). Primary anthropogenic particles result from processes involving either combustion (*e.g.* industrial activity, domestic wood heaters, vehicle exhaust) or abrasion (*e.g.* road vehicle tyre wear). Secondary PM is not emitted directly, but is formed by chemical reactions involving gas-phase components of the atmosphere. The main gaseous precursors are oxides of nitrogen (NO_X), ammonia (NH_3), sulfur oxides (SO_X) and volatile organic compounds (VOCs). Again, the origin of these may be natural or anthropogenic. Various studies have shown that secondary particles can contribute significantly to $PM_{2.5}$ and PM_{10}. For both primary and secondary PM there is a further division between inorganic and organic components. This is especially important for secondary PM. As suggested by the gaseous precursors mentioned above, the inorganic components of secondary PM typically include ammonium nitrate (with some sodium nitrate) and ammonium sulfate. The organic component is a complex mixture of compounds, commonly referred to as secondary organic aerosol (SOA).

The economic analysis focussed on primary anthropogenic PM; natural and secondary PM components were not explicitly modelled in the project. The reasons for this were as follows:

- The natural components of PM_{10} and $PM_{2.5}$ cannot easily be controlled. This therefore places more emphasis on the control of anthropogenic particles.
- From a toxicological perspective natural particles (notably sea salt) are likely to be more benign than anthropogenic particles. The control of the latter should therefore result in greater health benefits.
- National and state pollution-reduction policies and measures have historically focussed on the control of primary anthropogenic emissions. The precursors of secondary PM (NO_X, SO_X, NH_3 and VOC) from some sectors are also subject to legislation and control, but this has not usually been linked to their role in secondary PM formation.
- In terms of modelling there is a more direct relationship between primary PM emissions and primary PM concentrations than between the precursors of secondary PM and secondary PM concentrations. The modelling of secondary PM in Australia is still under development. Moreover, there are relatively few data on secondary nitrates from monitoring campaigns in Australia.
- At the outset of the project there were no suitable damage costs for secondary PM in Australia.

In terms of reducing exposure to PM it is currently more economical (and less uncertain) to focus on abatement measures that reduce primary PM emissions rather than those measures that reduce emissions of secondary PM precursors. This least-cost approach has been reflected in a recent regulatory impact analysis of proposed revisions to the national air quality standards in the US, which showed that when assessing effective control strategies direct $PM_{2.5}$ reductions accounted for 75-100% of the reductions of the least-cost abatement approach **(USEPA, 2012)**.

Abatement measures that are designed to reduce primary anthropogenic PM emissions will also often reduce emissions of the precursors of secondary PM. This should, in turn, lead to reduced formation of secondary PM. However, no practical and comprehensive models for estimating secondary PM in Australia were available at the time of the study, and therefore an evaluation of the effects of reducing emissions of secondary PM precursors was beyond the scope of the project.

Steps in the analysis

The approach used for each jurisdiction was tailored according to the available information. The most detailed treatment was possible in NSW and Victoria, as these jurisdictions had up-to-date gridded emission inventories that were in a format suitable for air quality modelling. The overall methodology for NSW and Victoria involved the tasks listed below. The links between the tasks are illustrated in **Figure ES1**.

- Task 2.1: Modelling of base year emissions and concentrations for 2011. Given the different air quality criteria used for PM_{10} and $PM_{2.5}$, it was necessary to consider the following four metrics:
  - The annual mean PM_{10} concentration.
  - The 6th highest 24-hour mean PM_{10} concentration. The NEPM goal for PM_{10} allows five exceedance days per year.
  - The annual mean $PM_{2.5}$ concentration.
  - The maximum 24-hour mean $PM_{2.5}$ concentration (***NB****: because the maximum measured values were very variable, the 98th percentile was used*).
- Task 2.2: The development of an emission-projection method, and the determination of population-weighted concentrations for a BAU scenario. The years covered were 2011 to 2036 inclusive.
- Task 2.3: The determination of the emission reductions required for compliance with the hypothetical air quality standards in each study year (with an emphasis on the target year of 2036). The treatment of the 24-hour air quality standards was computationally intensive, and therefore the assessment of these was limited to 2036 only.
- Task 3.1: The identification of health and other outcomes.
- Task 3.2: The quantification of health and other outcomes.
- Task 3.3: The monetisation of health and other outcomes.
- Task 4.1: The calculation of costs for abatement measures.
- Task 5.1: An assessment of the impacts of introducing an exposure-reduction framework.
- Task 6.1: The determination of the net benefits of the candidate air quality standards and exposure-reduction approaches/targets.
- Task 7.1: A sensitivity analysis.

These tasks implied a methodology that was similar to the so-called 'impact pathway' approach previously used in the European Union (EU) and the United Kingdom (UK) **(AEA, 2005; Defra, 2007)**. However, for the EU and UK analyses the resources available were much greater, the modelling data were more extensive, and the timescales for completion much longer, than those for the NEPC project.

An approach of intermediate sophistication was therefore used in the economic analysis; it was pragmatic and utilised the existing Australian data and modelling to the best advantage. It also recognised the underlying complexity of the processes involved and the limitations of the data. We valued health impacts mainly through the use of damage costs for primary $PM_{2.5}$, with a simplified impact pathway-type approach being used as checking mechanism for specific locations.

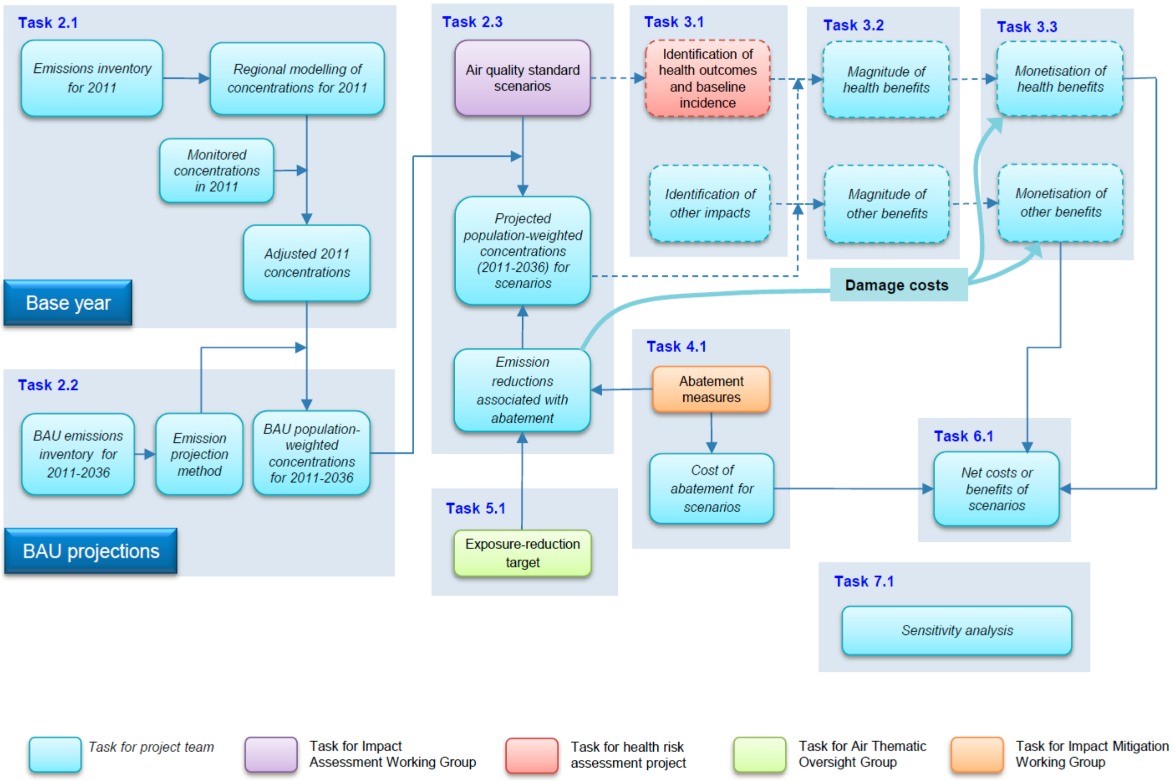

Figure ES1: Overview of economic analysis process

Less detailed information on emissions and air quality was available for other jurisdictions, and therefore an aggregated approach was applied. This did not involve air pollution modelling, and relied upon average data for the airsheds of the state capitals.

The complex nature of airborne PM was taken into account as far as possible. A major part of the work involved the isolation of primary anthropogenic PM from ambient measurements to enable direct comparison with the air pollution model outputs, and the development of the method for this is described in some detail in the Report. In general, a conservative approach was used to avoid overestimating the contribution of primary anthropogenic emission sources to ambient PM_{10} and $PM_{2.5}$ concentrations.

Evaluation of air quality standards and exposure-reduction target

A CBA was applied to calculate both the costs and benefits of nominal abatement measures in relation to the various air quality standards and the exposure-reduction target. The abatement measures selected were those that could potentially benefit from a national approach. The original intention of the project was to examine the incremental effects on air quality of different abatement measures, and to determine the least-cost routes to achieving compliance. However, it became apparent that - due to the combined effects of evaluating only primary anthropogenic PM, the growth in population, and the growth in emissions over the 2036 compliance period - many of the individual abatement measures did not have a large effect when treated in isolation and combinations of several measures would be required. Consequently, a simpler approach was taken, whereby two portfolios of national abatement measures were considered:

- A portfolio containing all abatement measures which could be applied in a logical combination to give the largest possible emission reduction (termed 'all feasible measures').
- A portfolio that gave the largest possible emissions reduction, but only including measures with a benefit:cost ratio (BCR[1]) of greater than one (termed 'all economic measures').

For each measure the cost items included were costs incurred by government in implementing and administering it, and capital investment or ongoing expenditure incurred by industry. The benefit items were savings in fuel consumption and the health (and other) benefits of reduced emissions of PM, NO_X and carbon dioxide (CO_2). The costs and benefits were aggregated across all years, and two metrics were calculated: the BCR and the net present value (NPV[2]).

Where a portfolio did not result in compliance with a hypothetical air quality standard an 'emissions gap' was calculated. This additional reduction was placed into context by quantifying it as a percentage of the 'residual' emissions (*i.e.* the total emissions in the inventory area minus the amount removed by the 'all feasible measures' portfolio). For the exposure-reduction target we used a similar approach, except that the 'gaps' related to the additional reductions required by 2025 to achieve a 10% reduction in the population-weighted $PM_{2.5}$ concentration. We then also estimated the costs and benefits of implementing further abatement measures to bridge the emission gaps. This analysis was only required for Western Australia, Tasmania and to a lesser extent the Australian Capital Territory (ACT). In Western Australia the emissions gap was allocated to industrial point sources, whereas in Tasmania and ACT it was allocated to wood heater sources (these were the largest remaining source of emissions, and the most cost-effective to address, in the respective inventories).

A sensitivity analysis was performed in order to test how results would vary based on alternative sets of assumptions.

Summary and conclusions

Before presenting the conclusions of the economic analysis, it is important to reiterate the context within which they are framed. The most important points are as follows:

- The analysis focussed on the reduction of emissions of primary anthropogenic particles. The results indicate that these are responsible for around 20-25% of PM_{10} and around 40-50% of $PM_{2.5}$ (depending on the season and location). A significant proportion is therefore natural or secondary in origin. For example, the contribution of sea salt to $PM_{2.5}$ ranges from around 10% to 25% on average. This has important implications in terms of the emission reductions required for compliance, and suggests that the current processes for defining air quality standards and monitoring compliance have limitations which should be considered thoroughly in the future.
- The level of an air quality standard relative to the level of the natural/secondary PM component at a given location is very important, and to a large extent determines whether compliance will be possible and, if so, the emission reduction that will be required. However, whilst natural and secondary anthropogenic particles contribute significantly to airborne PM, we could not fully account for their impact given the limitations of Australian models and data. In particular, the reduction of primary PM emissions will often be associated with a reduction in emissions of other pollutants that are precursors of secondary PM, thus reducing secondary PM formation. The required concentration and emission reductions that we have calculated are therefore probably overestimates (*i.e.* our approach is conservative). The current state of the knowledge does not allow us to quantify the extent of the overestimation with a high level of confidence.
- The emission and concentration projections are based on forecasts for growth in population, historical growth in industrial/commercial activity, and projected emissions from the Australian Bureau of Statistics (ABS) and Bureau of Infrastructure, Transport and Regional Economics (BITRE).

[1] The economic value of benefits expected from implementation of a policy divided by the economic costs.

[2] The economic cost expected from implementation of a policy subtracted from the economic benefit.

In some jurisdictions the projected values for some sectors are relatively high. If the rate of growth decreases in the future then smaller emission reductions than those stated in the Report will be required for compliance with the hypothetical air quality standards.

- The analysis dealt primarily with abatement measures that could benefit from a national approach. The emission reductions are based on a package of feasible abatement measures. A gap analysis approach was used where only one or more jurisdictions were not compliant with a hypothetical standard. This assumed that some additional economic abatement alternatives were available in these jurisdictions based on existing Australian air pollution abatement studies.

These issues highlight some of the complexities of setting (and evaluating) air quality standards for PM_{10} and $PM_{2.5}$, especially where the prevailing PM concentrations are relatively low so that natural and secondary PM components become very important. The exposure-reduction approach bypasses these problems to some extent, as it does not involve compliance with a fixed concentration.

Our responses to the questions posed in the project objectives are provided below.

Air quality standards

What total reductions in PM emissions would be required to meet the hypothetical air quality standards?

We estimated the reductions in emissions that would be required in the BAU case (*i.e.* with no new abatement measures) to achieve compliance with each of the hypothetical air quality standards in the target year of 2036. These emission reductions are shown in **Table ES2**. The green cells show where an air quality standard was met in 2036 in the BAU scenario and the burgundy cells show the estimated reduction in emissions that would be necessary to achieve compliance. The orange cells show where compliance would not be possible by reducing primary anthropogenic emissions alone.

Table ES2: Emission reductions in 2036 (no new abatement measures)

Jurisdiction	PM_{10} annual mean AQ standard (µg/m³)			$PM_{2.5}$ annual mean AQ standard (µg/m³)			PM_{10} 24-hour 6th highest AQ standard (µg/m³)			$PM_{2.5}$ 24-hour 98th %ile AQ standard (µg/m³)		
	20	16	12	10	8	6	50	40	30	25	20	15
NSW		113,832				15,463						
VIC		21,501				823						
QLD		8,674				1,684			8,522			2,921
SA		658			686	3,980			2,365			2,323
WA	1,502	7,224				2,116		235	7,704			147
TAS			1,674		959	2,573		1,449		2,000	3,083	
NT		90			47	129		29				78
ACT						576			414	513	1,018	

Key:

Concentration below standard in BAU case in 2036

Standard lower than natural/secondary PM component

34 Emission gap (tonnes per year)

What are the abatement measures that are feasible at the national level?

In the economic analysis marginal abatement cost curves (MACCs) were developed to compare the long-run costs and emission reductions of measures that were feasible at the national level. As an example, the data for the national $PM_{2.5}$ MACC are provided in **Table ES3**. The incremental abatement is defined as the additional abatement delivered by a variant[3] over and above the variant in the same

[3] Policies to reduce emissions from a given sector using the same mechanism (*e.g.* standards) can be implemented in a number of ways or levels of standard. Each alternative is termed a 'variant'.

sector immediately preceding it (in order of cost-effectiveness). The MACCs for individual jurisdictions are also presented in **Appendix E** of the Report.

Table ES3: $PM_{2.5}$ data for national MACC

Measure	Marginal cost ($/t$PM_{2.5}$)	Abatement (t$PM_{2.5}$/year)	Incremental abatement (t$PM_{2.5}$/year)
US 2006 & 2010 outboard and watercraft, and US phase 2 gardening emissions standards	-11,963	388	388
US2010 outboard and watercraft, and US phase 2 gardening emissions standards	-10,815	390	2
Regulating moisture content of wood fuel to be less than 20%	99	851	851
Wood heaters 60% efficiency, 3 g/kg emission standards	499	3,242	3,242
Wood heaters 65% efficiency, 3 g/kg emission standards and in-service measures	739	3,416	173
Wood heaters 60% efficiency, 3 g/kg emission standards and in-service measures	742	3,485	69
Wood heaters 60% efficiency, 1.5 g/kg emission standards and in-service measures	850	3,664	179
Diesel trains driver assistance software for line haul locomotives	5,426	110	110
Adoption of international best-practice PM control measures at coal mines	9,115	17,302	17,302
US non-road diesel standards in Australia (excluding <19kW)	9,191	13,699	13,699
Memorandum of Understanding (MOU) to reduce shipping vessel speed for ocean transits	10,632	638	638
Retrofitting non-road diesel engines at mine sites with Diesel Particulate Filters (DPFs)	15,893	2,426	2,426
Requiring new locomotives to meet US Tier 4 standards	21,598	297	297
Retrofitting high-polluting (urban) non-road diesel engines & equipment with DPFs	22,455	22	22
Mandatory low-sulfur fuel use by ships while at berth	50,066	969	969
Replacing old locomotives and requiring new locomotives to meet US Tier 4 standards	105,841	614	317
Targeted maintenance of high-polluting Light Commercial Vehicles (LCVs) using remote sensing	158,922	1	1
Penalty and incentive scheme for high polluting vehicles	202,673	10	10
Area-wide planting to remove PM from the atmosphere	407,418	66	66

What would be the effects on emissions and air quality of introducing all feasible abatement measures?

The emission reductions that would still be required after the introduction of all feasible national abatement measures are shown in **Table ES4**. The purple cells show the instances where the standard was not met in the BAU case but would be met with the 'all feasible measures' portfolio in place. Further (state-based) abatement would still be required to comply with some air quality standards. These state-based emission reductions are also framed in the context of the residual emissions in the inventory (*i.e.* the total emissions in the inventory in 2036 minus the emission reductions for all feasible national measures), as shown in **Table ES5**.

Table ES4: Emission reductions 2036 ('all feasible measures' portfolio)

Jurisdiction	PM_{10} annual mean AQ standard (µg/m³)			$PM_{2.5}$ annual mean AQ standard (µg/m³)			PM_{10} 24-hour 6th highest AQ standard (µg/m³)			$PM_{2.5}$ 24-hour 98 %ile AQ standard (µg/m³)		
	20	16	12	10	8	6	50	40	30	25	20	15
NSW		72,257				3,238						
VIC		17,517										
QLD		4,917				631			4,765			1,868
SA						3,027			1,277			1,369
WA	609	6,331				1,405			6,811			
TAS			1,249		553	2,167		1,024		1,594	2,667	
NT		27				68						59
ACT						242			216	39	544	

Key:

- Concentration below standard in BAU case in 2036
- Standard lower than natural/secondary PM component
- 34 Emission gap (tonnes per year)
- Compliant with abatement

Table ES5: Emission gaps as a percentage of residual emissions in 2036

Jurisdiction	PM_{10} annual mean AQ standard (µg/m³)			$PM_{2.5}$ annual mean AQ standard (µg/m³)			PM_{10} 24-hour 6th highest AQ standard (µg/m³)			$PM_{2.5}$ 24-hour 98th %ile AQ standard (µg/m³)		
	20	16	12	10	8	6	50	40	30	25	20	15
NSW		74%				11%						
VIC		93%										
QLD		27%				6%			26%			19%
SA						60%			24%			27%
WA	7%	77%				18%			83%			
TAS			37%		18%	69%		19%		51%	85%	
NT		18%				64%						1%
ACT						21%			18%	3%	48%	

Key:

- Concentration below standard in BAU case in 2036
- Standard lower than natural/secondary PM component
- 20% Emission gap as % of residual emissions
- Compliant with abatement

Under the BAU scenario there will be an overall increase in PM concentrations over the period 2011-2036. For example, the population-weighted annual mean PM_{10} concentration would increase by between 0.2 µg/m³ and 2.4 µg/m³, depending on the jurisdiction. We estimate that the introduction of all feasible national abatement measures will result in a relatively modest reduction in PM concentrations relative to the BAU case, but substantial monetised health benefits in the airsheds considered in the analysis (*i.e.* the inventory areas). We expect that there would be a reduction (relative to the BAU scenario) in the population-weighted annual mean PM_{10} concentration of between around 0.4 and 1.4 µg/m³ by 2036, depending on the airshed, and a reduction in the annual mean $PM_{2.5}$ concentration of between around 0.3 and 1.5 µg/m³. The fact that there is a larger upper limit for $PM_{2.5}$ is probably an artefact of the assumptions used in the analysis.

What would be the net economic benefit of compliance with the hypothetical air quality standards?

The net benefits[4] of compliance with the hypothetical air quality standards are shown in **Table ES6**.

Table ES6: Net benefits of compliance with air quality standards in 2036

Pollutant	Averaging period and metric	Concentration (µg/m³)	Net benefit (2011 $m)
PM_{10}	1 year	20.0	**$6,389**
		16.0	Not feasible to meet through primarily national measures
		12.0	Not possible to meet due to natural/secondary component
$PM_{2.5}$	1 year	10.0	Already met in BAU
		8.0	**$6,464**
		6.0	Not feasible to meet through primarily national measures
PM_{10}	24 hours (6th highest value)	50.0	Already met in BAU
		40.0	**$6,616**
		30.0	Not possible to meet due to natural/secondary component
$PM_{2.5}$	24 hours (98th percentile)	25.0	**$6,940**
		20.0	Not feasible to meet through primarily national measures
		15.0	Not possible to meet due to natural/secondary component

[4] In addition to health benefits of avoided PM and NO_x, benefits include fuel savings and abatement of CO_2.

The benefits are dependent upon the emission reductions and their spatial distribution (with reductions in more populated areas carrying more weight). Given that all standards have been assessed using the same portfolio of national measures (augmented with state-based measures on a much smaller scale), the net benefit of compliance is similar in each case (around $6.4 to $7 billion). Standards should not be considered additive. That is, if two standards are set simultaneously (*e.g.* one for $PM_{2.5}$ and one for PM_{10}), the one which requires the greater emission reduction will drive the costs and benefits.

What would be the net economic benefit of implementing all feasible national abatement measures?

The portfolio of all feasible measures is expected to deliver a significant net benefit ($6.3 billion) to the Australian community. This is due to the relatively low cost of emission reduction compared with the avoidance of health costs (primarily life expectancy extended). The gross monetised health benefit of the 'all feasible measures' portfolio is estimated to be $17.3 billion (63% of which is due to measures that are currently being progressed through national assessment processes[5]).

What would be the net economic benefit of implementing all economic national abatement measures?

All feasible measures with a BCR ratio greater than one are contained in the 'all economic measures' portfolio, as shown in **Table ES7**. This portfolio is expected to deliver a net benefit in excess of cost of $8.8 billion. This value is higher than that for the 'all feasible measures' portfolio as it excludes measures with a negative NPV. The gross monetised health benefit of the 'all economic measures' portfolio is estimated to be $15.9 billion (69% of which is due to measures that are currently being progressed through national assessment processes).

Table ES7: Net benefits[6] of 'all economic measures' portfolio

Abatement measure	BCR	NPV (2011 $m)
Regulating moisture content of wood fuel to be less than 20%	1,176	$1,034
Wood heaters 60% efficiency, 1.5 g/kg emission standards and in-service measures	114	$4,178
MOU to reduce shipping vessel speed for ocean transits	4.1	$352
US2010 outboard and watercraft, and US phase 2 gardening emissions standards	3.2	$616
Diesel trains driver assistance software for line haul locomotives	2.5	$80
Retrofitting high-polluting (urban) non-road diesel engines & equipment with DPFs	2.3	$6
Adoption of international best practice PM control measures at coal mines	1.3	$643
US non-road diesel standards in Australia (excluding < 19kW)	1.3	$1,922
Requiring new locomotives to meet US Tier 4 standards	1.0	$1
Total for portfolio	**1.9**	**$8,834**

Exposure-reduction framework

What reductions in PM emissions would be required to meet the exposure-reduction target?

Figure ES2 shows the change in exposure to $PM_{2.5}$ (based on the population-weighted annual mean concentration) between 2015 and 2030 with the 'all feasible measures' portfolio in place, and the reduction achieved by the target year 2025. The target of a 10% reduction by 2025 would be achieved

[5] Referred to as 'existing measures' in this analysis, and includes standards for non-road diesel engines, wood heaters and non-road spark ignition engines.

[6] The net benefit calculated using the damage cost approach is expected to be lower than net benefit calculated using the impact pathway approach. The lower (more conservative) of the two has been used in the economic analysis.

in the Northern Territory, largely as a consequence of abatement measures relating to shipping. New South Wales (NSW) would be close to compliance. There would also be net reductions in exposure between 2015 and 2025 in ACT, Victoria and South Australia, but net increases in Western Australia, Queensland and Tasmania.

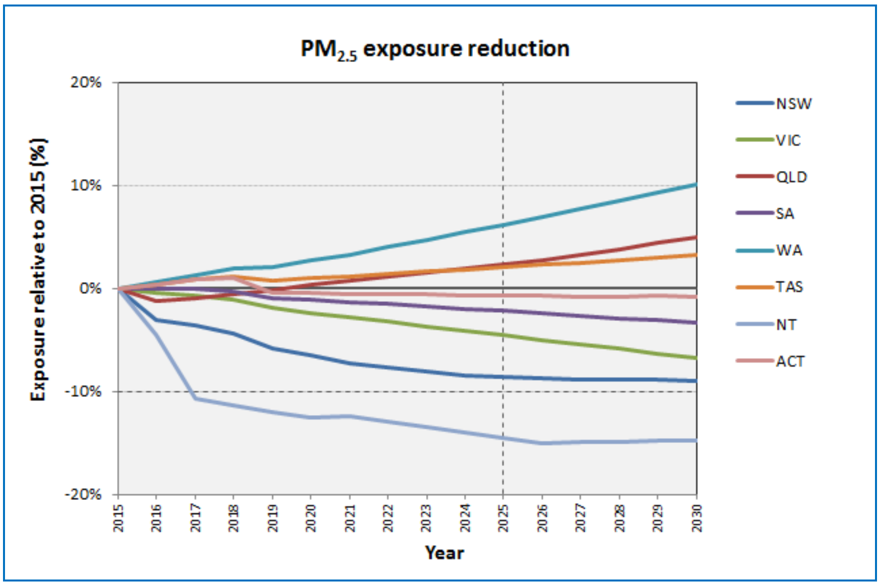

Figure ES2: Reduction in population exposure to $PM_{2.5}$ between 2015 and 2030 with all feasible abatement measures (target year 2025)

The gap analysis is given in **Table ES8**. The Table shows the emission gaps in both the BAU case and with all feasible abatement measures, and the percentage reduction in residual emissions in 2025 that would be required in each jurisdiction. In NSW the emission gap equated to 4% of residual emissions in the inventory. In the other jurisdictions the proportion was around 20-30%. Meeting the target of a 10% reduction in the annual mean $PM_{2.5}$ concentration between 2015 and 2025 would therefore require additional state-based measures in most jurisdictions. The overall emission reduction at the national level would be larger than that required for compliance with the (achievable) air quality standards.

Table ES8: Emission reductions required to meet exposure-reduction target 2025

Jurisdiction	$PM_{2.5}$ annual mean		
	BAU gap (t/y)	All feasible measures gap (t/y)	% of residual emissions in 2025
NSW	9,496	1,189	4%
VIC	4,691	2,947	28%
QLD	3,113	2,360	23%
SA	1,528	1,047	21%
WA	2,476	2,067	26%
TAS	1,004	806	26%
NT	40		
ACT	416	253	22%

Key:
34 Emission gap (tonnes per year)
Compliant with abatement

What would be the monetised health benefit of a new exposure-reduction framework for PM?

After implementation of the national 'all feasible measures' portfolio, no jurisdiction except Northern Territory will meet the exposure-reduction target of a 10% decrease in annual mean $PM_{2.5}$ between 2015 and 2025. The target could be met with a combination of national and state-based measures.

Further analysis of the cost of complying with the target was not undertaken. However, the health benefits of compliance were calculated for the jurisdictions other than Northern Territory. Compliance with the exposure-reduction target would require substantial state-based reductions in emissions, with correspondingly large further benefits. The overall health benefit of bridging the emission gaps was estimated to be $17.2 billion. Combining this with the total estimated health benefits of the 'all feasible measures' portfolio ($17.3 billion) provided a total estimated health benefit in Australia of $34.5 billion.

Sensitivity analysis

The two portfolios of measures performed well in the sensitivity tests and carried the benefit of diversifying the risk of individual measures. The performance of the 'all economic measures' portfolio was shown to be superior to that of the 'all feasible measures' portfolio. Variables tested in the sensitivity analysis included cost and emissions assumptions for abatement measures, discount rate, assumptions relating to growth in emissions under the BAU scenario, assumption relating to the value of a life year, and the method used to monetise the benefits of emission reductions.

Comparison with impact pathway approach

A simplified impact pathway-type approach to quantifying health benefits was followed for the specific locations covered by both the Australian Health Risk Assessment (HRA) of criteria pollutants project **(Frangos and DiMarco, 2012)** and the state emissions inventories. This was used to check the results of the damage cost calculations.

Over all years of the analysis, the impact pathway method resulted in a monetary estimate of benefits that was 1.5 times higher than that obtained using the damage cost method. While these results show an agreement with the impact pathway method within a reasonable range, they also indicate that damage cost results are likely to represent a conservative estimate of health benefits.

Guidance on air quality standards and exposure-reduction target

Air quality standards

Our conclusions from the economic analysis - in relation to each of the hypothetical air quality standards - are given in **Table ES9**.

We have assessed that annual mean standards for PM_{10} and $PM_{2.5}$ of 20 µg/m^3 and 8 µg/m^3 respectively could be achievable in Australia. In the case of PM_{10} some state-based abatement measures would be required in Western Australia to ensure national compliance if the current rate of economic growth in the state continues. Compliance with an annual mean standard for $PM_{2.5}$ of 8 µg/m^3 would be possible to achieve in all jurisdictions in principle, but would require some further state-based abatement in Tasmania.

For 24-hour PM_{10} both the 50 µg/m^3 and 40 µg/m^3 standards are assessed as achievable. A standard of 50 µg/m^3 would be achieved in the BAU case, and so the adoption of a lower value could drive environmental improvement. A value of 40 µg/m^3 would require state-based abatement in Tasmania, but should be achievable. For 24-hour $PM_{2.5}$ only a standard of 25 µg/m^3 (as a 98th percentile) is assessed as being achievable, although this would require further abatement action in both Tasmania and ACT.

Table ES9: Conclusions in relation to hypothetical air quality standards incorporating feasible national measures (assessment for 2036)

Pollutant	Averaging period and metric	Concentration (µg/m³)[(a)]	Conclusion from economic analysis		
			Feasible in principle?[(b)]	Further emission reduction required (by state)?[(c)]	Emission reductions likely to be achievable?
PM_{10}	1 year	20.0	Yes	WA	Yes
		16.0	Yes	NSW, VIC, QLD, WA, NT	No
		12.0	No	-	-
$PM_{2.5}$	1 year	10.0	Yes	None	No reduction required
		8.0	Yes	TAS	Yes
		6.0	Yes	NSW, QLD, SA, WA, TAS, NT, ACT	No
PM_{10}	24 hours (6th highest value)	**50.0**	Yes	None	No reduction required
		40.0	Yes	TAS	Yes
		30.0	No	-	-
$PM_{2.5}$	24 hours (98th percentile)	**25.0**	Yes	TAS, ACT	Possible
		20.0	Yes	TAS, ACT	No
		15.0	No	-	-

(a) Current Australian standards and advisory reporting levels are shown in bold.
(b) 'Feasible' cases are those where the air quality standard is not lower than the contribution of natural and secondary PM.
(c) Following the application of the 'all feasible national measures' portfolio.

Exposure-reduction target

A 10% exposure-reduction target over ten years could be met with a combination of national and state-based measures. However, alternative targets and timeframes may need to be considered to address the high industry growth rates for some jurisdictions.

It is important to emphasise again the likely benefits of an exposure-reduction target. As noted in the introduction, long-term exposure to the prevailing background PM concentration is the most important determinant of health outcomes. Even where a NEPM standard is not exceeded there is a health benefit associated with reducing concentrations, and an exposure-reduction framework provides an appropriate mechanism for this.

References

AEA (2005). Service contract for carrying out cost-benefit analysis of air quality related issues, in particular in the Clean Air for Europe (CAFE) Programme. AEA Technology Environment, Oxfordshire, UK.

Bawden K, Aust N, Moorcroft S, Laxen D and Williams M (2012). Evaluating Options for an Exposure Reduction Framework in Australia. PAEHolmes Report 6808. PAEHolmes, Brisbane.

Brook R D *et al*. (2010). Particulate matter air pollution and cardiovascular disease: An update to the scientific statement from the American Heart Association. Circulation, 2010, 121, pp. 2331-2378.

COAG (2012). Public statement on the development of the National Plan for Clean Air. The Council of Australian Governments Standing Council on Environment and Water, 31 May 2012.

COMEAP (2009). Long-term exposure to air pollution: effect on mortality. A report by the Committee on the Medical Effects of Air Pollutants. London, Department of Health, United Kingdom.

Defra (2007). An Economic Analysis to inform the Air Quality Strategy- Updated Third Report of the Interdepartmental Group on Costs and Benefits. July 2007. Department for Environment, Food and Rural Affairs, London.

Frangos J and DiMarco P (2012). Draft exposure assessment and risk characterisation to inform recommendations for updating ambient air quality standards for $PM_{2.5}$, PM_{10}, O_3, NO_2, SO_2. Report number 127643066-001-R-RevA. Golder Associates, Richmond, Victoria.

NEPC (2011a). National Environment Protection (Ambient Air Quality) Measure Review. National Environment Protection Council Service Corporation, Level 5 81 Flinders Street, Adelaide, South Australia.

NEPC (2011b). Methodology for Setting Air Quality Standards in Australia, Part A, February 2011. National Environment Protection Council, Canberra.

Pope C A 3rd and Dockery D W (2006). Health effects of fine particulate air pollution: lines that connect. J. Air Waste Manag. Assoc., Volume 56, pp. 709-742.

USEPA (2012). Regulatory Impact Analysis for the Proposed Revisions to the National Ambient Air Quality Standards for Particulate Matter. EPA-452/R-12-003, June 2012. United States Environmental Protection Agency.

Wilson C, Chiodo J and Grey F (2011a). National Environment Protection (Ambient Air Quality) Measure – Draft Cost Benefit Analysis Methodology, April 2011.

Wilson C, Chiodo J and Grey F (2011b). National Environment Protection (Ambient Air Quality) Measure – Draft Preliminary Cost Benefit Analysis, April 2011.

GLOSSARY OF TERMS AND ABBREVIATIONS

Term	Description
AAQ NEPM	National Environment Protection (Ambient Air Quality) Measure
ABS	Australian Bureau of Statistics
ACT	Australian Capital Territory
AIHW	Australian Institute of Health and Welfare
Air TOG	Air Thematic Oversight Group
ANSTO	Australian Nuclear Science and Technology Organisation
ANZSIC	Australian and New Zealand Standard Industrial Classification
BAM	Beta Attenuation Monitor
BAU	Business as usual
BCR	Benefit cost ratio
BITRE	Bureau of Infrastructure, Transport and Regional Economics
BTS	(NSW) Bureau of Transport Statistics
CBA	Cost-benefit analysis
CBD	Central Business District
CAFE	(EU) Clean Air for Europe (programme)
CIV	Capital investment value
COAG	Council of Australian Governments
CO	Carbon monoxide
CO_2	Carbon dioxide
CO_2-e	Carbon dioxide equivalents
COAG	Council of Australian Governments
CPM	Carbon Pricing Mechanism
CRF	Concentration-response function
CRIS	Consultation Regulation Impact Statement
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CTM	(TAPM) Chemical Transport Model
Defra	(UK) Department for Environment, Food and Rural Affairs
DERM	(Queensland) Department of Environment and Resource Management
DEWHA	Department of Environment, Water, Heritage and the Arts
DGRs	Director General's Requirements
DOAS	Differential Optical Absorption Spectroscopy
DoPI	(NSW) Department of Planning and Infrastructure
DPF	Diesel Particulate Filter
DRIS	Decision Regulation Impact Statement
DSEWPAC	(Commonwealth) Department of Sustainability, Environment, Water, Population and Communities
DSITIA	(Queensland) Department of Science, Information Technology, Innovation and the Arts

Term	Description
EAC	Equivalent Annual cost
EC	Elemental carbon
EDMS	(NSW) Emissions Data Management System
EIA	Environmental Impact Assessment
EIS	Environmental Impact Statement
EPA Victoria	Environment Protection Authority Victoria
EPHC	Environment Protection Heritage Council
ETS	Emissions trading scheme
EU	European Union
EV	Electric vehicle
FDMS	Filter Dynamic Measurement System
FTE	Full-time equivalents
GDP	Gross domestic product
GHG	Greenhouse gas
GLC	Ground-level concentration
GMR	(NSW) Greater Metropolitan Region
GRUB	Generally representative upper bound (for community exposure; monitoring sites)
GVA	Gross value added
HRA	Health risk assessment
HVAS	High volume air samplers
IAWG	Impact Assessment Working Group (of Air TOG)
IGCB	(UK) Interdepartmental Group on Costs and Benefits
IMWG	Impact Mitigation Working Group (of Air TOG)
LCV	Light commercial vehicle
LGA	Local Government Area
LRMC	Long-run marginal cost
MACC	Marginal abatement cost curve
MOU	Memorandum of Understanding
MSB	Marginal social benefit
MSC	Marginal social cost
MSB	Marginal social benefit
MSC	Marginal social cost
NEPC	National Environment Protection Council
NEPM	National Environment Protection Measure
NH_3	Ammonia
NO_2	Nitrogen dioxide
NO_x	Oxides of nitrogen
NPCA	National Plan for Clean Air
NPI	National Pollutant Inventory
NPV	Net present value

Term	Description
NSW	New South Wales
NT	Northern Territory
NSW EPA	New South Wales Environment Protection Authority
O_3	Ozone
OC	Organic carbon
OECD	Organization for Economic Cooperation and Development
OEH	(NSW) Office of Environment and Heritage
PCA	Principal component analysis
PM	Airborne particulate matter
PM_{10}	Airborne particulate matter with an aerodynamic diameter of less than 10 µm
$PM_{2.5}$	Airborne particulate matter with an aerodynamic diameter of less than 2.5 µm
PRP	(NSW) Pollution Reduction Program
PV	Present value
Q-Q	Quantile-quantile
QALY	Quality-adjusted life year
QLD	Queensland
RFS	(NSW) Rural Fire Service
RIS	Regulatory Impact Statement
RMS	(NSW) Roads and Maritime Services
RMSE	Root mean square error
SA	South Australia
SCEW	Standing Council on Environment and Water
SEQ	South-East Queensland
SO_2	Sulfur dioxide
SO_3	Sulfur trioxide
SO_x	Sulfur oxides
SOA	Secondary organic aerosol
SUA	Significant urban area
TAPM	The Air Pollution Model
TAS	Tasmania
TAPM-CTM	The Air Pollution Model – Chemical Transport Model
TEOM	Tapered Element Oscillating Microbalance
TEOM-FDMS	TEOM with Filter Dynamic Measurement System
TOG	Thematic Oversight Group
TSP	Total suspended particulate
UHAQMN	Upper Hunter Air Quality Monitoring Network
UK	United Kingdom
UN	United Nations
US	United States
USEPA	United States Environmental Protection Agency

Term	Description
VIC	Victoria
VKT	Vehicle-kilometres travelled
VOCs	Volatile organic compounds
VOLY	Value of a life year
VPF	Value of preventing a statistical fatality
WA	Western Australia
VSL	Value of a statistical Life
WHO	World Health Organisation
WTA	Willingness to accept
WTP	Willingness to pay
YOLL	Years of life lost

CONTENTS – VOLUME 1: MAIN REPORT

1 INTRODUCTION

The National Environment Protection Council (NEPC) Service Corporation commissioned a consortium led by Pacific Environment (formerly PAEHolmes) to undertake a project entitled *Economic Analysis to Inform the National Plan for Clean Air (Particles)* – referred to hereafter as 'the economic analysis'. The consortium also included Marsden Jacob Associates, Paul Watkiss Associates (UK) and Air Quality Consultants (UK). This document represents the Final Report from the project.

The project was complex and comprehensive; it brought together much of the data on emissions, air quality, air pollution abatement and health impacts in Australia. Significant advances were made in some areas to allow policymakers to pragmatically evaluate air quality management options.

The remainder of this introductory Chapter describes the context of the work, with subsequent Chapters dealing with the main stages of the analysis. The conclusions from the project are provided at the end of the Report.

1.1 National air quality standards

In 1998 Australia adopted a National Environment Protection (Ambient Air Quality) Measure (AAQ NEPM)[7] that established national standards for six criteria pollutants:

- Carbon monoxide (CO)
- Nitrogen dioxide (NO_2)
- Sulfur dioxide (SO_2)
- Lead (Pb)
- Photochemical oxidants as ozone (O_3)
- Particulate matter with an aerodynamic diameter of less than 10 µm (PM_{10})

The goal of the AAQ NEPM was to ensure compliance with the standards within 10 years of commencement, in order to attain 'ambient air quality that allows for the adequate protection of human health and wellbeing'. The pollutants, metrics, limit values and goals set out in the AAQ NEPM are summarised in **Table 1.1**.

States and Territories are required to monitor and report on air quality to determine whether the NEPM standards are met within populated areas. The NEPM monitoring protocol states that some monitoring stations should be located in populated areas which are expected to experience relatively high concentrations, providing a basis for reliable statements about compliance within the region as a whole. These stations are called 'generally representative upper bound (GRUB) for community exposure' sites. However, it is also necessary to ensure that any NEPM monitoring network provides a widespread coverage of the populated area in a region, and yields data that are indicative of the air quality experienced by most of the population in the region.

The AAQ NEPM was extended[8] in 2003 to include advisory reporting standards for PM with an aerodynamic diameter of less than 2.5 µm ($PM_{2.5}$). The standards for $PM_{2.5}$ were underpinned by a monitoring study at thirteen locations in four cities over a three-year period **(NEPC, 2002)**. The current annual mean standard of 8 µg/m^3 was selected as it represented an improvement in air quality across most urban centres, thereby delivering significant improvement in health in these locations.

[7] National Environment Protection (Ambient Air Quality) Measure (1998). http://www.comlaw.gov.au/Details/C2004H03935/Download

[8] National Environment Protection (Ambient Air Quality) Measure variation (2003), Gazette 2003, no. S190.

Table 1.1: Metrics and limit values in AAQ NEPM

Pollutant	Averaging period	Maximum concentration	Goal within 10 years (maximum allowable exceedances)
CO	8 hours	9.0 ppm	1 day per year
NO_2	1 hour 1 year	0.12 ppm 0.03 ppm	1 day per year None
SO_2	1 hour 24 hours 1 year	0.20 ppm 0.08 ppm 0.02 ppm	1 day per year 1 day per year None
Pb	1 year	0.50 µg/m³	None
O_3	1 hour 4 hours	0.10 ppm 0.08 ppm	1 day per year 1 day per year
PM_{10}	24 hours	50 µg/m³	5 days per year
$PM_{2.5}$[(a)]	24 hours 1 year	25 µg/m³ 8 µg/m³	Not applicable

(a) Advisory reporting standards.

It is worth noting that in the United States (US) a recent review has led to the tightening of the annual mean standard for $PM_{2.5}$ from 15 µg/m³ to 12 µg/m³ **(USEPA, 2013)**. The aim of this was to provide increased protection against the health effects associated with both long-term and short-term exposure (including premature mortality, increased hospital admissions and emergency department visits, and development of chronic respiratory disease).

1.2 Reducing population exposure to particulate matter

As noted above, the current approach to air quality management in Australia focuses on reducing exceedances of ambient air quality standards at specific locations. These standards are designed to protect human health. However, for PM_{10} and $PM_{2.5}$ there is no evidence of a threshold concentration below which adverse health effects are not observed **(Pope and Dockery, 2006**; **Brook *et al.*, 2010; USEPA, 2009; COMEAP, 2009)**. Over the typical range of ambient PM concentrations the relationship between the concentration and the health response is, broadly speaking, linear. Therefore, even where a NEPM standard is not exceeded – and PM_{10} concentrations in Australian cities are below the standards for most of the time[9] **(Commonwealth of Australia, 2011)** – there is still a health benefit to be gained from reducing overall exposure to PM, especially in areas of high population density. Overall health outcomes are driven by large-scale population exposure to the prevailing background PM concentration.

By way of example, the health benefits associated with reducing the average PM concentration by 1 µg/m³ across a population of 100,000 people are ten times greater than those from reducing the average PM concentration by 10 µg/m³ across a population of 1,000 people. These benefits are not affected by the absolute concentration. Thus, for a given population reducing the average PM concentration from 28 µg/m³ to 27 µg/m³ is expected to deliver the same health benefits as reducing the average concentration from 8 µg/m³ to 7 µg/m³ **(Bawden *et al.*, 2012)**.

So, whilst air quality standards have an important role to play in driving down PM concentrations where exceedances are measured or predicted, localised remedial actions are unlikely to lead to large-scale

[9] High observed PM concentrations are typically a result of bushfires and dust storms.

reductions in population exposure. In addition, in areas of higher population density where there are no exceedances of the standards, there is currently no driver to implement measures to reduce exposure to PM **(Bawden *et al.*, 2012)**.

1.3 Characterisation of airborne particulate matter

Airborne PM is a complex mixture of materials from different sources, and the contributions of these sources vary considerably both temporally and spatially. The components of PM can be categorised in a number of different ways depending on, say, the requirements of a study or the analytical techniques used to determine PM composition. However, it is usually necessary to distinguish between the following:

- Primary natural PM
- Primary anthropogenic PM
- Secondary natural PM
- Secondary anthropogenic PM

Primary natural PM is emitted directly into the atmosphere as a result of processes such as wind erosion (mineral dust) and the production of marine aerosol (sea salt). Primary anthropogenic particles result from processes involving either combustion (*e.g.* industrial activity, domestic wood heaters, vehicle exhaust), resuspension (*e.g.* resuspension of dust on haul roads at coal mines) or abrasion (*e.g.* road vehicle tyre wear). Secondary PM is not emitted directly, but is formed by chemical reactions involving gas-phase components of the atmosphere. The main gaseous precursors are oxides of nitrogen (NO_X), ammonia (NH_3), sulfur oxides (SO_X) and volatile organic compounds (VOCs). Again, the origin of these may be natural or anthropogenic. Various studies have shown that secondary particles can contribute significantly to $PM_{2.5}$ and PM_{10} (see, for example, the extensive review by the United States Environmental Protection Agency **(USEPA, 2009)**). For both primary and secondary PM there is a further division between inorganic and organic components. This is especially important for secondary PM. As suggested by the gaseous precursors mentioned above, the inorganic and organic components of secondary PM typically include the following:

Inorganic:	Ammonium nitrate (with some sodium nitrate) Ammonium sulfate
Organic:	A complex mixture of compounds, commonly referred to as secondary organic aerosol (SOA)

In practice, there are several difficulties associated with identifying and quantifying the different components in ambient PM measurements, a process which is commonly termed 'source apportionment'. For example, whilst the gaseous precursors of inorganic secondary PM are largely anthropogenic it is very difficult to know what fractions of SOA result from anthropogenic and natural sources; the theoretical borderline between these two source types effectively disappears when SOA formation processes are considered **(Gelencsér *et al.*, 2007)**.

There is a growing body of literature of PM source apportionment in Australia. Extensive studies have been undertaken in Brisbane - and to a lesser extent in Melbourne, Sydney and Adelaide - by Griffith University **(Chan *et al.*, 1997, 1999, 2000, 2008, 2011)**. These studies have shown that secondary PM forms a significant component of PM_{10} and $PM_{2.5}$. It was observed by **Chan *et al.* (1999)** that secondary organic compounds and secondary sulfates accounted for 21% and 14% of $PM_{2.5}$ respectively at a suburban site in Brisbane. In a study in the four cities mentioned above, **Chan *et al.* (2008)** found that, on average, secondary nitrates/sulfates contributed about 25% of $PM_{2.5}$.

The Commonwealth Scientific and Industrial Research Organisation (CSIRO) has investigated the 'natural'[10], 'primary' and 'secondary' contributions to $PM_{2.5}$ at one location (Westmead, NSW), and how they vary seasonally **(Cope, 2012)**. Some results from this work are shown in **Figure 1.1**. The component labelled 'Other (mass balance)' in the Figure is used to conserve mass between the estimates of $PM_{2.5}$ in the NSW GMR emissions inventory and the estimated breakdown of $PM_{2.5}$ from the monitoring data. This component will include dust emissions from industrial sources such as mining. In the summer months, the primary PM component constitutes about 30% of the monthly mean particle mass, and in June this rises to 50% **(Cope, 2012)**. This partial contribution complicates the policy management of PM concentrations.

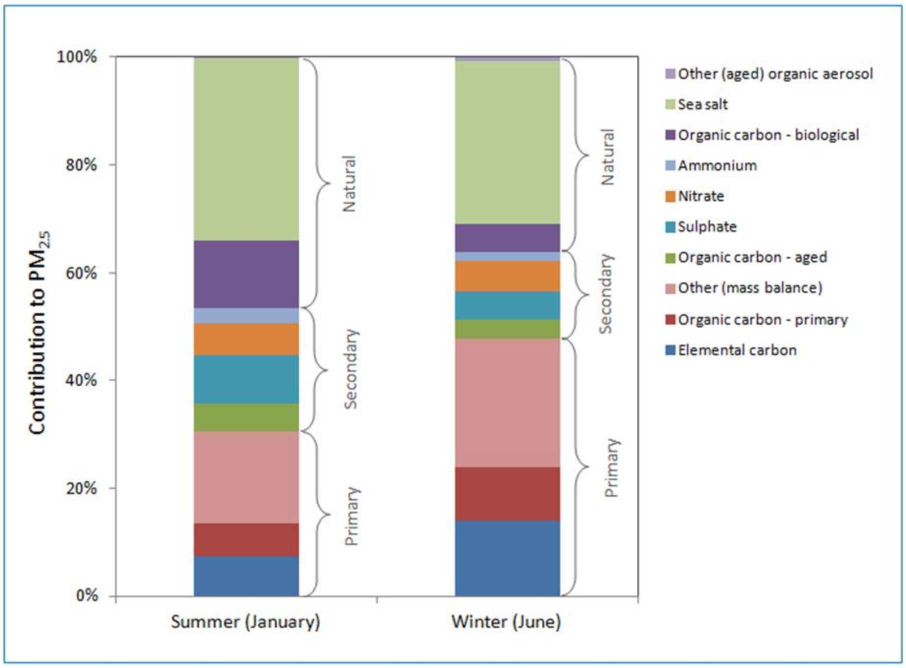

Figure 1.1: Modelled breakdown of $PM_{2.5}$ during summer and winter months at Westmead NSW (adapted from Cope, 2012)

1.4 National Plan for Clean Air

1.4.1 Overall approach

In 2010 the then-Environment Protection and Heritage Council (EHPC) recommended that air quality management in Australia should take a strategic approach that integrates the setting of air quality standards with actions that reduce air pollution and the community's exposure to it. In 2011 a number of further steps were taken towards improving the regulation of air pollution in Australia, notably:

- The National Environment Protection Council (NEPC) published a review of the AAQ NEPM which recommended updating the standards for PM_{10}, $PM_{2.5}$, NO_2, O_3, and SO_2 **(NEPC, 2011a)**.
- NEPC published a methodology for the setting of air quality standards **(NEPC, 2011b)**.
- The Council of Australian Governments (COAG) identified air quality as an issue of national priority **(COAG, 2012)**, and agreed that its Standing Council on Environment and Water (SCEW)

[10] As noted earlier, natural PM can also be either primary or secondary in origin.

would implement a strategic approach to air quality management in the form of a National Plan for Clean Air (NPCA).

The development of an exposure-reduction framework for PM was another important recommendation of the AAQ NEPM review, and the options for developing such a framework were investigated by Pacific Environment **(Bawden *et al.*, 2012)**.

In response to the recommendations of the NEPM review and COAG's recognition of air quality as a priority issue, SCEW established an Air Thematic Oversight Group (Air TOG)[11] to develop the NPCA. The aims of the NPCA include the following **(COAG, 2012)**:

- Bringing together Commonwealth, State and Territory actions into a national plan to reduce the risk of health impacts due to air pollution.
- Integrating air quality standard-setting with actions to reduce pollution and exposure to pollution.
- Modernising standards and responding to the latest science by introducing an exposure-reduction framework for pollutants which have no safe threshold (such as PM).
- Prioritising measures that achieve a net benefit to the community.
- Responding to emerging trends by working with sectors from which emissions are growing.

The NPCA is being developed in two stages:

- Stage 1, which involves the following:
  a. A health risk assessment (HRA) of the criteria pollutants (except Pb and CO).
  b. The development of potential air quality standards for PM.
  c. The consideration of an exposure-reduction framework.
  d. The identification of possible PM-abatement options, including options for implementing national product standards to control emissions from a range of products and equipment.
  e. A cost-benefit analysis (CBA) of potential air quality standards, an exposure-reduction framework and abatement measures for PM (including $PM_{2.5}$).
- Stage 2, which involves drafting the NPCA documents and public consultation, and consideration of whether to proceed with revised standards for NO_X, SO_2 and O_3. It also includes a revision of the AAQ NEPM monitoring and reporting protocols, the regulatory steps associated with implementing any new air quality standards for PM, and the steps to implement emission-reduction actions.

The economic analysis described in this Report deals with the CBA for the NPCA (Stage 1e above).

1.4.2 Hypothetical air quality standards

In a separate project the Impact Assessment Working Group (IAWG) of the Air TOG developed a range of potential new air quality standard scenarios for both PM_{10} and $PM_{2.5}$. For the purpose of the economic analysis these are referred to as 'hypothetical' air quality standards, though they also

[11] The Air TOG consists of a representative from each jurisdiction and the Commonwealth. Two groups report to the Air TOG: (i) an Impact Assessment Working Group tasked with air quality health risk assessment studies, and (ii) an Impact Mitigation Working Group tasked with identifying emission-reduction actions.

include the existing standards. The standards for PM_{10} and $PM_{2.5}$ proposed by the IAWG are given in **Table 1.2**. The scenarios are based on international guidance (*e.g.* from the World Health Organisation (WHO) and US Environmental Protection Agency (USEPA), but were informed by Australian conditions. The most stringent standards were considered to reflect minimum realistic values for Australia, taking into account natural background and current air quality trends. The IAWG also developed scenarios for NO_2, SO_2 and O_3, but these were not used in the economic analysis and are not shown in the Table. The assumed implementation dates for the air quality standards was 1 January 2015.

Table 1.2: Hypothetical air quality standards proposed by IAWG. Current Australian standards and advisory reporting levels are shown in bold

Pollutant	Averaging period	Concentration (µg/m³)
PM_{10}	1 year	20.0
		16.0
		12.0
$PM_{2.5}$	1 year	10.0
		8.0
		6.0
PM_{10}	24 hours (5 exceedances allowed)	**50.0**
		40.0
		30.0
$PM_{2.5}$	24 hours (no exceedances allowed) *[See comment below]*	**25.0**
		20.0
		15.0

It should be noted that although the 24-hour $PM_{2.5}$ standards relate to the maximum concentration, in practice this is highly variable and difficult to evaluate on a consistent and meaningful basis. We have therefore used the 98th percentile 24-hour $PM_{2.5}$ concentration as the level required for compliance in this case.

1.4.3 Exposure-reduction framework

1.4.3.1 Justification for an exposure-reduction framework

As noted in **Section 1.2**, an exposure-reduction framework is a potentially useful policy mechanism as there is no convincing evidence of a threshold for health effects arising from exposure to PM. **Bawden *et al.* (2012)** emphasised the importance of drawing a distinction between approaches which maximise equity (whereby individuals most at risk of exposure to the highest concentrations are protected to a uniform, minimum standard, and those which maximise efficiency (which relates to the ability to maximise health benefits across the population, *e.g.* life-years saved). NEPM standards for PM have an important role to play in maximising equity, but can be usefully complemented by an exposure-reduction approach which seeks to maximise efficiency.

The exposure-reduction approach is currently applied in Europe. The Ambient Air Quality Directive (2008/50/EC) aims towards a general reduction of concentrations in the urban background to ensure that large sections of the population benefit from improved air quality. Again, to ensure equity the approach should be combined with a traditional air quality standard to provide a minimum degree of health protection everywhere.

1.4.3.2 Investigation of options

Bawden *et al.* (2012) presented four potential options for an exposure-reduction approach in Australia, based around monitoring and/or emission ceilings:

- Option 1: A Cleaner Air Programme (CAP) approach[12], with no fixed targets but a requirement placed on all jurisdictions to set out programmes to reduce emissions of both primary PM and precursors of secondary PM.
- Option 2: An exposure-reduction system based on monitoring, with target reductions set on an Australia-wide basis. The target reduction could be advisory or mandatory.
- Option 3: An exposure-reduction system based on an emission ceiling for primary PM, with targets set for individual jurisdictions based on the damage cost approach (see **Section 2.1**). The target reduction could be advisory or mandatory (it would differ from Option 1 in that targets are established).
- Option 4: A hybrid approach between Options 1 and 3. The emissions ceiling for primary PM would be supported by the CAP approach to reduce emissions of secondary PM precursors.

Air TOG members and other government stakeholders attended a workshop in Sydney in September 2012 to discuss the Options. It was concluded that no single option was preferable, and an integrated approach was needed to capture the benefits of each one.

1.4.3.3 Proposed exposure-reduction framework

The next steps for the development of an exposure-reduction framework in Australia were discussed in a meeting of the Air TOG in November 2012. The principal aim of the meeting was to provide direction for the economic analysis assessment, and the main elements of the proposed approach were:

1. Exposure reduction in addition to traditional air quality standards.
2. An exposure-reduction target of a 10% reduction in measured long-term average $PM_{2.5}$ concentrations, with:
   - 10 years to achieve the target.
   - A baseline concentration based on at least three years of monitoring data to reduce inter-annual variability.
   - The target being applicable at monitors located in populated regions.
3. Annual reporting of emission-reduction actions including the quantified effectiveness of each action, expressed in terms of mass emission reduction of each pollutant (primary $PM_{2.5}$ and secondary $PM_{2.5}$ precursors).
4. Annual reporting of $PM_{2.5}$ emissions and trends.
5. Annual reporting of ambient levels of $PM_{2.5}$ and trends.
6. Development of regional air quality modelling capability for major population centres.

The implications of the 10% exposure-reduction target were addressed in the economic analysis.

[12] Similar to an existing Canadian programme.

1.5 The need for cost-benefit analysis in the NPCA

CBA is a widely-used economic tool for evaluating environmental policy options. Its main strength is that it permits decision-makers to develop pollution-control strategies in an objective manner, and allows the economics of environmental protection to be framed in a wider context. Essentially, in a CBA the health benefits (and savings) associated with improved air quality are weighed against the costs of implementing specific pollution-abatement actions. This enables the measures with the highest net economic benefit to be prioritised before implementation. Continuous reductions in PM emissions and improvements in air quality could be pursued as long as a net benefit can be demonstrated, taking into account costs and benefits to government, industry and the community.

Exposure to airborne PM is correlated with a range of detrimental effects on human health. These health effects are divided into two broad categories - premature mortality and morbidity - and each of these are, in turn, associated with different economic impacts. The health benefits that accompany reduced ambient air pollution are substantial, and the benefits of reducing PM outweigh the benefits of reducing the other criteria air pollutants **(Jalaludin *et al.*, 2011)**. For Sydney alone it has been estimated that reducing exposure to PM_{10} could save $4.7 billion per year **(NSW DEC, 2005)**. More recently, **Jalaludin *et al.* (2011)** found that if the PM_{10} concentration in the NSW Greater Metropolitan Region (GMR) could be reduced to 10 µg/m³, 491 respiratory disease hospitalisations would be avoided each year. If the $PM_{2.5}$ concentration could be reduced to 5 µg/m³, then on average 864 deaths and 509 cardiovascular disease hospitalisations would be avoided annually. The associated health benefit for the NSW GMR as a consequence of reducing ambient $PM_{2.5}$ and PM_{10} to these levels was $5.65 billion. Transport is a major source of PM; the health costs of transport emissions of PM_{10} in Australia have been estimated to be $2.7 billion per year **(BTRE, 2005)**.

Premature death is the most significant health endpoint in any air pollution CBA. For the NSW GMR **Jalaludin *et al.* (2011)** noted that the greatest proportion (>99%) of the health benefits were accrued from avoiding premature deaths due to long-term exposure to $PM_{2.5}$. Premature death is the major driver of the health benefits because of the high monetary value allocated to a human life. For example, **Jalaludin *et al.* (2011)** used a value of a statistical life (VSL) of $6.54 million, compared with $5,367 for the cost of a respiratory disease hospital admission and $9,096 for the cost of a cardiovascular disease hospital admission.

Policies and measures for controlling air pollution act by either prevention (to reduce emissions) or mitigation (to reduce ambient concentrations or exposure). Prevention generally involves legislation at a national or regional level (*e.g.* limits on road vehicle exhaust emissions), whereas mitigation is often local in nature (*e.g.* barriers or improved ventilation). The available policies and measures are therefore wide-ranging, especially for PM, with substantial variations in both cost and effectiveness.

Understandably, because of the size of the potential health benefits, the current population exposure, and the range of actions available, in the first stage of the development of the NPCA the focus is on PM **(COAG, 2012)**.

1.6 Project objectives

The overall objective of the economic analysis project was to provide the information required to develop a package of standards, exposure-reduction targets and possible actions on PM which will provide the greatest social benefits net of resources invested. The project was designed to answer the following specific questions, which have been adapted from the original project objectives:

- What total reductions in PM emissions would be required to meet the hypothetical air quality standards?
- What are the abatement measures that are feasible at the national level?

- What would be the effects on emissions and air quality of introducing all feasible abatement measures?
- What would be the net economic benefit of compliance with the hypothetical air quality standards?
- What would be the net economic benefit of implementing all feasible national abatement measures?
- What would be the net economic benefit of implementing all economic national abatement measures?
- What reductions in PM emissions would be required to meet the exposure-reduction target?
- What would be the monetised health benefit of implementing a new exposure-reduction framework for PM?

1.7 Report structure

The development of the overall methodology for the economic analysis is summarised in **Chapter 2.** The subsequent Chapters provide details of the following:

- The determination of base-year PM emissions and concentrations in each jurisdiction, and 'business-as-usual' (BAU) scenarios involving the projection of the base year values into the future (**Chapter 3**).
- The characterisation (emission-reduction potential, implementation costs, timeframe, *etc.*) of the potential new abatement measures that would be available, and the selection of actual measures for inclusion in the economic analysis (**Chapter 4**).
- The identification, quantification and monetisation of the benefits associated with reduced PM_{10} and $PM_{2.5}$ concentrations (**Chapter 5**).
- The overall economic analysis of the hypothetical air quality standards and exposure-reduction target (**Chapter 6**).

Chapter 7 provides the conclusions from the work, and input/advice from third parties is acknowledged in **Chapter 8**.

2 DEVELOPMENT OF COST-BENEFIT ANALYSIS METHODOLOGY

2.1 Valuing the health impacts of air pollution

The most detailed method for valuing the health impacts of air pollution is often referred to as the 'impact pathway' approach. This approach has been applied in a number of European Union (EU), UK and US studies **(***e.g.* **AEA, 2005; Defra, 2007; Fann *et al*., 2009)**, and involves the following main steps:

- Step 1: *Quantification of air pollutant emissions*, with spatially disaggregated (*e.g.* grid-based) emission inventories and source apportionment.
- Step 2: *Analysis of pollutant dispersion and chemistry*. This includes the consideration of primary pollutants and secondary pollutants (secondary PM such as sulfates, or gaseous pollutants such as ozone), and the assessment of changes in pollutant concentrations.
- Step 3: *Quantification of the exposure* of people, the environment and buildings that are affected by air pollution. For health impacts this involves linking pollution data and population data.
- Step 4: *Quantification of the impacts of air pollution*. The impacts of air pollution on human health are assessed in relation to defined health endpoints such as mortality and hospital admissions for respiratory disease. The outcomes are typically determined using relationships from epidemiological studies that link pollutant concentrations with physical impacts.
- Step 5: *Valuation of the impacts*. This is usually undertaken using a 'willingness to pay' (WTP) approach based on stated and revealed preference techniques.
- Step 6: *An analysis of the uncertainties* associated with the quantification and valuation of health effects.

The impact-pathway approach is the recommended best practice for monetising the impacts of major new air quality standards and policies because it uses detailed, location-specific data and has the potential to provide a relatively high degree of precision. However, there are considerable uncertainties associated with each step of the pathway. The approach is also resource intensive - prohibitively so for many impact assessments - with a large volume of information being required.

As a consequence, simplified approaches have been developed. Some countries have produced tables or models to permit the valuation of air quality impacts based solely on the change in the amount of a pollutant emitted. These are frequently referred to as 'damage cost' or 'unit cost' methods. The specific damage costs for a particular country or region are usually a spin-off from a detailed impact pathway assessment. The damage cost approach may be used either as an alternative where the impact pathway approach is not practical, or as a verification of the results from the impact pathway approach. Damage costs have typically been used for policy applications such as revisions to air quality standards and regulatory assessments for specific sectors.

2.2 Cost-benefit analysis of air quality standards

Where a revision to air quality standards is being considered (as in the NPCA) it is desirable to conduct a CBA to compare at least one hypothetical scenario - in which concentrations have been driven down to meet a more stringent standard - with a BAU case. The BAU case reflects the anticipated future trends in emissions and air quality based on current and planned policies and actions. The overall net monetary benefit to society of the hypothetical scenario is expressed as the difference between the results of two calculations:

(a) The pollution-related costs (mainly health costs) that are avoided when moving from the BAU case to the hypothetical scenario. The health savings associated with the hypothetical scenario are over and above those that would have been achieved in the BAU case.

(b) The changes in pollution abatement costs between the two scenarios. Again, the abatement costs of the hypothetical scenario are in addition to the abatement costs for the BAU scenario.

In other words, the CBA should assess whether the marginal benefits of compliance with a hypothetical air quality standard exceed the marginal costs of implementing additional abatement strategies.

As noted by **Wilson *et al.* (2011b)**, undertaking a comprehensive CBA of the type required for the NPCA is a complex, multi-step process. For example, pollutants have diverse sources, control measures, health impacts and atmospheric interactions. The general impact pathway and damage cost approaches described in **Section 2.1** mask a number of subtleties, and some of these are discussed below.

An important consideration is the timescale for the assessment. The availability of different abatement actions over different time frames necessitates a multi-period framework **(Hohnen *et al.*, 2011)**. The long lifetime of some of abatement measures (in terms of both costs and benefits) means that emission projections are required well into the future. The effects of abatement therefore need to be considered relative to a BAU scenario in which emissions and concentrations are projected into the future. In the BAU scenario the emission projections need to incorporate the anticipated trends in economic activity, population growth and various other factors. **Figure 2.1** shows two simplified examples of BAU scenarios. In the first example the BAU case involves a reduction in the PM concentration with time. This might represent, for example, an area in which emissions are dominated by road transport, with an ongoing development of emission-control technology and a continual replacement of older vehicles driving down emissions. In the second example the PM concentration is increasing with time in the BAU scenario. This would be typical of an area in which growth in activity has outstripped the capacity of technology to control emissions. For instance, emissions due to domestic activity would be likely to increase in line with population growth in the absence of controls on, say, wood heaters. In most locations the BAU scenario will be a complex superimposition of the effects of different sectors, each with its own set of assumptions concerning the pattern in the future.

Wilson *et al.* (2011a) have emphasised that the BAU case for each pollutant needs to be carefully considered to ensure that emissions and abatement strategies are accurately allocated between the BAU and hypothetical scenarios. It would be relatively easy to attribute an abatement strategy to the wrong scenario and significantly alter the outcome of the CBA. For example, it could be assumed that an abatement policy is part of a scenario rather than a discretionary event to be determined by future circumstances. Projecting the BAU scenario requires forecasting the timing and introduction of abatement policies that are likely to happen without a change in the standard.

The date for compliance with an air quality standard also needs to be clearly stated. **Figure 2.1** shows how a new standard would be implemented in a given year (Y_i), with the expectation of compliance by a target year (Y_t). Compliance with the standard requires a net reduction in the ambient PM concentration, and hence a corresponding reduction in the annual emission rate between the base year of the study (Y_b) and the target year. An air quality standard can rarely be achieved instantaneously **(Hohnen *et al.*, 2011)**. The reduction in emissions is achieved via the implementation of a portfolio of abatement actions, with the selection of actions being based on availability[13] within the time frame, effectiveness and cost.

[13] The implementation of abatement actions is often restricted by availability of technology, duration required to implement, and timing of proposed and existing regulations **(Hohnen *et al.*, 2011)**.

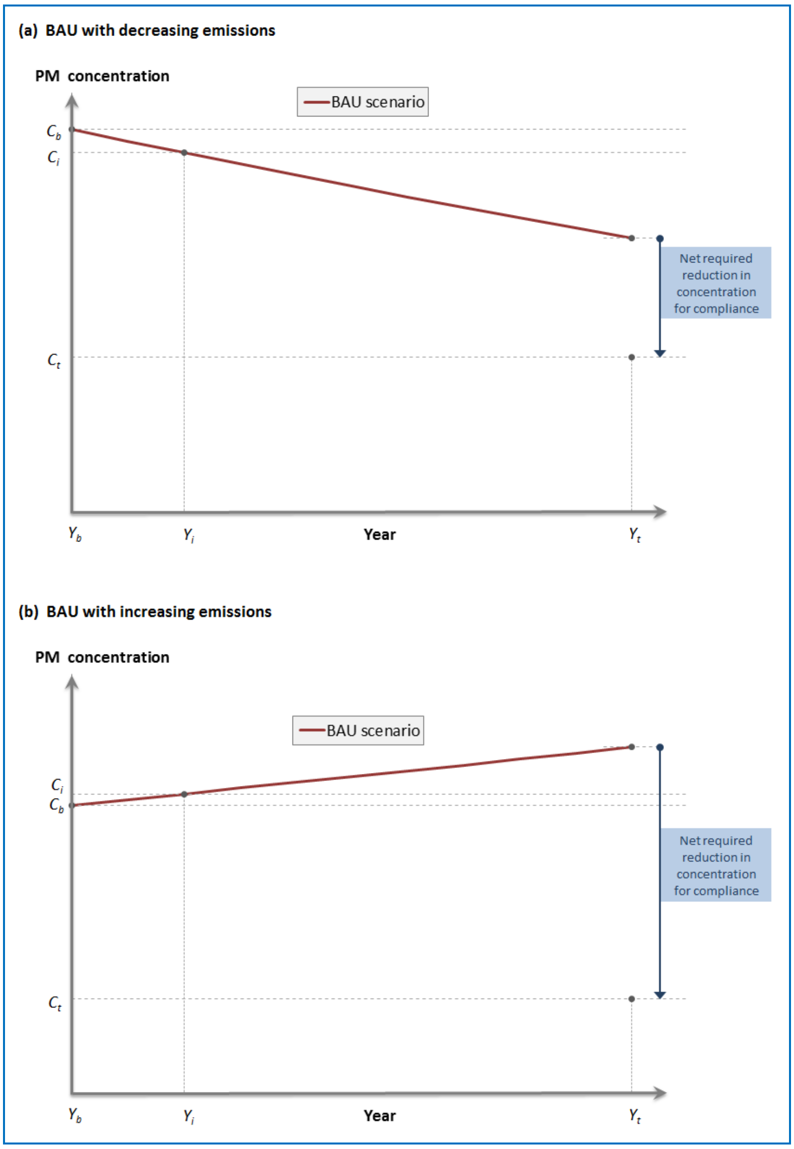

Figure 2.1: Compliance with an air quality standard target for PM with (a) decreasing BAU emissions and (b) increasing BAU emissions (Y_b, Y_i and Y_t are the base year, introduction year and target years. C_b, C_i and C_t are the PM concentrations in these years).

Figure 2.1 gives a generic picture; the concentrations for the base and implementation years will vary considerably from location to location, and therefore different emission reductions will be required for each location. The required emission reductions must therefore include all constituent areas (this applies equally to the quantification of health benefits). However, as we will show later in this Report, in the real world, with its complexity of emission sources, there is actually no such thing as a definitive emission reduction to achieve compliance with an air quality standard, as this depends on which sectors of activity are being addressed.

There are various options for reducing emissions to meet a hypothetical air quality standard. The emphasis is usually on reducing anthropogenic emissions from sources such as industry and road transport, as opposed to biogenic emissions (*e.g.* volatile organic compounds emitted by vegetation). Hence, a CBA requires the development and evaluation of a range of emission abatement options and should include an assessment of their cost-effectiveness. The cost-effectiveness assessment of abatement strategies should ideally take place prior to inclusion in the CBA framework. This assessment allows various strategies to be ranked in order of most effective to least effective. Effectiveness is determined by, in most cases, the cost per unit of air quality improvement **(Wilson *et al.*, 2011a)**.

Pollutants are often assumed to act independently in affecting any given health endpoint. There are assumed to be no synergistic or antagonistic effects, and the effects of different pollutants on the same endpoint are taken to be additive. In reality some degree of synergism or antagonism may be expected **(Wilson *et al.*, 2011b)**. A common approach to quantifying the health effects of air pollution is to select a single pollutant to estimate the cases attributable to air pollution. This method avoids aggregating the effects of each individual air pollutant, which would overestimate the health impact. $PM_{2.5}$ is considered the best marker of PM for quantitative assessments of the effects of policy interventions **(COMEAP, 2009)**.

2.3 Project methodology

This Section explains, in general terms, the CBA methodology that was applied in the project, taking into account the issues identified so far in the Report. The methodology built upon the provisional approach and CBA developed as part of the AAQ NEPM review, as described in the following:

- National Environment Protection (Ambient Air Quality) Measure – Draft Cost Benefit Analysis Methodology **(Wilson *et al.*, 2011a)**.
- National Environment Protection (Ambient Air Quality) Measure – Draft Preliminary Cost Benefit Analysis **(Wilson *et al.*, 2011b)**.

Wilson *et al.* (2011a) set out the approaches for assessing the health benefits of complying with air quality standards, and the costs (to both industry and government) of the actions required to achieve compliance. Whilst the study identified a net overall benefit of new air quality standards, the provisional CBA was based on hypothetical changes to a limited number of pollutants and airsheds.

Our analysis was more comprehensive in scope. It strengthened the methods for estimating the impacts of abatement measures on emissions and air quality (especially in NSW and Victoria), as well as the costing and assessment of these measures. The economic analysis project also generated jurisdiction-specific 'cost curves'. These ranked actions and showed least-cost pathways to achieve compliance with the hypothetical air quality standards. In this way the project identified the set of actions, standards and targets that maximised the benefits for the Australian population.

The economic analysis was conducted for the different Australian airsheds, and for the hypothetical air quality standards for PM_{10} and $PM_{2.5}$ (see **Table 1.2**) as well as the exposure-reduction target (**Section 1.4.3.3**). The base year for the assessment was 2011, and the target year for achieving the air quality standards was 2036. We considered the health (and other) benefits of the various hypothetical air quality standards and exposure-reduction target. Where significant residual emission reductions (or costs) associated with a specified abatement measure continued beyond 2036, these were also calculated.

There was also a need to define a 'compliance metric' – in other words a metric that could be used to determine when and where compliance with a given hypothetical air quality standard had been achieved. Two options were considered:

- Compliance with a standard on a population-weighted basis for a whole region (a similar approach has previously been used in previous CBAs).
- Where gridded data were available, compliance with a standard in all grid cells.

These options, and their relevance to the AAQ NEPM, are discussed in more detail later in the Report.

The project was informed by a number of major studies, including:

- Regulatory Impact Analysis for the Proposed Revisions to the National Ambient Air Quality Standards for Particulate Matter **(USEPA, 2012)**.

- An Economic Analysis to inform the Air Quality Strategy - Updated Third Report of the Interdepartmental Group on Costs and Benefits **(Defra, 2007)**.
- A Methodology for Cost-Benefit Analysis of Ambient Air Pollution Health Impacts **(Jalaludin *et al*., 2009)**.
- Health benefits of reducing ambient air pollution levels in the Greater Metropolitan Region **(Jalaludin *et al*., 2011)**.
- Air Quality Appraisal – Valuing Environmental Limits **(Defra, 2010)**.
- Air Quality Appraisal – Damage Cost Methodology **(Defra, 2011)**.

The overall methodology was broken down into the following tasks:

- Task 1.1: The development of the project methodology.
- Task 2.1: Modelling of baseline emissions and concentrations in 2011(where data allowed this).
- Task 2.2: The development of an emission projection method, and the determination of population-weighted concentrations for a BAU scenario in future years (2012-2036).
- Task 2.3: The determination of the emission and concentration reductions required for compliance with hypothetical air quality standards in each study year.
- Task 3.1: The identification of health and other outcomes.
- Task 3.2: The quantification of health and other outcomes.
- Task 3.3: The monetisation of health and other outcomes.
- Task 4.1: The calculation of costs for abatement measures. Most of the measures were identified by the Impact Mitigation Working Group (IMWG) of the Air TOG.
- Task 5.1: An assessment of the impacts of introducing a national exposure-reduction framework.
- Task 6.1: The determination of the net benefits of the candidate air quality standards and exposure-reduction approaches/targets.
- Task 7.1: A sensitivity analysis.

This list of tasks implied a methodology which would be similar to the impact pathway approach previously used for CBA in the EU and the UK[14]. However, for the EU and UK analyses the resources available were much greater, the modelling data were more extensive, and the timescales for completion much longer, than those for the NEPC project. Moreover, recent work[15] conducted for NSW Environment Protection Authority (EPA) by Pacific Environment (working with Air Quality Consultants and Paul Watkiss Associates from the UK) has indicated that in Australia there is insufficient information for a full impact pathway evaluation. We therefore used an approach of intermediate sophistication; it was pragmatic and utilised the existing Australian data and modelling to the best advantage. However, it also recognised the underlying complexity of the processes involved and the limitations of the data. The overall process and the links between the different tasks are outlined in **Figure 2.2**.

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[14] Examples include the cost-benefit analyses for the EU Clean Air for Europe (CAFE) programme and the review of the Air Quality Strategy in the UK.

[15] NSW EPA projects *Methodology for valuing the health impacts of changes in particle emissions* (Reference OEH-1072-2011) and *Evaluating Options for an Exposure-Reduction Framework in Australia* (Reference OEH-147-2012).

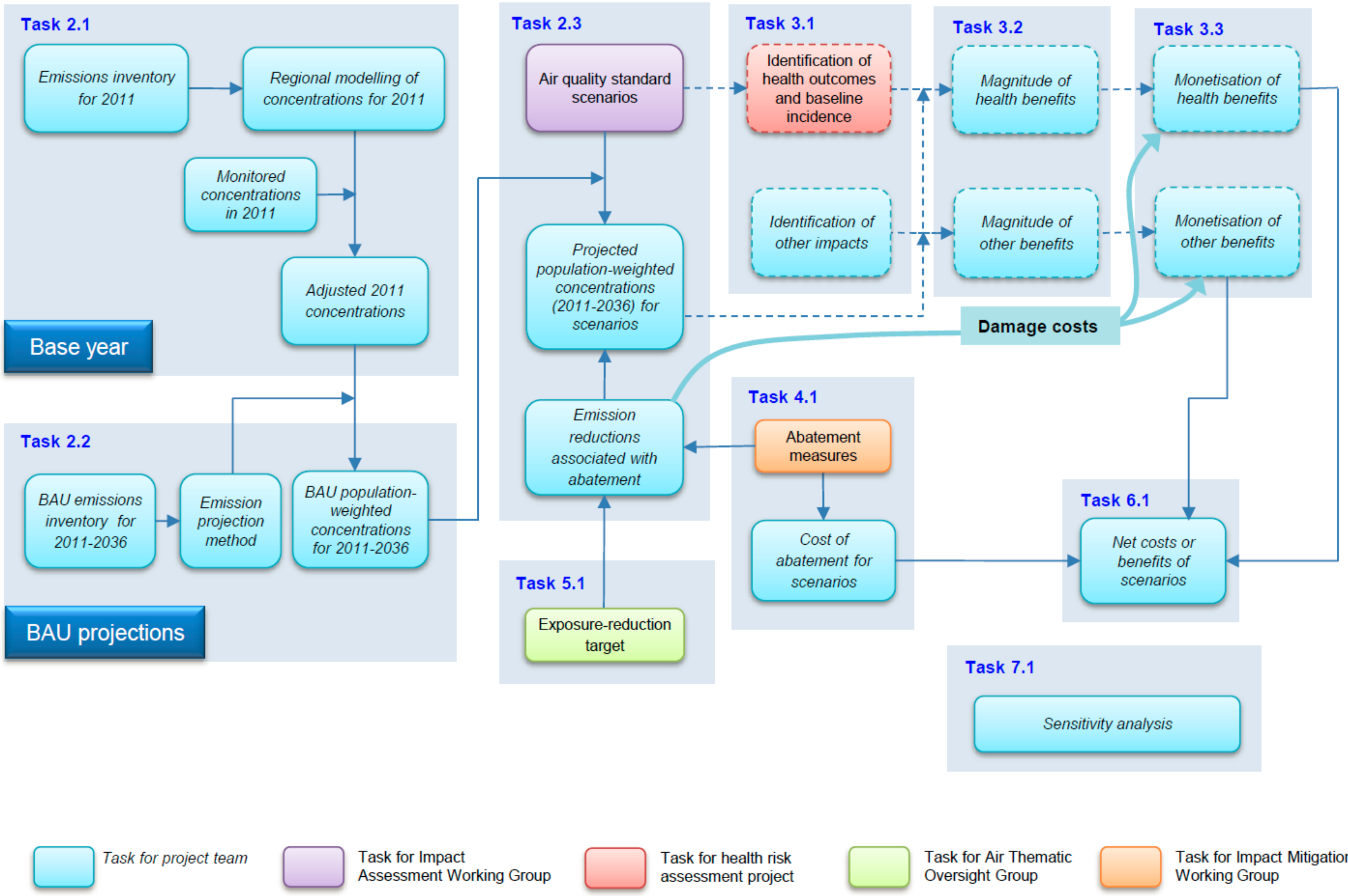

Figure 2.2: Overview of economic analysis process

Task 2.1 required the state-wide collection of spatially disaggregated emissions data and modelling of pollutant concentrations. For reasons that will be explained in the next Chapter of the Report, this was only possible in NSW and Victoria, and a simpler approach was applied to other jurisdictions.

In relation to Task 3.2, the usual steps for each health endpoint are:

- Determination of the baseline incidence for the endpoint.
- Determination of the concentration-response relationship for the endpoint.
- Determination of the decrease in incidence of the endpoint due to a reduced pollutant concentration.

Given the available data our valuation of health benefits necessarily focussed on the use of the damage cost approach (as shown in **Figure 2.2**) in preference to an impact pathway-type approach. For this we used the unit damage costs[16] for primary $PM_{2.5}$ in Australia developed by **Aust *et al.* (2013)**. A simplified impact pathway approach was then used as a ‘reality-check’ of the results for specific locations as far as the data allowed, with the baseline health incidence being quantified by the HRA project **(Frangos and DiMarco, 2012)**. This secondary checking process is shown through the use of dashed lines in **Figure 2.2**.

Another important issue was that of secondary PM, and this is treated in more detail in **Chapter 3**.

The specific Tasks in **Figure 2.2** are described in more detail in the relevant Chapters and Appendices.

[16] These relate damage costs of emissions in A$/tonne of pollutant to population density.

3 EMISSIONS AND CONCENTRATIONS

3.1 Base year emissions and concentrations

In this part of the work (see Task 2.1 in **Figure 2.2**) data were obtained to enable changes in ambient PM concentrations to be estimated from changes in primary PM emissions for subsequent use in the testing of scenarios. The methodology was influenced to a large extent by the emission inventory data that were available for each jurisdiction.

In Australia there are two types of inventory: the National Pollutant Inventory (NPI) and regional (state-based) inventories. The current status of these was reviewed by **Bawden *et al.* (2012)**. The NPI emissions data do not, in general, have the temporal and spatial variation that would be required for detailed air quality modelling purposes. The NPI data are also only collected on an annual basis and are limited in terms of coverage. There is no requirement within the NPI for data suppliers to provide the source parameters that are needed for air quality modelling, such as stack height, exit temperature, exit velocity or stack diameter **(Bawden *et al.*, 2012)**. Regional air emission inventories are maintained by some jurisdictions to inform air quality management decisions and policy analysis. Five jurisdictions in Australia – addressing the major urban centres (*i.e.* Sydney, Melbourne, Brisbane, Perth and Adelaide) - currently use air emission inventories to manage air quality in some way.

A summary of the current status of each regional inventory is provided in **Table 3.1**. The remaining jurisdictions (Tasmania, Northern Territory and ACT) have developed inventories in the past, but these have been less detailed and are not being updated. At present there is no consistency across the inventories; the methodology to estimate emissions from each source is likely to differ significantly, and some inventories are not suitable for regional air quality modelling **(Bawden *et al.*, 2012)**.

The implication of the information in **Table 3.1** was that in the economic analysis a detailed air quality modelling approach was possible in NSW and Victoria, as these jurisdictions had up-to-date gridded emission inventories that were in a suitable format. However, model limitations meant that PM concentrations could only be estimated for two sub-state regions: the NSW GMR and the Port Phillip region. The gridded inventories for these regions included both urban and rural areas, and covered a population of ten million people (approximately 40% of Australia's population). Due to the more limited nature of the data in the other jurisdictions, a simpler approach was applied (see **Appendix A**).

Our economic analysis also focussed on primary anthropogenic PM. Natural and secondary PM components (including biogenic/geogenic emissions, and anthropogenic emissions of some secondary PM precursors[17]) were not explicitly modelled in the project. The reasons for this were as follows:

- The natural components of PM_{10} and $PM_{2.5}$ cannot easily be controlled. These are clearly important in terms of the size of their contribution. For example, **Figure 1.1** suggests that sea salt alone can account for more than 30% of $PM_{2.5}$. This therefore places more emphasis on the control of anthropogenic particles.
- From a toxicological perspective natural particles (notably sea salt) are likely to be more benign than man-made ones. The control of the latter should therefore result in greater health benefits.
- National and state pollution-reduction policies and measures have historically focussed on the control of primary anthropogenic emissions. The precursors of secondary PM (NO_X, SO_X, NH_3 and

[17] Anthropogenic NO_X and SO_2 emissions and concentrations were modelled in NSW and Victoria, but not emissions of organic compounds.

VOC) from some sectors are also subject to legislation and control[18], but this has not usually been linked to their role in secondary PM formation.

- In terms of modelling there is a more direct relationship between primary PM emissions and primary PM concentrations than between the precursors of secondary PM and secondary PM concentrations.
- The PM emission and concentration data were used in health impact calculations involving the use of 'damage costs' values for $PM_{2.5}$. At the outset of the project there were no suitable damage costs for secondary PM in Australia.

Table 3.1: Summary of current status of emission inventories for major Australian urban centres (Bawden *et al.*, 2012)

NSW GMR (a)	Victoria	SEQ (b)	Perth	Adelaide
Base year				
2008	*2006*	*2000*	*Motor vehicles: 2006/07; Other sources: 1998/99*	*Motor vehicles: 2006; Other sources: 1998/99*
Projection years				
2011, 2016, 2021, 2026, 2031, 2036	*2030*	*2005 and 2011 for some source groups*	*None*	*None*
All major sources included				
Yes	**No** The most significant source not included is marine aerosol.	**No** No fugitive windborne, marine aerosols, paved road dust.	**No** Fugitive windborne and marine aerosols were not included.	**No** Biogenic/geogenic emission sources have not been estimated for the Adelaide airshed.
Model ready				
Yes Inventory suitable for regional air quality modelling and readily exportable in model-ready formats.	**Yes** EPA Victoria currently updating inventory to a base year of 2011.	**No** Inventory will be in a format suitable for regional air quality modelling when current update is completed.	**No** Inventory designed for diffuse sources only. Spatial and temporal variation of emissions not assigned.	**No** Inventory designed for diffuse sources only. Spatial/ temporal variation of emissions not assigned. Significant emission sources (*e.g.* biogenic) excluded.
Primary pollutants				
Yes TSP, PM_{10}, $PM_{2.5}$	**Yes** TSP, PM_{10}, $PM_{2.5}$	**Yes** TSP, PM_{10}, $PM_{2.5}$	**No** PM_{10} and $PM_{2.5}$ are included, but not TSP.	**No** PM_{10} and $PM_{2.5}$ are included, but not TSP.
Secondary precursor pollutants				
No Does not include elemental/organic carbon.	**Yes** Includes emissions of all substances.	**No** Does not include SO_3 or elemental/ organic carbon.	**No** Does not include SO_3 or elemental/ organic carbon.	**No** Does not include SO_3 or elemental/ organic carbon.

(a) NSW GMR: NSW Greater Metropolitan Region
(b) SEQ: South-East Queensland

As part of the PM valuation project undertaken for NSW EPA, Pacific Environment reviewed the measurement and modelling of secondary particles in Australia **(Aust *et al.*, 2013)**. It was concluded that whilst secondary PM can be responsible for a large fraction of $PM_{2.5}$ and PM_{10}, the data on secondary PM at Australian monitoring sites are rather limited. The modelling of secondary PM in Australia is still under development. In particular, there is a lack of comprehensiveness in the representation of SOA-formation pathways **(Keywood and Cope, 2008)**. The decision not to explicitly

[18] Reducing precursor emissions would be beneficial, but this was beyond the scope of the project.

model SOA formation in the economic analysis is borne out by modelling studies in Melbourne, which have shown an underestimation of the SOA:$PM_{2.5}$ ratio by a factor of 6 to 10 **(Keywood and Cope, 2008)**. This level of under-prediction of SOA is typical of that reported by others **(Vutukuru *et al.*, 2006)**. Moreover, there are relatively few data on secondary nitrates from monitoring campaigns in Australia.

It was estimated that regional air quality modelling including secondary PM would cost up to A$250,000 per jurisdiction. However, it was also noted that the overall regional effects of secondary pollutants will be less important in Australia than in, say, Europe, because the population exposed to them will be so much smaller. The economic analysis therefore involved only a basic approach for secondary particles, reflecting a conservative estimate of health impacts.

It is worth adding that in terms of reducing exposure to PM it is currently more economical (and less uncertain) to focus on abatement measures that reduce primary PM emissions rather than those measures that reduce emissions of secondary PM precursors. This least-cost approach has been reflected in a recent regulatory impact analysis of proposed revisions to the national air quality standards in the US, which showed that when assessing effective control strategies direct $PM_{2.5}$ reductions accounted for 75-100% of the reductions of the least-cost abatement approach **(USEPA, 2012)**.

Given the different air quality criteria used in Australia for PM_{10} and $PM_{2.5}$ (see **Table 1.1**), it was necessary to consider the following four metrics:

- The annual mean PM_{10} concentration.
- The 6th highest 24-hour mean PM_{10} concentration. The 24-hour NEPM standard for PM_{10} allows five exceedances per year.
- The annual mean $PM_{2.5}$ concentration.
- The maximum 24-hour mean $PM_{2.5}$ concentration (***NB****: Assuming 98th percentile concentration rather than the maximum*).

Extensive information on the calculation methods and results for base year emissions and concentrations is provided in **Appendix A**. A major part of the work involved the isolation of primary anthropogenic PM from ambient measurements to enable direct comparison with the air pollution model outputs, and the development of the approach for this is described in some depth in **Appendix B**.

3.2 Emissions and concentrations in BAU scenario

3.2.1 Overview

To determine the long-run costs and benefits of abatement measures in each jurisdiction, it was firstly necessary to project emissions and concentrations of PM_{10} and $PM_{2.5}$ into the future (up to 2036) under the BAU scenario. In the BAU scenario existing emission controls and expected trends were allowed to continue, and there were no additional interventions to reduce air pollution. The BAU scenario then defined the base case against which the impacts of any measures or policies to reduce anthropogenic emissions and improve air quality could be evaluated in the economic analysis.

The projection methods for all jurisdictions are described in **Appendix C** and are summarised briefly below. This Chapter also discusses the use of different compliance metrics in the economic analysis.

3.2.2 Method

3.2.2.1 Emission projections

As before, the approaches for NSW and Victoria were more sophisticated than those for the other jurisdictions, and were based upon the projections supplied by the respective EPAs. To fill the gaps in the NSW and Victoria data, and also to determine the projections for the other jurisdictions, some basic assumptions were made concerning future activity and emissions relative to the original inventories. Emissions were estimated using a combination of the following:

- Population projections for the states and the main conurbations from **ABS (2008)**.
- Economic growth based on historical 'gross value added' (GVA) by industry from ABS Catalogue 5220.0 (*Australian National Accounts - State Accounts*)[19]. Annual average annual changes in GVA were determined for each state and for each type of industry.
- National projections of PM_{10} and $PM_{2.5}$ emissions from **BITRE (2010)**, which were used to fill gaps for road vehicles and other transport modes.

3.2.2.2 Concentration projections

In all jurisdictions it was assumed that future primary anthropogenic concentrations would change in direct proportion to future anthropogenic emissions. Scaling factors for PM_{10} and $PM_{2.5}$ concentrations in all years (relative to 2011) were therefore derived based on emissions. In NSW and Victoria the scaling factors for projections were developed from the larger emissions inventory domain rather than the smaller TAPM (The Air Pollution Model) domain. In the other jurisdictions total emissions – summated over all source groups - were considered.

To determine annual mean concentrations in future years the scaling factors were applied to the annual mean primary anthropogenic concentration in 2011. In NSW and Victoria each modelled source type was treated separately, and for each source type the scaling factors were assumed to apply equally to all grid cells. A contribution from natural and secondary particles was added to each grid cell; although it varied spatially, this was assumed to be constant with time.

> **NB**: *Abatement measures that reduce primary anthropogenic PM may also, as a co-benefit, reduce emissions of secondary PM precursors. Therefore, the use of a constant secondary PM component could be viewed as an over-simplification, with the implication that the required primary anthropogenic PM reductions could be overestimated. In this sense the approach used was conservative. However, no reliable and comprehensive models for estimating secondary PM in Australia were available at the time of the study*[20]*. We did investigate the co-benefits of abatement where possible, including the health benefits of reduced NO_X emissions (in terms of reduced secondary nitrate).*

[19] http://www.abs.gov.au/AUSSTATS/abs@.nsf/DetailsPage/5220.02010-11

[20] The Australian literature is limited, but some studies are available from the US. For example, **Tsimpidi *et al.* (2008)** found that reducing NO_X emissions in the eastern US by 50% during summer lowered $PM_{2.5}$ by 8% on average. Nitrate decreased by between 45% and 58%. SOA slightly decreased in rural areas, whereas it increased in cities by a few percent. However, reduction of NO_X during winter caused an increase in oxidant levels and a rather complicated response in the PM components, leading to small net changes. Both SO_X and NO_X emissions need to be reduced, otherwise there is the potential for an increase in PM mass due to the formation of ammonium nitrate in preference to ammonium sulfate **(Dennis *et al.*, 2007)**.

A similar approach was used for 24-hour concentration metrics in the other jurisdictions. In other words, we also applied the emission scaling factors to determine the 6th highest PM_{10} concentration[21] and 98th percentile $PM_{2.5}$ concentrations in future years. For the 24-hour calculations in NSW and Victoria a more sophisticated approach was possible, whereby the 2011 concentrations were adjusted on a daily basis for each grid cell. A fixed (annual mean) contribution from natural and secondary particles was added to each grid cell. The relevant metrics for PM_{10} (the sixth highest 24-hour concentration) and $PM_{2.5}$ (the 98th percentile 24-hour concentration) were then determined for each grid cell from the results. This calculation was computationally very intensive, and therefore by necessity the 24-hour evaluation was narrower in scope (*i.e.* fewer years were assessed).

3.2.2.3 Compliance metric

In order to determine whether PM_{10} and $PM_{2.5}$ concentrations in each jurisdiction were compliant with the hypothetical air quality standards it was necessary to define a suitable metric. In the economic analysis we defined this metric as the population-weighted concentration in the inventory area, as this value was available in each jurisdiction. The population-weighted approach to standard setting has been used in previous CBAs. Population-weighted annual mean and 24-hour concentrations were calculated using a method that was analogous to that described for emissions in **Appendix A**.

It was important to consider the AAQ NEPM. The NEPM states that compliance is determined either through measurement at 'performance' monitoring stations or by equivalent means (including dispersion modelling) to determine concentrations at these sites (Section 11). The NEPM adds that monitoring stations must be located '…*in a manner such that they contribute to obtaining a representative measure of the air quality likely to be experienced by the general population*…' (Section 13). Our modelling approach in the economic analysis is effectively an equivalent method. However, the use of modelling to assess compliance does not appear to have been explored in detail. The review of the AAQ NEPM concluded that '…*the role of modelling should be strengthened and appropriate modelling approaches to generate reports on population exposure patterns be incorporated into the clause dealing with evaluation of performance against standards and goals'* **(NEPC, 2011a)**. Because we calibrated TAPM from monitoring sites that are used for evaluating NEPM compliance, we concluded that all the predictions are broadly NEPM-equivalent.

As gridded data were available for NSW and Victoria it was, in principle, possible to define other metrics. For example, we could have adopted a 'zero tolerance' approach, whereby compliance would have been required in all grid cells, or we could have defined a threshold in terms of population exposure (*e.g.* 95% of population below the standard). However, because there was a shortfall in abatement in NSW and Victoria - in other words, introducing a portfolio of all feasible national abatement measures would not result in compliance with some of the standards (see **Chapter 8**) – it was not possible to use grid-cell-based metrics. This was because, where a shortfall had been identified, there was no straightforward mechanism for allocating the required reduction in emissions to specific sectors to ensure compliance[22].

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[21] It is acknowledged that, because monitoring data were removed to account for days with extreme natural events, the use of the sixth highest concentration will not in principle give the precise level of protection intended by the NEPM.

[22] Another way of looking at this is to imagine a case where only one grid cell is non-compliant. In this situation one could examine the relative contributions of the different sectors to the concentration in that grid cell, and introduce additional abatement measures to reduce emissions from the most influential sector(s). However, it is not difficult to see that this process could quickly become very complicated when there are tens or hundreds of non-compliance cells.

3.2.3 Results

3.2.3.1 NSW and Victoria

The BAU emission projections for PM_{10} and $PM_{2.5}$ in the NSW GMR and the Port Phillip region of Victoria are shown in **Figure 3.1**. There was an inflection point at 2030 in Victoria resulting from the change in calculation methodology from the EPA one to projections based on population growth and gross value added. In NSW it is anticipated that future PM emissions will be increasingly dominated by coal mining. In Victoria the contribution of wood heaters was projected to increase with time.

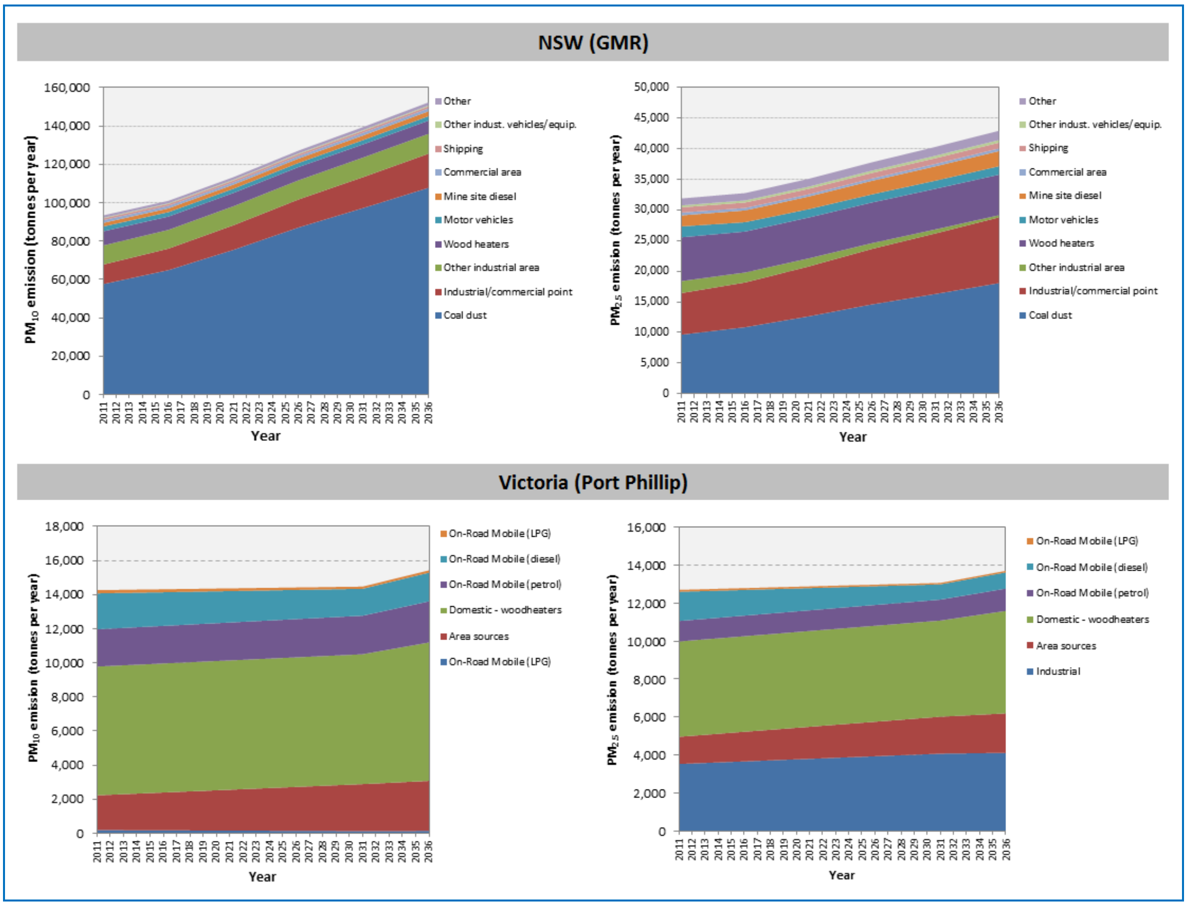

Figure 3.1: Projected emissions of PM_{10} and $PM_{2.5}$ in NSW GMR and Port Phillip region

The resulting domain-wide population-weighted annual mean PM_{10} and $PM_{2.5}$ concentrations in the modelled areas under the BAU scenario are shown in **Figure 3.2** and **Figure 3.3**. The equivalent plots for the 24-hour metrics are depicted in **Figure 3.4** and **Figure 3.5**. Given that much detail was lost in the population-weighted averages, the predictions at the grid cell level were also examined. Therefore, the percentile concentrations across all grid cells are also shown in **Figure 3.2** and **Figure 3.3** (for readability the *y*-axes are truncated to exclude the highest values).

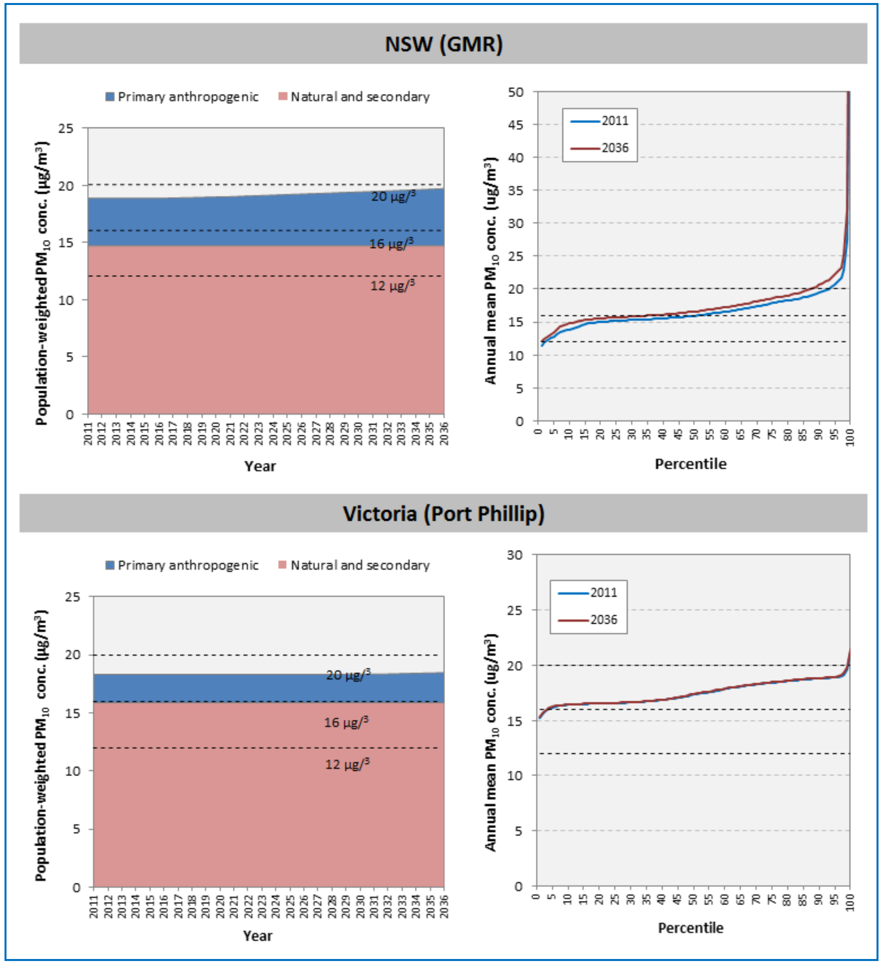

Figure 3.2: Projected population-weighted annual mean PM_{10} concentrations and percentiles in NSW GMR and Port Phillip region

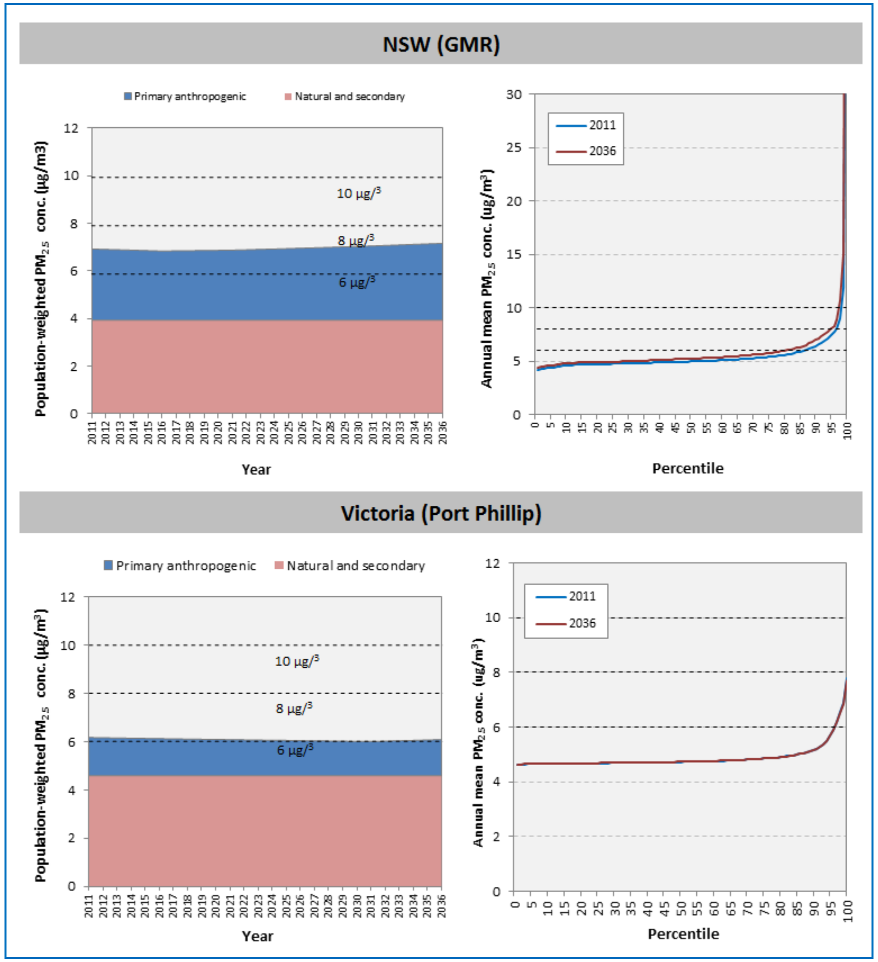

Figure 3.3: Projected population-weighted annual mean $PM_{2.5}$ concentrations and percentiles in NSW GMR and Port Phillip region

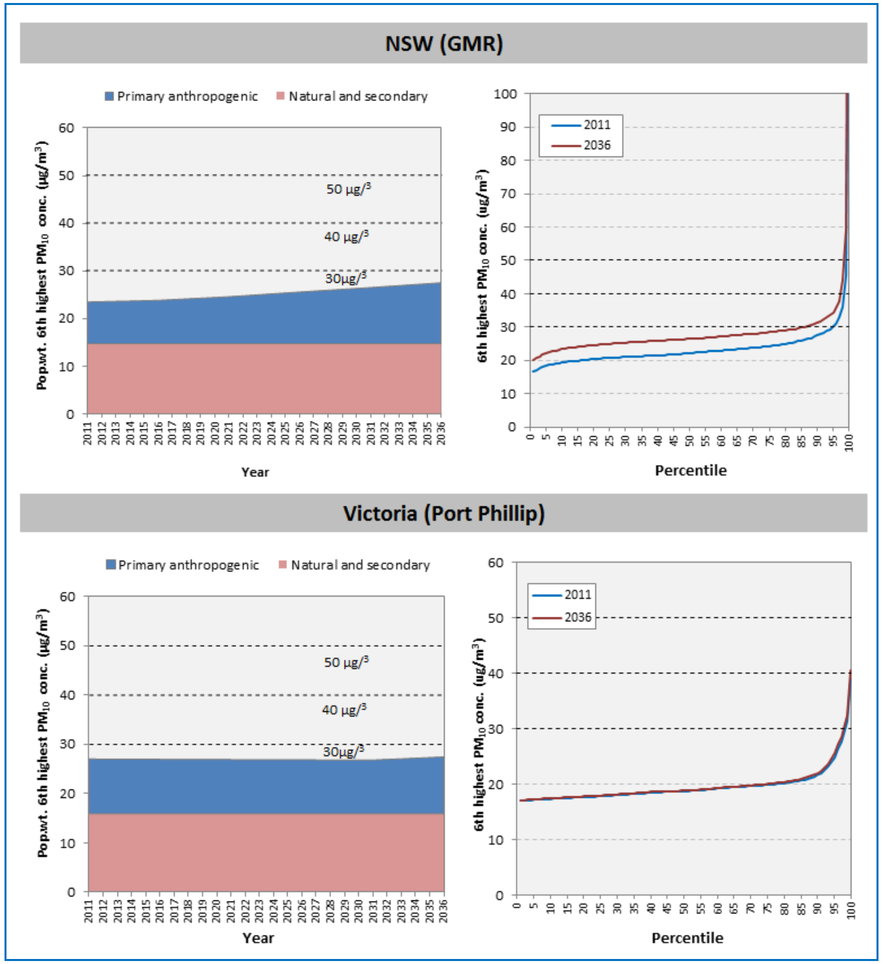

Figure 3.4: Projected population-weighted 24-hour PM_{10} concentrations and percentiles in NSW GMR and Port Phillip region

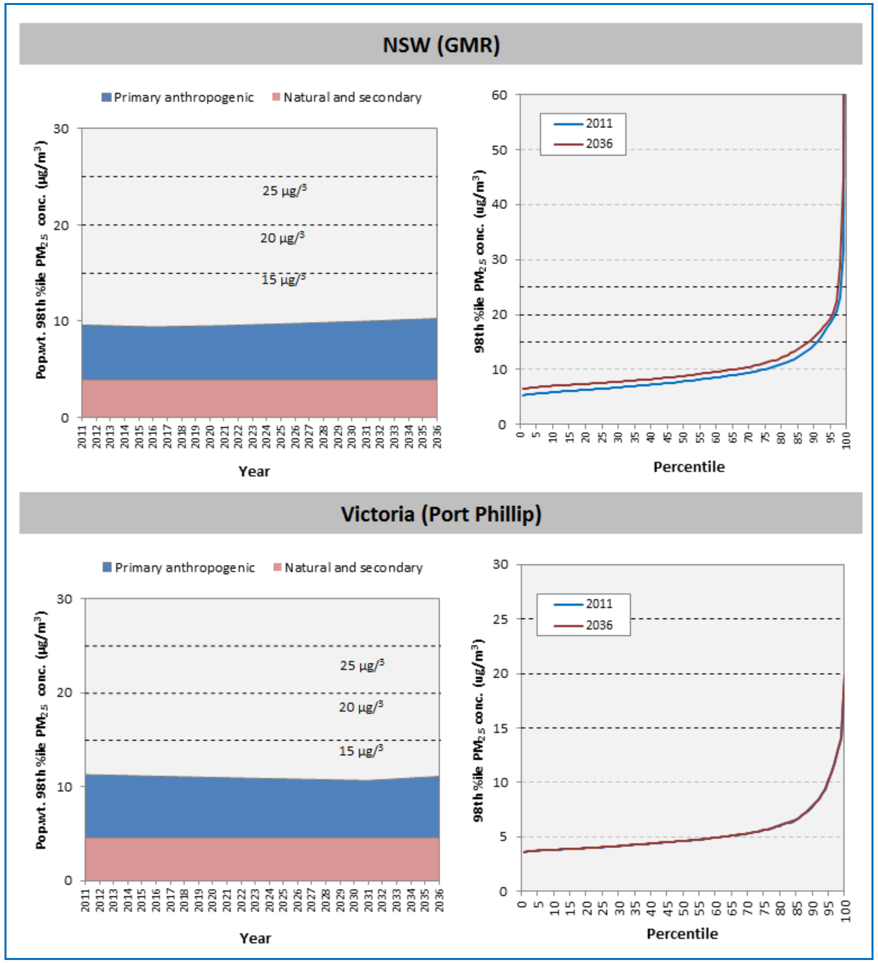

Figure 3.5: Projected population-weighted 24-hour $PM_{2.5}$ concentrations and percentiles in NSW GMR and Port Phillip region

Some features stand out from the concentration projections:

- The changes in the total concentration are more subtle than the changes in anthropogenic emissions. This is partly because the changes in the primary anthropogenic component are added to an unvarying natural/secondary component, and partly because the values are population-weighted. For example, in NSW the main driver of the increasing emissions is coal mining, which takes place in areas with relatively low population and this reduces its overall importance (although it does remain important).

- The level of an air quality standard relative to the level of the natural/secondary PM component is very important, and to a large extent determines whether compliance will be possible and the emission reduction that will be required. For example, the lowest hypothetical annual mean standard for PM_{10} of 12 µg/m^3 cannot be achieved on a population-weighted basis in both NSW and Victoria by reducing primary anthropogenic emissions alone, as the standard is actually below the level of the natural/secondary contribution. In Victoria the natural/secondary component of PM_{10} is very close to 16 µg/m^3, and therefore a compliance with this standard would imply the virtual elimination of primary anthropogenic emissions. This issue is considered later in the Report.

- In some cases the concentrations in the BAU case were lower than the hypothetical air quality standard by 2036.

- The percentile plots show that there was generally a fairly even distribution of the annual mean and 24-hour concentration metrics across the modelling domains, with only a small percentage of grid cells having very high concentrations (the results for 2011 and 2036 were very similar in this respect).

These issues highlight some of the complexities of setting (and evaluating) air quality standards for PM_{10} and $PM_{2.5}$, especially where the prevailing PM concentrations are relatively low so that natural and secondary PM components become very important.

It is worth adding that the exposure-reduction approach bypasses these problems to some extent, as it does not involve compliance with a fixed concentration, although the calculations involved are very similar to those required for the population-weighted concentration approach.

3.2.3.2 Other jurisdictions

The emission projections for the source groups in the other jurisdictions are shown in **Figure 3.6**. The source groups were defined differently in each jurisdiction, and the most important contributors varied. In SEQ and Perth growth in emissions was projected to be driven by growth in the industrial-commercial sectors, whereas in Adelaide, Hobart and ACT the domestic-commercial group was a stronger determinant of emissions growth.

Figure 3.7 to **Figure 3.12** show the annual mean population-weighted concentration projections (the 24-hour projections are not shown). As in NSW and Victoria, the PM_{10} standard of 12 µg/m^3 could not be achieved in some jurisdictions by reducing primary anthropogenic emissions alone.

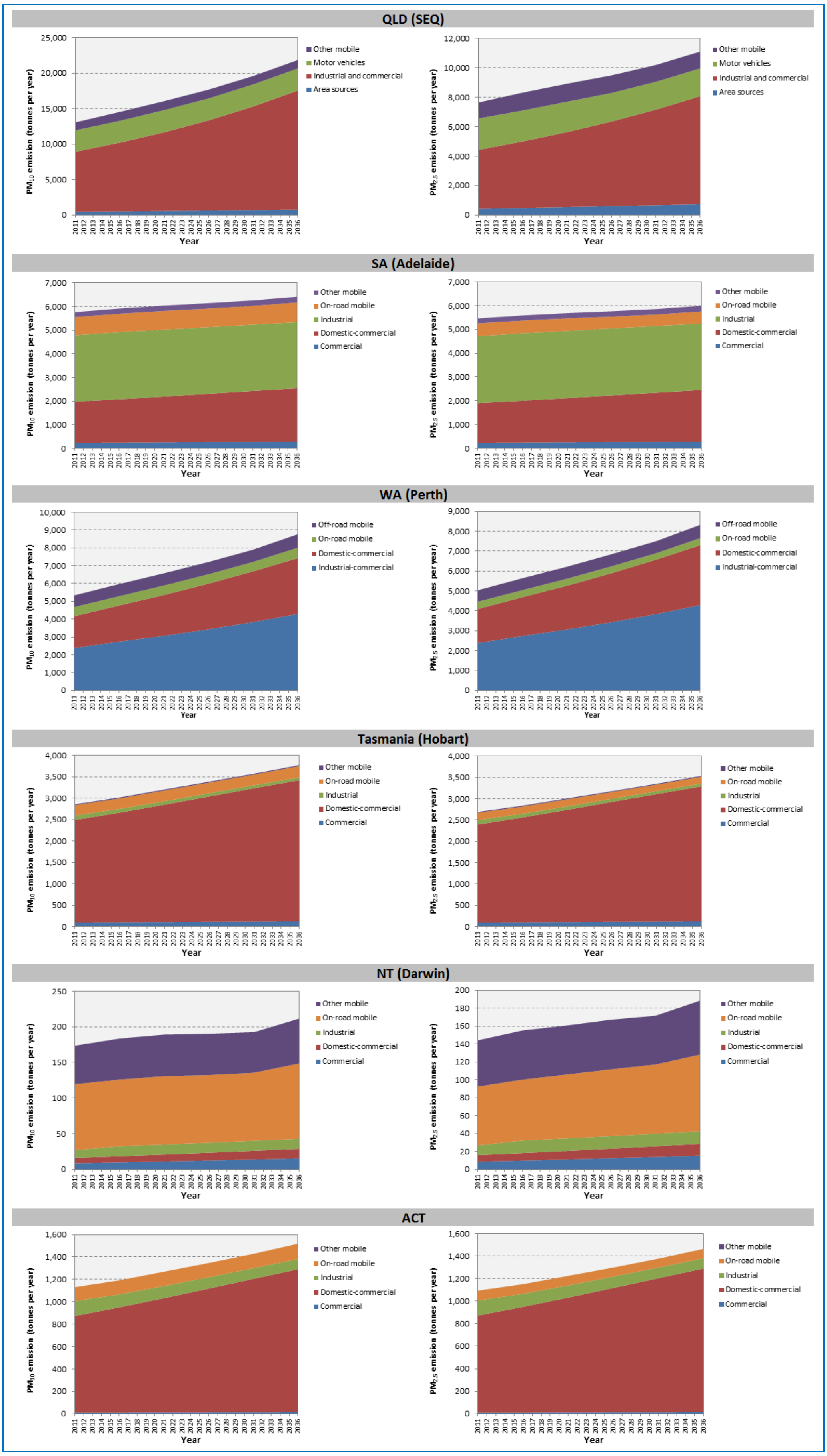

Figure 3.6: Projected emissions of PM_{10} and $PM_{2.5}$ in other jurisdictions

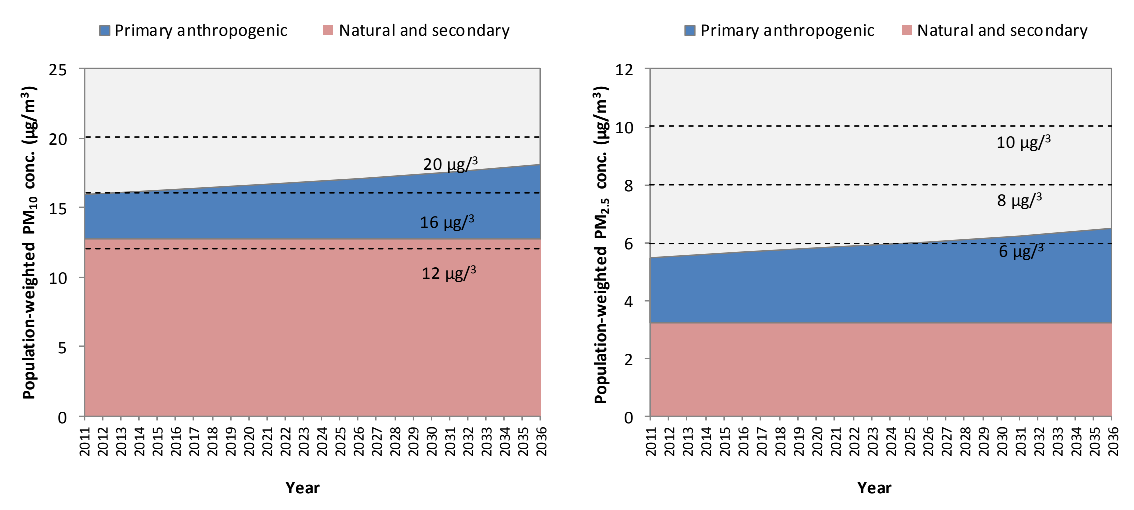

Figure 3.7: Projected population-weighted annual mean PM_{10} and $PM_{2.5}$ concentrations in SEQ

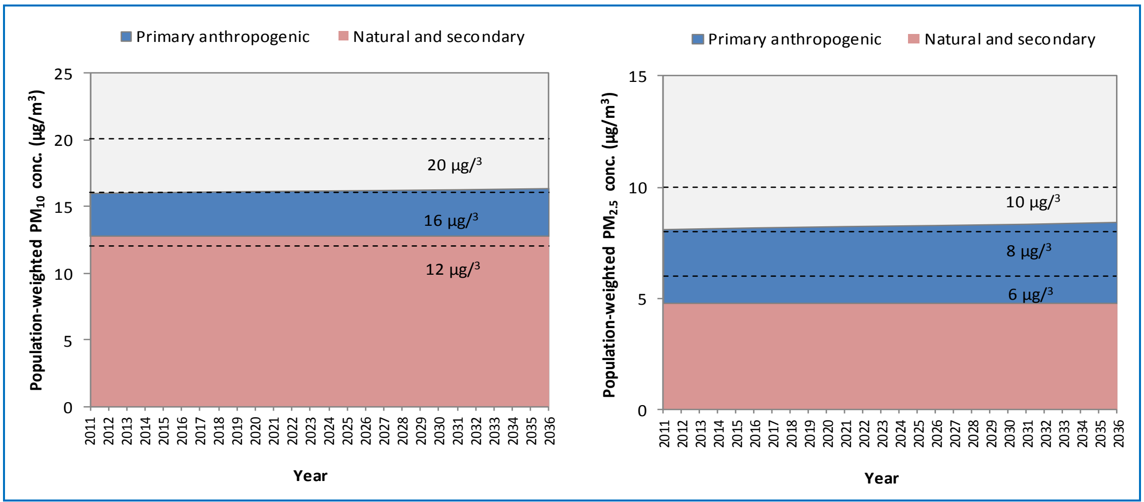

Figure 3.8: Projected population-weighted annual mean PM_{10} and $PM_{2.5}$ concentrations in Adelaide

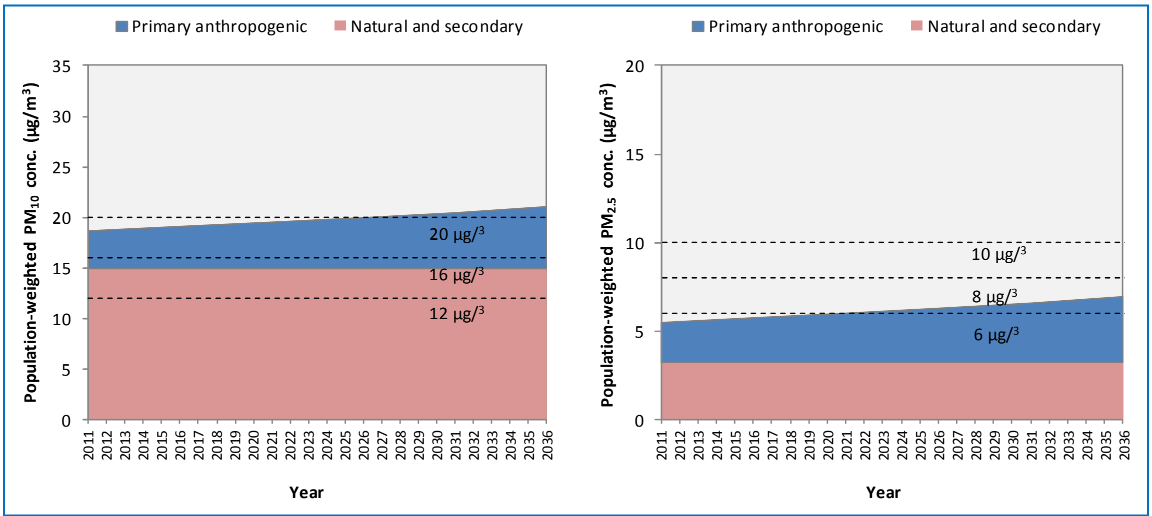

Figure 3.9: Projected population-weighted annual mean PM_{10} and $PM_{2.5}$ concentrations in Perth

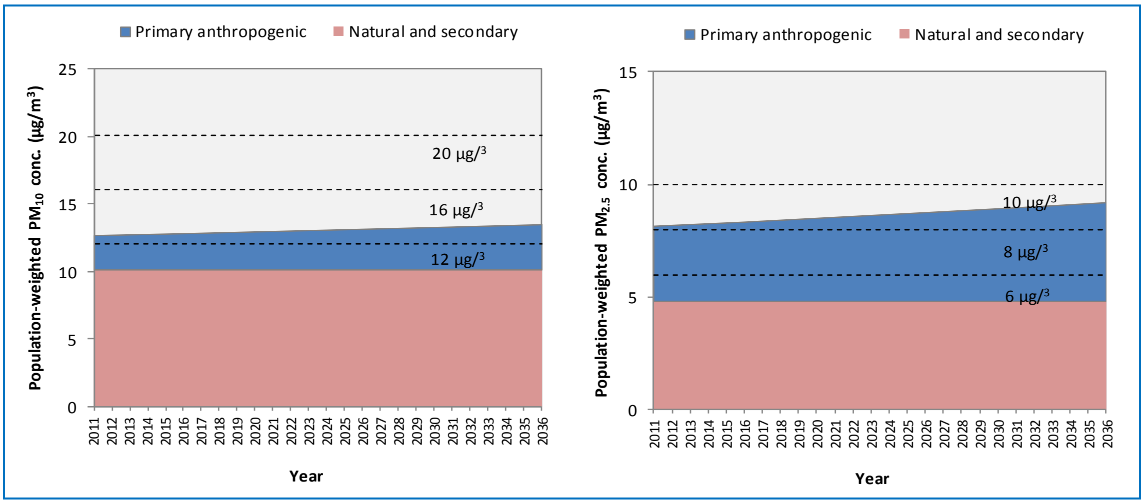

Figure 3.10: Projected population-weighted annual mean PM_{10} and $PM_{2.5}$ concentrations in Hobart

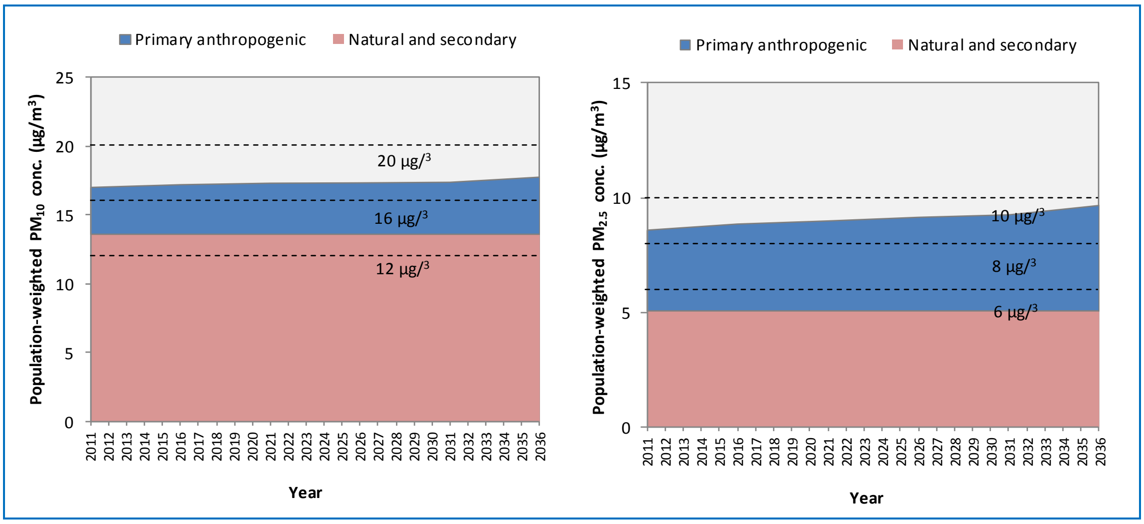

Figure 3.11: Projected population-weighted annual mean PM_{10} and $PM_{2.5}$ concentrations in Darwin

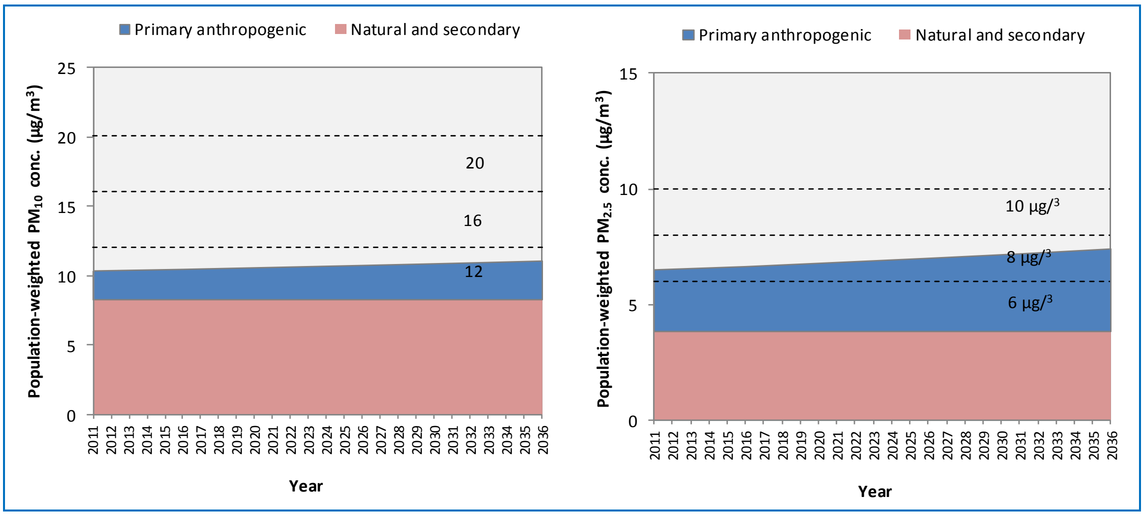

Figure 3.12: Projected population-weighted annual mean PM_{10} and $PM_{2.5}$ concentrations in Canberra

3.2.3.3 Compliance metrics

As noted earlier, the use of gridded data in NSW and Victoria meant that alternative compliance metrics were available. In addition to the domain-wide population-weighted concentration, three other metrics were also calculated for these two jurisdictions: the maximum concentration in populated cells, the number of grid cells with a concentration above each hypothetical standard, and the percentage of the population in grid cells above each hypothetical standard. **Table 3.2** contains the values of the different metrics (annual mean values only), as well as the domain-wide population-weighted concentration, for the modelled areas of NSW and Victoria in 2011 and 2036. The alternative metrics are shown for purposes of illustration; as mentioned previously they could not be used in the analysis.

Table 3.2: Concentrations and other metrics in NSW GMR and Port Phillip region (BAU, annual mean)

PM metric	Scenario	Evaluation metric	NSW GMR 2011	NSW GMR 2036	Victoria Port Phillip 2011	Victoria Port Phillip 2036
PM_{10} annual mean	BAU	Population-weighted conc. (µg/m³)	18.9	19.7	18.3	18.5
		Max conc. in cells with >= 1 person (µg/m³)	82.8	111.7	21.2	21.5
	Standard: 20 µg/m³	No. of grid cells above standard	256	469	19	30
		% of population above standard	40%	50%	7%	12%
	Standard: 16 µg/m³	No. of grid cells above standard	1,073	1,317	2,844	3,101
		% of population above standard	85%	92%	97%	98%
	Standard: 12 µg/m³	No. of grid cells above standard	1,679	1,751	2,876	3,125
		% of population above standard	100%	100%	100%	100%
$PM_{2.5}$ annual mean	BAU	Population-weighted conc. (µg/m³)	6.9	7.2	6.2	6.1
		Max conc. in cells with >= 1 person (µg/m³)	63.5	88.4	7.8	7.7
	Standard: 10 µg/m³	No. of grid cells above standard	35	61	0	0
		% of population above standard	0%	1%	0%	0%
	Standard: 8 µg/m³	No. of grid cells above standard	95	173	0	0
		% of population above standard	17%	28%	0%	0%
	Standard: 6 µg/m³	No. of grid cells above standard	497	672	152	151
		% of population above standard	74%	80%	59%	55%

4 CHARACTERISATION OF POTENTIAL NEW ABATEMENT MEASURES

4.1 Overview

Achieving compliance with hypothetical new air quality standards for PM_{10} and $PM_{2.5}$ will typically require the introduction of new abatement measures. Abatement measures are available for each sector, and they act by either reducing emissions (the main approach), by reducing ambient concentrations, or by reducing exposure.

In the economic analysis we considered various measures that might benefit from a national approach. For each measure included in the analysis the following information is provided:

- A brief description of the measure.
- The timeframe for implementation.
- The PM_{10} and $PM_{2.5}$ emission-reduction potential (in tonnes per year).
- The co-benefits and dis-benefits (focussing on reduced emissions of other pollutants).
- The implementation costs ($). These included capital costs and annual operating, maintenance and any other relevant costs. Costs to both industry and government were considered.
- The uncertainty in the estimates.

We assessed the hypothetical air quality standards out to 2036, and the exposure-reduction target to 2025. We assumed that most abatement measures would be initiated around 2015 or 2016, thus providing a twenty-year time horizon for assessing their operation. Where significant residual emission reductions (or costs) associated with a specified abatement measure continued beyond 2036, these were also calculated (*e.g.* ongoing emission benefits from the introduction of emission standards for non-road engines with very long working lifetimes).

Much of the information on abatement measures was provided by the IMWG of the Air TOG. The IMWG comprises representatives from the Commonwealth and all States and Territories. The IMWG considered a range of feasible new actions to reduce PM emissions and concentrations - based on the data available to the jurisdictions - for input into the economic analysis. The IMWG prioritised potential new measures with potential to significantly and economically reduce PM emissions.

4.2 Identification of specific abatement measures

Potential abatement measures for achieving compliance with the hypothetical air quality standards were divided into the following three categories:

- ‘Existing’ measures currently being assessed through national assessment processes.
- ‘Additional’ measures identified by the IMWG and approved for assessment in the economic analysis by the Air TOG.
- ‘Other’ potential measures identified the economic analysis project team.

The specific measures that were identified are summarised below. It is important to note that these measures were not included in BAU emission inventory scenarios (see **Section 3.2**).

> **NB**: *In selecting these actions the IMWG took into account the major PM sources, the potential for abatement, and the potential costs. No decisions have been made by Government at this time to pursue these actions. However, the information and data*

associated with the measures may be used to inform future emission/exposure-reduction priorities and actions.

4.2.1 Existing measures currently being assessed

Firstly we addressed the 'existing' abatement measures that are being considered through Council of Australian Governments processes. Existing measures were identified for the following sectors:

- **Non-road diesel engines** – Introduction of national emission standards.
- **Wood heaters** – Introduction of national measures to reduce emissions through wood heater design, or performance standards to promote compliance of retail models with these standards and to influence in-service operational performance.
- **Non-road spark ignition engines and equipment** – Introduction of national emission standards.

4.2.2 Additional potential measures

The IMWG also identified potential additional PM-abatement measures based on a review of Australian studies and successful programs. These measures related to the following emission sources:

- **Diesel trains** – Introduction of emission standards, accelerated replacement of old locomotives, and driver assistance software to reduce fuel use.
- **In-service diesel equipment** – Extension (to other jurisdictions) of the NSW framework for retrofitting high-polluting diesel engine equipment with diesel particulate filters (DPFs).
- **Shipping** – Use of low-sulfur fuel at berth, and a memorandum of understanding (MOU) to reduce vessel speed as ships approach and depart ports.
- **Coal dust** – Application of best practice controls for PM at coal mines.
- **Light commercial vehicles** – Behaviour change programme ('eco-driving' to reduce engine idling), and a targeted inspection and maintenance programme using a remote-sensing device to identify high-emitting vehicles.

4.2.3 Other potential measures

In addition to the measures identified by the IMWG, we identified several other potential abatement measures from the literature. These measures were:

- Penalties and incentives to reduce emissions from **gross-polluting heavy-duty diesel vehicles**.
- Use of licence conditions at **mines sites** to reduce emissions from in-service non-road diesel engines.
- Measures to reduce emissions from **in-service wood heaters.**
- The use of **vegetation** to reduce atmospheric concentrations of PM.

4.2.4 Measures considered but not included

We also considered the following measures for the economic analysis, but excluded them for the reasons provided later in the Report:

- Measures to encourage the uptake of **electric and hybrid electric passenger vehicles**.
- Managing the timing of **planned burning** to minimise the health impacts of PM.

4.3 Summary of characteristics

Full details of the cost and benefit assumptions for the various measures are provided in **Appendix D**. Costs were extracted from the sources surveyed, but were adjusted and standardised for consistency in the economic analysis. Specifically, we took the following steps:

- Costs to government (*e.g.* regulation, administration, *etc.*) were estimated where these were not provided in the original source document.
- The discount rate was standardised (7% real).
- Figures were adjusted based on information that became available after the publication of the original studies.
- Growth in emission reductions into the future was taken into account where appropriate.
- A phase-in period was assumed for some measures.

The emission reductions - the primary benefits accounted for in the economic analysis - were also extracted from the source documents. Again, we adjusted the figures to account for growth (or decline) in emission reductions into the future where appropriate, and we assumed a phase-in period for some measures.

The quantification of co-benefits (including savings in fuel consumption and pollutants other than PM) was restricted to dollar savings from fuel efficiency, NO_X and in some cases, CO_2. While the implementation of some measures is also expected to result in a change to emissions of CO, VOCs and SO_2, these were not quantified as the health impact of these pollutants, relative to PM or NO_X, is minimal and assumed to be nil.

The analysis of CO_2 reductions required careful consideration. While some measures may result in a reduction in CO_2 from one sector, genuine reductions in Australian CO_2 emissions may not accrue from emission reductions in all sectors. Some sectors are currently covered by an Australian Emissions Trading System administered by the Commonwealth Government. This means that a reduction in CO_2 emissions from a covered sector will lead to an increase in emissions in another. While not resulting in an environmental benefit, some emission reductions might result in a small financial benefit. Forecasting this also has a lot of uncertainty because it is contingent on the expected carbon price (driven by the EU scheme which at the time of writing trades at less than €5/t). Due to these complicating factors, in some cases, CO_2 reductions are acknowledged but are largely not quantified.

4.4 Selection of abatement measures

4.4.1 Overview

It is clear that air quality management is complicated due to the various pollutants and metrics, the various emission sources and their emission behaviour, the various abatement measures that are available, and the shifting nature of emission baselines. Abatement measures differ in terms of cost, emission-reduction profiles, implementation years, duration, *etc*. Often, no single abatement measure will achieve the desired objectives, and it is therefore useful to consider portfolios of measures and to choose optimal combinations. To enable portfolios of abatement measures to be selected it is necessary to consider them on a common basis. For this purpose, marginal abatement cost curves (MACCs) were developed in the economic analysis.

4.4.2 Marginal abatement cost curves

Economic efficiency is achieved when the marginal social cost (MSC) of an action equates to its marginal social benefit (MSB) (**Figure 4.1**). In the context of air pollution this is notionally represented by the quantity of abatement (*e.g.* tonnes of PM reduction), where the incremental cost of reducing pollution is equal to the incremental benefit of doing so.

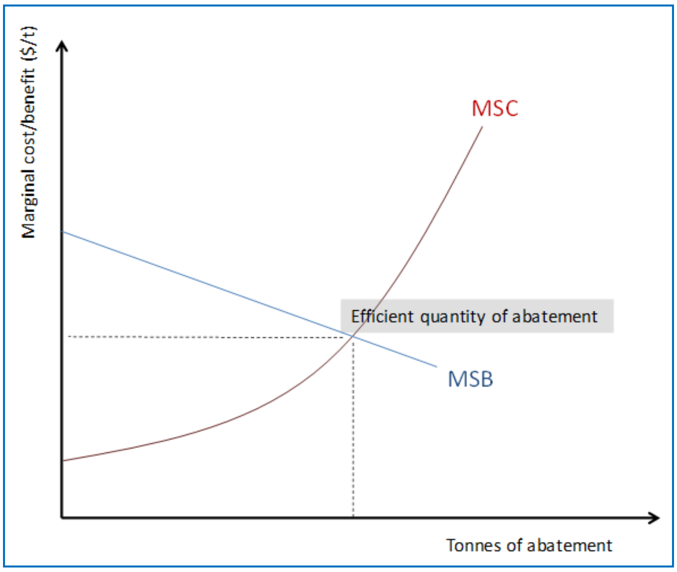

Figure 4.1: Efficient quantity of pollution abatement

This idealised representation does not fully reflect the complexity of air quality management, in which the social benefit is not simply a function of reduced emissions but is also dependent on changes in ambient concentrations and population exposure, dose-response functions, and co-benefits/dis-benefits. Noting these complexities, the construction of MACCs facilitates the selection of effective packages of measures for achieving emission-reduction targets. MACCs are somewhat analogous to the 'levelised' cost curves used in utility industries for similar purposes (*e.g.* to select the most cost-effective portfolio of assets to deliver a certain supply of energy, water, *etc.*).

The MACC provides information on the additional cost (in $/tonne) for each additional unit of abatement (tonne). Assuming that relatively low-cost opportunities are preferred, additional abatement is possible only at increasing costs. **Figure 4.2** shows how each segment of the MACC represents an abatement opportunity, with the width of the measures representing the additional abatement achieved and the height representing the associated unit cost.

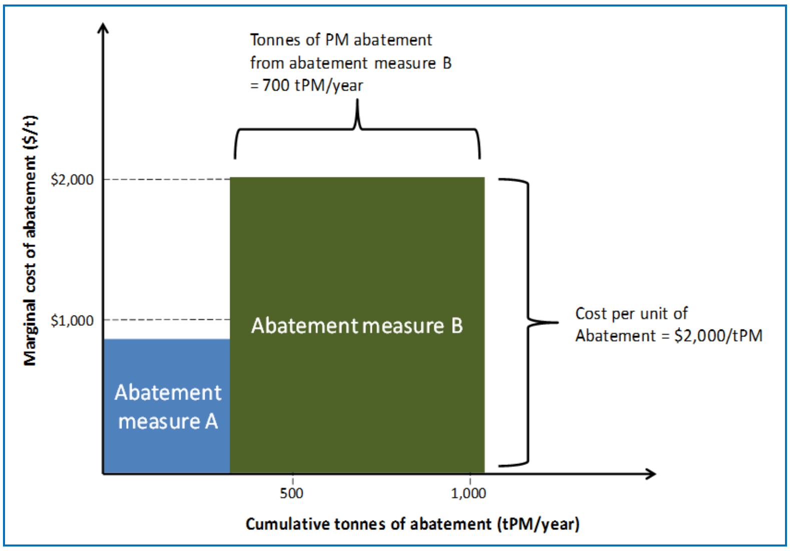

Figure 4.2: Illustration of MACC principles

4.4.3 Alternative approaches for MACC construction

The cost-effectiveness of individual measures may be calculated using a number of alternative methods. All methods typically involve a division, with a calculation of cost ($) for the numerator and a calculation of abatement quantity (tonnes) for the denominator. While the MACC is a useful tool, the approach used to construct them does not influence the results of a CBA, which ultimately considers all costs and benefits of measures and the year in which they are incurred.

Two approaches were considered in this study. These were:

1. A levelised cost approach (net present value (NPV) method)
2. An annualised cost approach (equivalent annual cost (EAC) method)

The NPV method divides the net present value of all incremental costs associated with an abatement measure by the sum of emission reductions for the time horizon of analysis. This is expressed as:

$$Cost\ of\ abatement\ \left(\frac{\$}{t}\right) = \frac{\sum \frac{(Total\ annual\ cost_i)}{(1+r)^i}}{\sum \ Emissions\ reduced_i}$$

Where ***r*** is the discount rate to be applied, and the sum is performed over the selected time horizon for each year ***i***[23].

This approach has been adopted in many greenhouse gas (GHG) abatement cost curve analyses in Australia, state and national cost-benefit analyses, and Regulatory Impact Statements for pollution-reduction measures.

The NPV method more precisely accounts for time value of money[24], as all costs are discounted by a factor that depends on the year in which they are incurred (costs further into the future are discounted more heavily than costs closer to the present). On the other hand, the NPV method can distort the cost-effectiveness of measures due to costs being discounted but not emissions:

- The profile of emission reduction does not influence the calculation, whereas in reality earlier emission reductions may be preferred as these may have higher monetary values.
- The calculation is sensitive to the time horizon, as the addition of an extra year adds a small cost (heavily discounted) but the full (undiscounted) emissions.

The EAC method translates capital costs into an annual 'capital charge' and adds operating costs to give a total annualised cost, and then divides this by annual emissions as follows:

$$Cost\ of\ abatement\ \left(\frac{\$}{t}\right) = \frac{C \times \frac{r}{1-(1+r)^{-n}} + O}{Annual\ emissions\ reduction}$$

Where ***r*** is the discount rate to be applied and ***n*** is the number of years in the time horizon.

[23] The levelised cost typically requires discounting of both costs in the numerator and outcomes (*e.g.* energy supply, water supply) in the denominator. In the levelised approach emissions reductions are usually not discounted, effectively suggesting that pollution reduced today is no more or less preferred to pollution reduced tomorrow.
[24] The time value of money refers to differences in the value of money (in this case a cost or benefit) depending on when that cost or benefit is incurred.

This approach has been adopted in studies on greenhouse gas abatement costs **(***e.g.* **Climate Works, 2010)**.

The EAC method tends to calculate a value that may be more comparable to damage costs. That is, damage costs provide a proxy for the marginal social benefit (the marginal benefit to society of abatement expressed as $/t), and annualised costs provide a proxy for marginal social cost (marginal cost to society of abatement expressed as $/t).

A disadvantage of the EAC method is that operating costs and emission reductions need to be expressed as annual values. An obvious approach to doing this is to calculate simple annual averages. However, this approach results in the profiles of operating cost and emissions (which can, and often do, vary over time) being lost.

4.4.4 Cost-effectiveness of measures compared

Prior to selecting measures for inclusion in MACCs, an assessment of their cost-effectiveness was undertaken using the NPV method (for consistency with Australian studies, as previously stated). Whilst not all measures are presented in the MACCs (see **Section 4.4.5**), the cost-effectiveness of all measures has been assessed, taking into account the following:

- Costs incurred by government, industry or consumers, excluding fuel efficiency benefits.
- Costs incurred by government, industry or consumers, including fuel efficiency benefits.
- The (**incremental**) value of including co-benefits.

The calculation of cost-effectiveness ($/tonne) incorporated all costs and benefits over the lifetime of a measure within the time horizon of the analysis, whilst the calculation of the total emission reduction (tonnes of PM_{10} or $PM_{2.5}$) incorporated effects up to 2036.

The results are shown in **Table 4.1**. Where a measure results in negative costs per tonne of PM reduction - that is, there is a saving per tonne of PM reduction rather than a cost (*e.g.* non-road spark ignition engines due to fuel savings) - the $/t$PM_{2.5}$ is higher than the $/t$PM_{10}$ as the same savings are spread over a lower base.

Table 4.1: Cost-effectiveness of measures

Measure	Total costs (excl. fuel efficiency) ($M PV)	Abatement		Cost -effectiveness (excl. fuel efficiency)		Total cost-effectiveness		Value of co-benefits[a]	
		$tPM_{2.5}$	tPM_{10}	$\$/tPM_{2.}$	$\$/tPM_{10}$	$\$/tPM_2$	$\$/tPM_{10}$	$\$/tPM_2$	$\$/tPM_{10}$
US non-road diesel standards in Australia (excluding <19kW) [F]	$9,909	301,377	310,698	$14,009	$13,589	$9,191	$8,915	-$7,930[b]	-$7,692
Wood heater national audits and education	$18	13,641	14,165	$1,314	$1,266	$1,314	$1,266	[c]	
Wood heater national audits, education and replacement initiatives	$33	18,962	19,691	$1,752	$1,687	$1,752	$1,687		
Wood heater emissions labelling, education and audit	$24	24,812	25,766	$977	$941	$977	$941		
Wood heater emissions labelling, star-rating, education and audit	$27	29,047	30,163	$919	$885	$919	$885		
Wood heater emission labelling, star-rating, education, audit and 60% effiic. Stand.	$27	33,634	34,926	$815	$785	$815	$785		
Wood heater 60% efficiency, 3g/kg emission standards	$31	61,603	63,970	$499	$480	$499	$480		
Wood heater 60% efficiency, 3g/kg emission standards and in-service measures	$49	66,210	68,753	$742	$715	$742	$715		
Wood heater 65% efficiency, 3g/kg emission standards and in-service measures	$48	64,897	67,390	$739	$711	$739	$711		
Wood heater 60% efficiency, 1.5g/kg emission standards and in-service measures	$59	69,617	72,292	$850	$819	$850	$819		
Mandatory low sulfur fuel use by ships while at berth	$970	19,378	21,069	$50,066	$46,049	$50,066	$46,049	-$1,085	-$998
MOU to reduce shipping vessel speed for ocean transits	$149	14,034	15,258	$10,632	$9,779	$10,632	$9,779	-$25,468	-$23,425
Diesel retrofit at mine sites (emissions reduction program)	$810	50,951	52,527	$15,893	$15,416	$15,893	$15,416		
Diesel trains driver assistance software for line haul locomotives	$73	2,422	2,497	$13,622	$13,213	$5,426	$5,263	-$52,548[d]	-$50,972
Requiring new locomotives to meet US Tier 4 standards	$310	6,527	6,729	$21,598	$20,950	$21,598	$20,950	-$33,831	-$32,816
Replacing old line locomotive and requiring new locomotives to meet US Tier 4	$3,139	13,499	13,917	$105,841	$102,666	$105,841	$102,666	-$50,480	-$48,966
US2010 outboard and watercraft, and US phase 2 gardening emissions standards	$388	8,189	8,853	$41,396	$38,291	-$10,815	-$10,003	[e]	
US 2006 then 2010 outboard and watercraft, and US phase 2 gardening standards	$375	8,138	8,797	$40,132	$37,122	-$11,963	-$11,065		
Adoption of international best practice PM control measures at coal mines	$3,425	363,351	2,371,393	$9,115	$1,397	$9,115	$1,397		
Targeted maintenance of high polluting LCVs using remote sensing	$2	14	15	$158,922	$151,072	$158,922	$151,072		
Penalty and incentive scheme for high polluting vehicles	$24	119	125	$202,673	$192,661	$202,673	$192,661		
Area-wide planting to remove PM from the atmosphere	$823	1,442	1,442	$407,418	$407,418	$407,418	$407,418	-$2,903	-$2,903
Requiring wood heaters to be removed or rendered inoperable on sale of house	$39	166,824	173,234	$234	$225	$234	$225		
Regulating moisture content of wood fuel to be less than 20%	$2	15,313	15,902	$99	$95	$99	$95		
Retrofitting high-polluting (urban) diesel engines & equipment with DPFs	$6	282	291	$22,455	$21,781	$22,455	$21,781		

(a) Co-benefits estimated include NOx and CO_2 only. Reductions in VOC, SO_2 and CO are expected for some measures but these are either uncertain and/or of a much smaller scale of benefit. CO_2 reductions for some measures are acknowledged (see footnotes) but not estimated as they are uncertain.

(b) Implementation of non-road diesel engine standards is expected to result in reductions in NOx, VOC, SO_2 and CO_2. However, these are either uncertain and/or of a much smaller scale of benefit.

(c) CO_2 benefits for wood heater measures depend on the sustainability of wood fuel utilised.

(d) Uptake of driver assistance may result in CO_2 benefits but these are uncertain and not estimated.

(e) Implementation of non-road spark ignition engine standards is expected to result in a small increase in NOx emissions but offsetting decreases in VOC, CO_2 and CO

(f) Commonwealth and NEPM non-road diesel engine measures are represented by one generic option given the close similarities of results.

4.4.5 Selection of 'not inferior' packages in construction of MACCs

Given that multiple (mutually exclusive) variants of certain measures are available, the selection of the 'best' option(s) is complicated where multiple implementation choices are possible. One variant can be considered 'superior' to another if it achieves a greater level of emission reduction at a lower cost.

If one of these conditions is not true (*i.e.* a variant is more cost-effective but delivers less abatement **or** a variant delivers more abatement but is less cost-effective) then that variant cannot be considered superior, as the alternative may still be preferred under certain circumstances.

To recognise this, the MACCs were constructed using a model that automatically selected only measures that were **not inferior** (*i.e.* a measure is inferior if there is another mutually exclusive measure that is both lower cost and delivers greater reductions). The implicit assertion here is that an inferior measure will never be preferred under any conditions[25].

In plotting a measure which already has variants preceding it on the MACCs:

- Only the **marginal abatement** (tonnes additional to other variants preceding) are shown; and
- The **marginal cost-effectiveness** of that specific measure is shown.

In reading cost curves, one should not consider mutually exclusive variants as being implemented simultaneously. Rather, they should be considered as alternatives.

4.4.6 $PM_{2.5}$ and PM_{10} MACCs for Australia

The MACCs for PM_{10} and $PM_{2.5}$ in Australia are provided in **Figure 4.3** and **Figure 4.4** respectively. These have been developed using the NPV method to be consistent with previous Australian studies. The ranking of measures is unaffected by the method chosen, although the absolute estimate of cost-effectiveness is higher applying the EAC method.

Some measures are not visible in the Figures as cost-effectiveness is close to $0/t or the estimated emission reductions are small relative to those for other measures. Additionally, the cost-effectiveness of some measures is lower or higher than the range shown on the *y*-axis, but the range of the *y*-axis has been limited to improve readability. To address these issues, the data in the MACCs have also been provided in **Table 4.2** and **Table 4.3**. In these Tables the incremental abatement is defined as the additional abatement delivered by a variant over and above the variant in the same sector immediately preceding it (in order of cost-effectiveness).

For the purpose of MACC construction the cost-effectiveness (*y*-axis) is calculated on the basis of total costs and benefits over the lifetime of a measure within the time horizon of the economic analysis. However, the calculation of average annual tonnes ($tPM_{2.5}$ and tPM_{10}) is limited to emission reductions up to 2036 (target year for compliance with air quality standards).

Total costs are defined as costs to industry, government and consumers (including fuel efficiency) but not pollution-reduction co-benefits. The impact of including co-benefits was presented in **Table 4.1.**

[25] An exception to application of this logic in constructing MACCs is the measure 'phase-out of wood heaters'. Other wood heater measures would, under this logic, be considered inferior to a phase-out of wood heaters, but because of the high level of uncertainty with the phase-out option and practical difficulties with applying it, the option has been excluded from the MACCs presented here.

Figure 4.3: PM_{10} national MACC

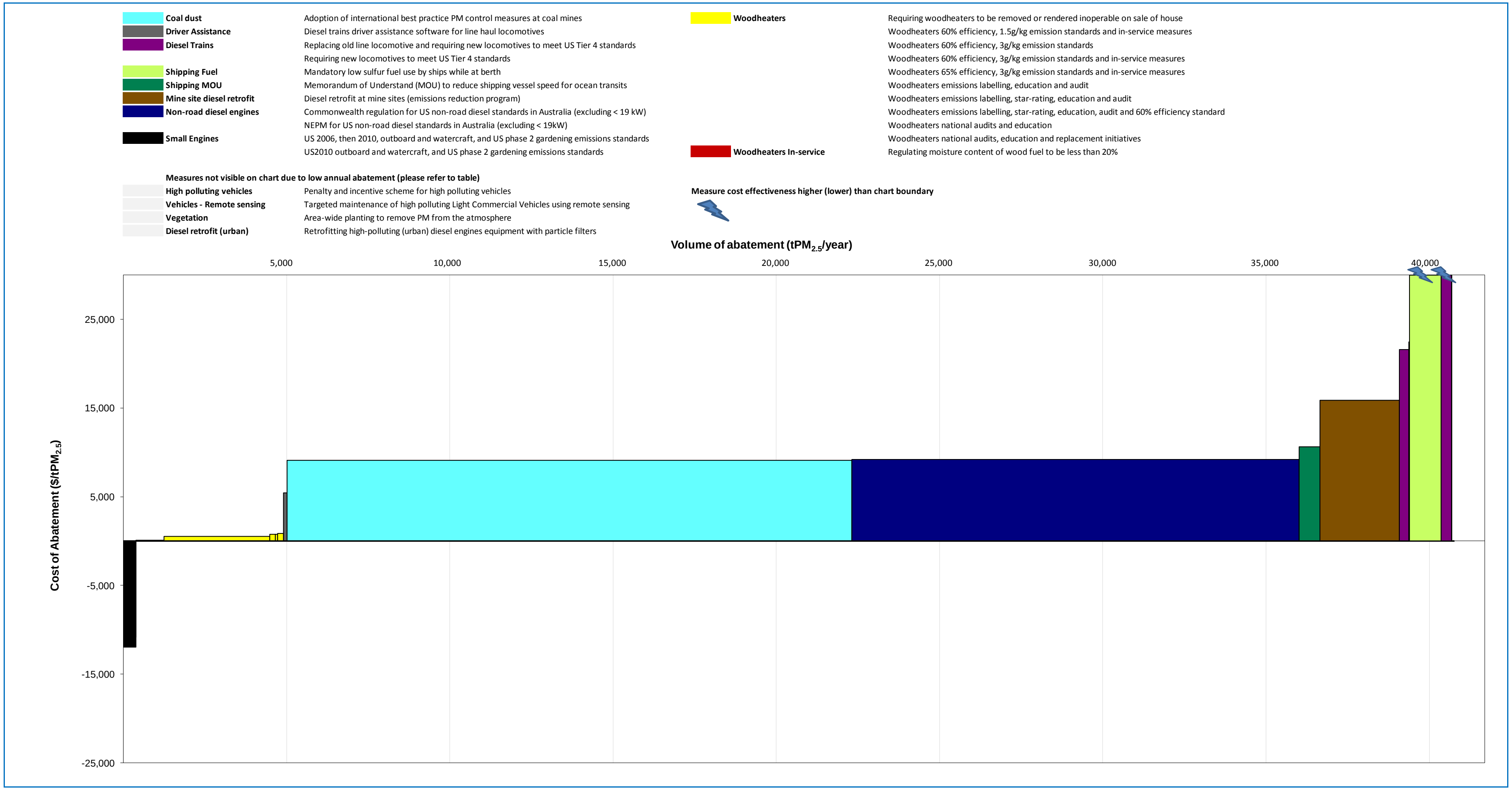

Figure 4.4: $PM_{2.5}$ National MACC

Table 4.2: PM_{10} MACC data

Measure	Marginal cost ($/t$PM_{10}$)	Abatement (tPM_{10}/year)	Incremental abatement (tPM_{10}/year)
US 2006 & 2010 outboard and watercraft, and US phase 2 gardening emissions stand.	-11,065	419	419
US2010 outboard and watercraft, and US phase 2 gardening emissions standards	-10,003	422	3
Regulating moisture content of wood fuel to be less than 20%	95	883	883
Wood heaters 60% efficiency, 3 g/kg emission standards	480	3,367	3,367
Wood heaters 65% efficiency, 3 g/kg emission standards and in-service measures	711	3,547	180
Wood heaters 60% efficiency, 3 g/kg emission standards and in-service measures	715	3,619	72
Wood heaters 60% efficiency, 1.5 g/kg emission standards and in-service measures	819	3,805	186
MOU to reduce shipping vessel speed for ocean transits	949	7,150	7,150
Adoption of international best-practice PM control measures at coal mines	1,397	112,923	112,923
Diesel trains driver assistance software for line haul locomotives	5,263	114	114
US non-road diesel standards in Australia (excluding <19kW)	8,915	14,123	14,123
Retrofitting non-road diesel engines at mine sites with DPFs (emissions reduction program)	15,416	2,501	2,501
Requiring new locomotives to meet US Tier 4 standards	20,950	306	306
Retrofitting high-polluting (urban) non-road diesel engines & equipment with DPFs	21,781	22	22
Mandatory low-sulfur fuel use by ships while at berth	46,049	1,053	1,053
Replacing old locomotives and requiring new locomotives to meet US Tier 4 standards	102,666	633	327
Targeted maintenance of high-polluting LCVs using remote sensing	151,072	1	1
Penalty and incentive scheme for high polluting vehicles	192,661	10	10
Area-wide planting to remove PM from the atmosphere	407,418	66	66

Table 4.3: $PM_{2.5}$ MACC data

Measure	Marginal cost ($/t$PM_{2.5}$)	Abatement (t$PM_{2.5}$/year)	Incremental abatement (t$PM_{2.5}$/year)
US 2006 & 2010 outboard and watercraft, and US phase 2 gardening emission standards	-11,963	388	388
US2010 outboard and watercraft, and US phase 2 gardening emissions standards	-10,815	390	2
Regulating moisture content of wood fuel to be less than 20%	99	851	851
Wood heaters 60% efficiency, 3 g/kg emission standards	499	3,242	3,242
Wood heaters 65% efficiency, 3 g/kg emission standards and in-service measures	739	3,416	173
Wood heaters 60% efficiency, 3 g/kg emission standards and in-service measures	742	3,485	69
Wood heaters 60% efficiency, 1.5 g/kg emission standards and in-service measures	850	3,664	179
Diesel trains driver assistance software for line haul locomotives	5,426	110	110
Adoption of international best-practice PM control measures at coal mines	9,115	17,302	17,302
US non-road diesel standards in Australia (excluding <19kW)	9,191	13,699	13,699
MOU to reduce shipping vessel speed for ocean transits	10,632	638	638
Retrofitting non-road diesel engines at mine sites with DPFs (emissions reduction program)	15,893	2,426	2,426
Requiring new locomotives to meet US Tier 4 standards	21,598	297	297
Retrofitting high-polluting (urban) non-road diesel engines & equipment with DPFs	22,455	22	22
Mandatory low-sulfur fuel use by ships while at berth	50,066	969	969
Replacing old locomotives and requiring new locomotives to meet US Tier 4 standards	105,841	614	317
Targeted maintenance of high-polluting LCVs using remote sensing	158,922	1	1
Penalty and incentive scheme for high polluting vehicles	202,673	10	10
Area-wide planting to remove PM from the atmosphere	407,418	66	66

4.4.7 $PM_{2.5}$ and PM_{10} MACCs for individual jurisdictions

The total Australia-wide emission reductions for each abatement measure were allocated *pro rata* to the states and territories using relevant indicators (*e.g.* current emissions, fuel use). The resulting MACCs for individual jurisdiction are presented in **Appendix E**.

5 METHOD FOR MONETISING BENEFITS

5.1 Overview

This Chapter describes the methodology for the 'benefit' part of the economic analysis. The results of the calculations are presented in **Chapter 6**.

The main benefit calculations were based upon the damage cost approach. Health benefits were estimated using unit damage costs ($ per tonne) for primary $PM_{2.5}$ emissions. However, the introduction of abatement can lead to co-benefits associated with reduced emissions of other pollutants (notably NO_X). We therefore also used a damage cost approach to value these co-benefits.

Whilst computationally intensive, we considered that a limited impact pathway assessment would provide a useful check of the damage cost results. We therefore followed (as far as practicable) the impact pathway approach for the locations which were covered by both the HRA project and the state emissions inventories.

5.2 Damage cost approach

5.2.1 $PM_{2.5}$ health benefits

Health benefits were estimated using the unit damage costs ($ per tonne of primary $PM_{2.5}$ emitted at 2011 prices) developed for Australia by **Aust *et al.* (2013)**. The unit damage costs are proportional to population density and relate to specific geographical areas of Australia based on the ABS Significant Urban Area (SUA) structure for urban centres with more than 10,000 people. They allow users to link the location of emissions to an approximate population-weighted exposure.

The unit damage costs for primary $PM_{2.5}$ included the following impacts:

- Mortality (based on years of life lost) associated with chronic exposure to $PM_{2.5}$
- Acute effects on morbidity:
  - Respiratory hospital admissions associated with $PM_{2.5}$
  - Cardio-vascular hospital admissions associated with $PM_{2.5}$
- Building soiling

Mortality associated with acute exposure to $PM_{2.5}$ was not included. Hence, the damage cost results are likely to represent conservative estimates of total health impacts from exposure to $PM_{2.5}$.

Guidance on the calculation of damage costs in economic analyses is provided in the report by **Aust *et al.* (2013)**. This includes advice on the adjustment of unit damage costs for future years, with an 'uplift' to reflect future growth in willingness to pay and a 'discount' to give net present values. The Value of a Life Year (VOLY) assumptions underpinning the damage costs in **Aust *et al.* (2013)** are consistent with those used in our economic analysis following a review of the alternatives. This review is outlined in **Appendix G**.

Damage cost calculators were developed to support the estimation of health benefits in the CBA. The project team developed multiple calculators (one for NSW, one for Victoria, and one for the other jurisdictions) due to the computational intensity of some steps (*i.e.* apportionment of emission reductions to specific areas). Therefore, the evaluation was duplicated for each jurisdiction, and the results summated to produce Australia-wide results.

5.2.1.1 New South Wales and Victoria

For the NSW GMR and the Port Phillip region, health benefits were valued using the gridded emissions data (1 km x 1 km for the GMR, and 3 km x 3 km for Port Phillip). The following steps were taken:

1. Firstly, for each separate type of emission source that was modelled the proportion of the total emissions from the source occurring in each grid cell during 2011 was determined (*i.e*. sum over all grid cells = 1). To simplify the calculation in NSW (where the use of relatively high-resolution data resulted in a large number of grid cells), grid cells with zero emissions in all years and grid cells which only contained bodies of water were excluded.

2. For each grid cell this proportion was then multiplied by the total reduction in emissions in the overall area (for a given year) associated with the abatement measure(s) for each source type, and the reductions in emissions for all source types were summated for the grid cell.

3. An SUA was allocated to each grid cell in the inventory area (**Figure 5.1** and **Figure 5.2** show the SUAs for NSW and Victoria respectively), and the unit damage costs for each SUA (based on 2011 population and at 2011 prices) are provided in **Table 5.1** and **Table 5.2**.

4. The SUA was used to determine the base year unit damage cost ($/tonne of $PM_{2.5}$ at 2011 prices and for population density in 2011) for the grid cell, and this was multiplied by the following to determine the actual damage cost (saving):

    a. A population scaling factor for the year relative to 2011 from **ABS (2008)**. This allowed for any increase in population within an SUA, and was applied as an average value for all the grid cells within an SUA.

    b. An uplift factor, taken to be 2.1%[26].

    c. A discount to adjust for changes in willingness to pay by year (7%).

    d. The change in emissions in the grid cell with abatement (tonnes/year).

5. The actual benefits ($) were then summated over all grid cells.

6. The process was repeated for each year between 2011 and 2036, and the total benefit across all years was calculated.

Areas outside the modelled NSW GMR and Port Phillip regions were also addressed as above, but using composite unit damage costs in conjunction with emission estimates. These unit damage costs are also shown in **Table 5.3.**

[26] This reflects the fact that WTP for deaths avoided is likely to increase over time in line with increases in the general standard of living and/or income. The value of 2.1% is derived from ABS estimates of real national income growth per capita and Gross Domestic Product (GDP) growth per capita over the last 50 years.

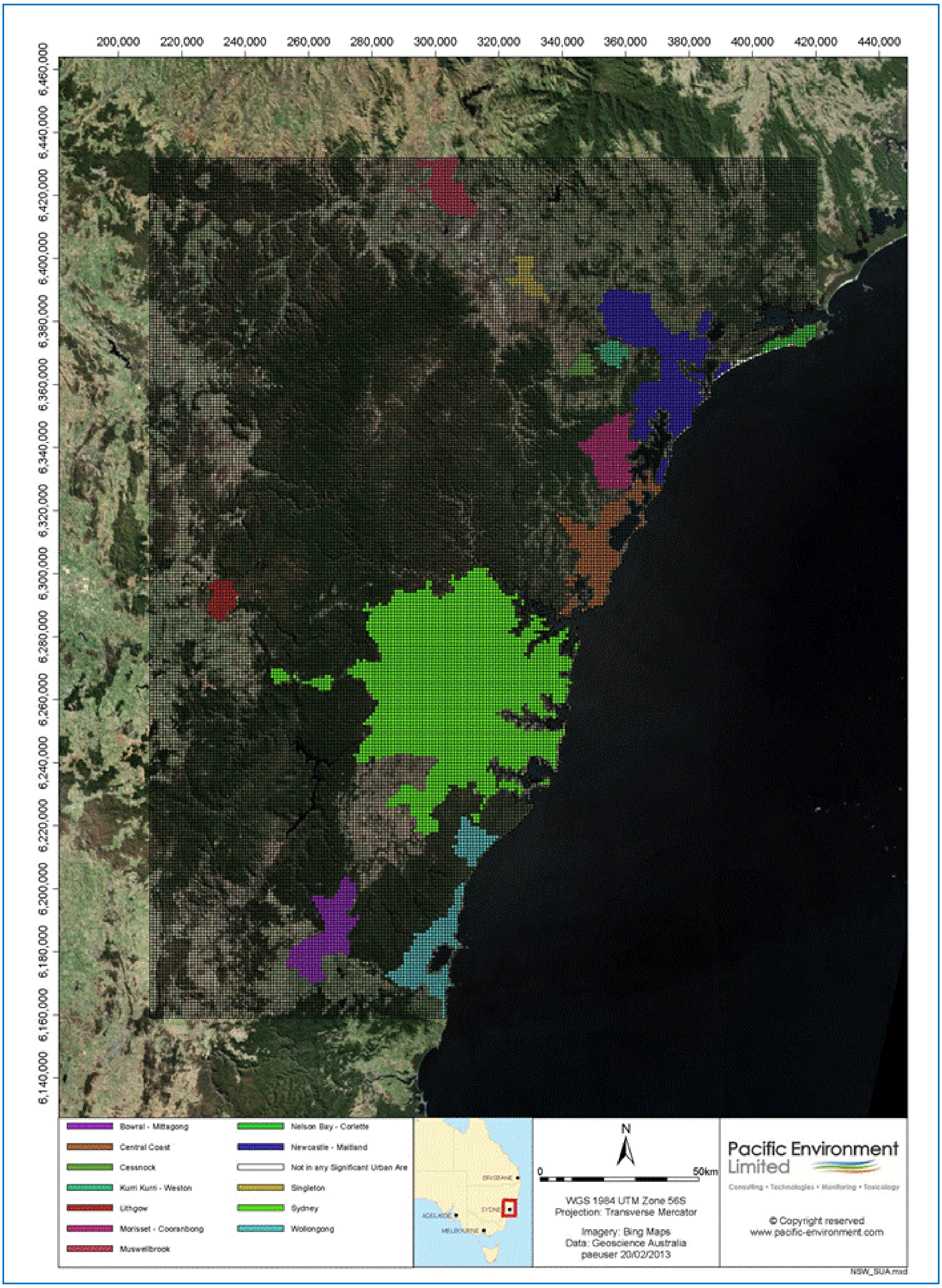

Figure 5.1: Significant urban areas in NSW GMR (1 km x 1 km grid).

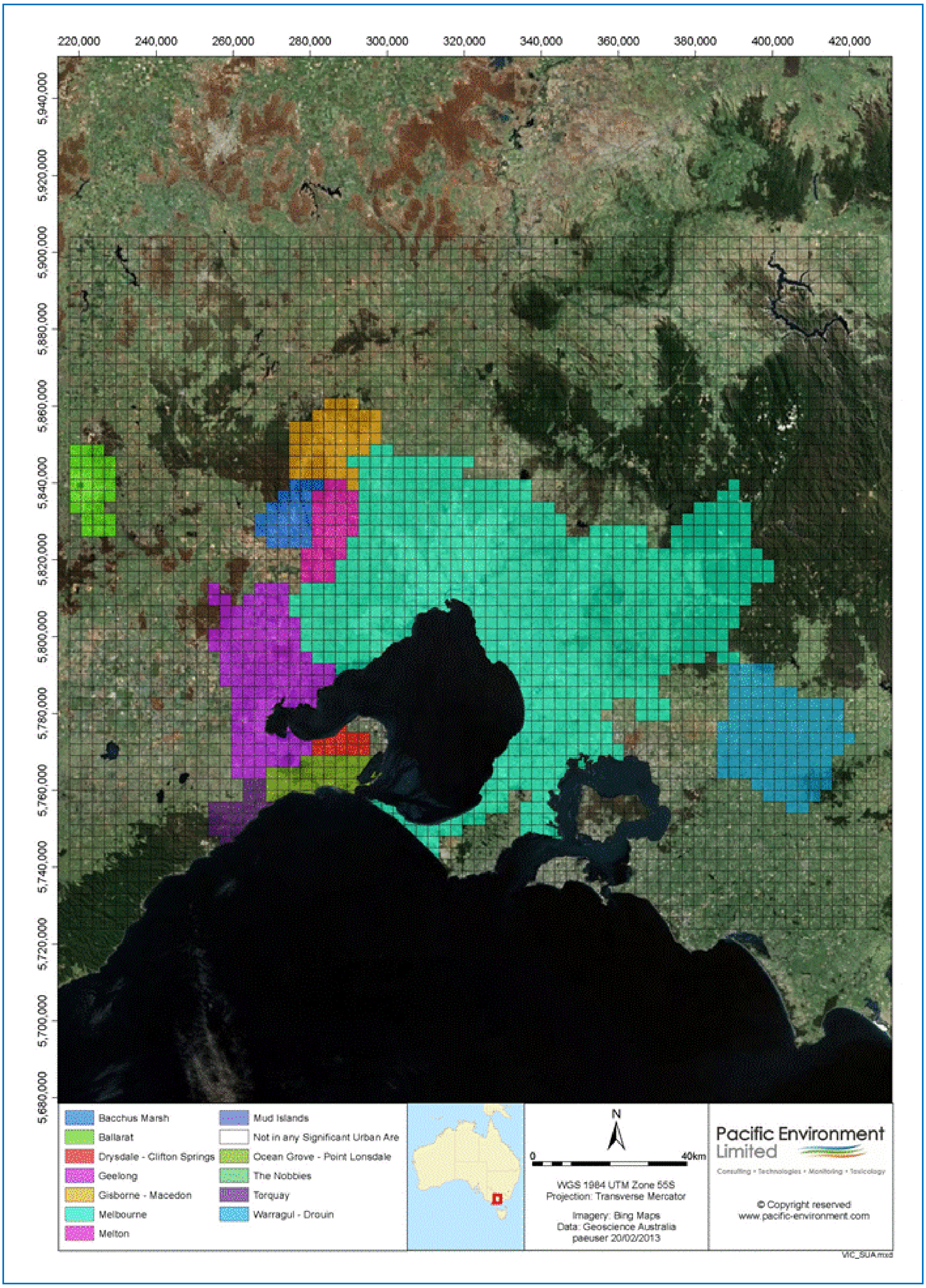

Figure 5.2: Significant urban areas in Victoria (3 km x 3 km grid).

Table 5.1: Unit $PM_{2.5}$ damage costs for SUAs covered by modelled area in NSW

SUA code	SUA name	Area (km²)	2011 Population	2011 Pop. density (people/km²)	2011 unit damage costs (A$/tonne $PM_{2.5}$)
1000	Not in any Significant Urban Area[(a)]	788,116	999,873	1	$360
1006	Bowral - Mittagong	422	34,861	83	$23,000
1009	Central Coast	566	304,755	538	$150,000
1010	Cessnock	69	20,262	294	$82,000
1017	Kurri Kurri - Weston	91	16,198	179	$50,000
1019	Lithgow	120	12,251	102	$29,000
1020	Morisset - Cooranbong	341	21,775	64	$18,000
1021	Muswellbrook	262	11,791	45	$13,000
1022	Nelson Bay - Corlette	116	25,072	217	$61,000
1023	Newcastle - Maitland	1,019	398,770	391	$110,000
1028	Singleton	127	16,133	127	$36,000
1030	Sydney	4,064	4,028,525	991	$280,000
1035	Wollongong	572	268,944	470	$130,000

(a) Only a fraction of the area/population was in the modelled area.

Table 5.2: Unit $PM_{2.5}$ damage costs for SUAs covered by modelled area in Victoria

SUA code	SUA name	Area (km²)	2011 Population	2011 Pop. density (people/km²)	2011 unit damage cost (A$/tonne $PM_{2.5}$)
2000	Not in any Significant Urban Area[(a)]	216,296	693,578	3	$900
2001	Bacchus Marsh	196	17,156	87	$24,000
2003	Ballarat	344	91,800	267	$75,000
2006	Drysdale - Clifton Springs	65	11,699	180	$50,000
2008	Geelong	919	173,450	189	$53,000
2009	Gisborne - Macedon	367	18,014	49	$14,000
2011	Melbourne	5,679	3,847,567	677	$190,000
2012	Melton	266	47,670	179	$50,000
2015	Ocean Grove - Point Lonsdale	219	22,424	103	$29,000
2018	Torquay	126	15,043	119	$33,000
2021	Warragul - Drouin	680	29,946	44	$12,000

(a) Only a fraction of the area/population was in the modelled area.

Table 5.3: Unit $PM_{2.5}$ damage costs for SUAs covered by non-modelled areas of NSW and Victoria

SUA code	SUA name	Area (km²)	2011 Population	2011 Pop. density (people/km²)	2011 unit damage cost (A$/tonne $PM_{2.5}$)
Composite	Rest of NSW	758,819	1,868,386	2.5	$690
Composite	Rest of Victoria	189,616	1,036,777	6	$1,500

5.2.1.2 Other jurisdictions

A simplified approach was used for the other jurisdictions. The approach was broadly similar to that used for NSW and Victoria, except that savings in any given year were determined for the total reduction in emissions over all sectors, and mainly for the state capital. Areas outside the state capitals were not ignored, but benefits were calculated using composite unit damage costs which were rather low. We therefore have a lower confidence in the results for other jurisdictions.

The SUAs used are given in **Table 5.4**. The uplift and discount factors used for NSW and Victoria were also used here.

Table 5.4: SUAs in other jurisdictions

Jurisdiction	SUA code	SUA name	Area (km^2)	2011 Population	2011 Pop. density (people/km^2)	2011 unit damage cost (A$/tonne $PM_{2.5}$)
QLD	3001	Brisbane	5,065	1,977,316	390	$110,000
	Composite	Rest of QLD	1,725,267	2,422,741	1.4	$400
SA	4001	Adelaide	2,024	1,198,467	592	$170,000
	Composite	Rest of SA	982,154	398,107	0.4	$110
WA	5009	Perth	3,367	1,670,952	496	$140,000
	Composite	Rest of WA	2,523,207	295,603	0.1	$30
TAS	6003	Hobart	1,213	200,498	165	$46,000
	Composite	Rest of TAS	66,805	294,851	4	$1,200
NT	7002	Darwin	295	106,257	361	$100,000
	Composite	Rest of NT	1,347,905	105,691	0.1	$20
ACT	8001	Canberra - Queanbeyan	482	391,643	812	$230,000

5.2.2 Co-benefits

Whilst Australian unit damage costs for primary $PM_{2.5}$ were provided by **Aust *et al.* (2013)**, no values were provided for NO_X. We therefore developed unit damage costs for NO_X (which relate to the role of NO_X in secondary PM formation) as part of the economic analysis project. Their derivation is explained in **Appendix F**. These unit damage costs for NO_X again take into account population density, but for the reasons given in **Appendix F** only a broad distinction was made according to area type (*i.e.* metropolitan areas and other areas). The resulting values are given in **Table 5.5**.

Table 5.5: Unit damage costs for NO_X

State	Area name	Total area (km^2)	Total 2011 population	Total 2011 pop. density (people/km^2)	2011 unit damage cost (A$/tonne NO_X)
NSW	Greater Sydney	4,630	4,333,280	936	$4,992
	Other NSW	795,710	2,505,659	3.1	$17
VIC	Greater Melbourne	6,508	3,930,407	604	$3,221
	Other VIC	221,045	1,398,984	6.3	$34
QLD	Greater Brisbane	5,065	1,977,316	390	$2,082
	Other QLD	1,725,267	2,422,741	1.4	$7
SA	Greater Adelaide	2,024	1,198,467	592	$3,158
	Other SA	982,154	398,107	0.4	$2
WA	Greater Perth	3,472	1,699,754	490	$2,611
	Other WA	2,523,102	266,801	0.1	$1
TAS	Greater Hobart	1,213	200,498	165	$882
	Other TAS	66,805	294,851	4.4	$24
NT	Greater Darwin	295	106,257	360	$1.921
	Other TAS	1,347,905	105,691	0.1	$0.4
ACT	Greater Canberra	482	391,643	813	$4,334
	Other ACT	1,914	1,662	0.9	$5

Abatement measures may also result in increases or decreases in operating costs of equipment or vehicles (*e.g.* fuel consumption, operations and maintenance, *etc.*). These co-benefits (reduction in operating costs) or dis-benefits (increase in operating costs) were accounted for by adjusting the cost of the measure by an amount equal to the co-benefit/dis-benefit, rather than by explicit quantification.

Valuing the co-benefit of reductions in GHGs is a contested issue, and there are several possible approaches. At one end of the spectrum it is argued that Australia's GHG emissions represent a miniscule contribution to global emissions and the latter are more important when considering global warming and associated welfare losses. At the other end of the spectrum preliminary estimates of the marginal social cost of carbon in **Stern (2006)** were US \$85/tCO_2e. However, the Stern methodology drew some criticism, notably for the use of a very low discount rate. The forecast cost of abatement and traded market price of carbon permits in Australia may also serve as proxies for the value of changes in GHG emissions. The former is expected to increase in line with increasingly stringent pollution caps, ranging from approximately \$30/tCO_2e to approximately \$150/tCO_2e **(Australian Treasury, 2011)**. The latter will be heavily influenced by the expected price of carbon in the European Union Emissions Trading Scheme (EU ETS) which is uncertain, although current EU ETS permits are trading at \$10/tCO_2e[27]. Based on the above, the central estimate and sensitivity range in **Table 5.6** were used in the economic analysis.

Table 5.6: Assumptions to be applied for valuing changes to GHG emissions

Assumption	Value	Source
Value of GHG emissions – central estimate	\$30/tCO_2e	**Australian Treasury (2011)**
Value of GHG emissions – lower bound	\$10/tCO_2e	Approximate EU ETS price
Value of GHG emissions – upper bound	\$100/tCO_2e	Approximate **Stern (2006)**, inflated to 2011 prices but using current USD to AUD exchange rates

5.3 Impact pathway approach

5.3.1 Method

A simplified impact pathway-type approach to quantifying health benefits was followed for the specific locations that were covered by both the HRA project and the state emissions inventories (**Table 5.7**). The impact pathway approach was only used to check the results of the damage cost calculations.

Table 5.7: Locations covered by impact pathway approach

Jurisdiction	HRA Location	Economic analysis location(s)
NSW	Illawarra	Wollongong SUA
	Lower Hunter	Newcastle SUA
	Sydney	Sydney SUA
	Upper Hunter	Muswellbrook & Singleton SUAs
VIC	Geelong	Geelong SUA
	Melbourne	Melbourne SUA
QLD	South East QLD (including Brisbane)	SEQ airshed
SA	Adelaide	Adelaide airshed
WA	Perth	Perth airshed
TAS	Hobart	Hobart airshed
NT	Darwin	Darwin airshed
ACT	Canberra	Canberra airshed

[27] Carbon and Environment Daily newsletter based on Westpac Institutional Bank data, accessed February 2013.

The method used for the impact pathway calculations is explained in **Appendix G**. This involved quantifying and monetising mortality outcomes (all years, based on annual mean concentrations) and morbidity outcomes (2036 only, based on 24-hour concentrations). Long-term (mortality) benefits were estimated for all HRA locations using modelled annual mean PM concentration changes for the different scenarios from 2011 to 2036. Because of the lengthy calculation involved, short-term (morbidity) benefits were only calculated using the 24-hour PM concentrations for the target year of 2036, and just for the HRA locations in NSW (which had the greatest detail on air pollution). Both mortality and morbidity outcomes were estimated based on the baseline incidence data from the HRA project **(Frangos and DiMarco, 2012)**. The results for NSW in 2036 were used to derive a ratio of avoided morbidity costs to mortality costs that could then be applied as an 'uplift factor' to the locations in the other jurisdictions.

Before comparing the impact pathway and damage cost results, a population adjustment was applied to the impact pathway calculations. This was to allow for the fact that, in general terms, the populations used in the economic analysis were lower than those used in the HRA project, and by a considerable margin in some cases. The economic analysis generally applied smaller ABS statistical population areas than those used in the HRA. The derivation of these adjustments is shown in **Table 5.8**. These differences in population were due to differences in the area definitions (*e.g*. Statistical Levels in the HRA and SUAs in the economic analysis) and differences in the ABS population data sets used.

Table 5.8: Impact pathway population adjustment factors

Jurisdiction	Location	2036 population in HRA project	2036 population in economic analysis	Population adjustment factor
NSW	Illawarra	365,557	244,714	0.67
	Lower Hunter	498,261	381,385	0.77
	Sydney	5,972,259	4,661,456	0.78
	Upper Hunter	285,706	33,099	0.12
VIC	Geelong	303,441	196,728	0.65
	Melbourne	6,005,518	4,984,830	0.83
QLD	South East QLD (inc. Brisbane)	4,745,067	5,314,367	1.12
SA	Adelaide	1,565,989	1,547,469	0.99
WA	Perth	2,997,596	2,806,019	0.94
TAS	Hobart	290,988	296,931	1.02
NT	Darwin	233,593	230,595	0.99
ACT	Canberra	525,345	543,856	1.04

5.3.2 Results for NSW in 2036

Table 5.9 shows the health benefits for the 'all feasible measures' portfolio for NSW in 2036. It is clear that the morbidity benefits represented only a very small fraction (0.04%) of overall health benefits. The initial impact pathway estimate of benefits in NSW in 2036 was $3.4 billion. After adjusting for population differences between the impact pathway and damage cost approaches, the impact pathway estimate decreased to $2.2 billion. The estimate of $2.2 billion was still more than twice as high as the equivalent damage cost result of $946 million.

Table 5.9: Health benefits of 'all feasible measures' portfolio for NSW in 2036 (comparing impact pathway and damage cost approaches)

Health outcome		Estimated change (reduction) in outcome	Monetised health benefit ($000's)
Morbidity	Hospital Admission All respiratory (< 15 years)	17.8	101
	Hospital Admission All respiratory (15 – 64 years)	18.2	114
	Hospital Admission All respiratory (65+ years)	45.9	260
	Hospital Admission Cardio-vascular	83.4	456
	Emergency visits (asthma)	3.3	6
	Hospital Admissions Cardiac	54.7	547
Mortality	Chronic	303.8	3,392,434
Total (unadjusted[a]) estimate using impact pathway			**3,393,918**
Total (adjusted) estimate using impact pathway			**2,245,472**
Total estimate using damage cost			**945,844**

(a) The results are presented prior to applying a population adjustment necessary to compare the impact pathway and damage cost approaches.

5.3.1 Results for all locations in 2036

The results for all HRA locations in 2036 are shown in **Table 5.10**. The impact pathway method generally produced a higher estimate of benefits than the damage cost method, although the reverse was true for Melbourne and Canberra.

Table 5.10: Health benefits of 'all feasible measures' portfolio in 2036

Jurisdiction	Location	Impact pathway estimate ($)	Damage cost estimate ($)	Impact pathway as a multiple of damage cost
NSW	Illawarra	99,695,357	31,240,594	3.2x
	Lower Hunter	347,753,245	70,652,978	4.9x
	Sydney	1,731,376,133	829,071,133	2.1x
	Upper Hunter	66,316,360	14,879,675	4.5x
VIC	Geelong	18,185,457	12,447,053	1.5x
	Melbourne	525,578,099	887,215,281	0.6x
QLD	South East QLD (inc. Brisbane)	567,363,728	339,433,709	1.7x
SA	Adelaide	458,498,765	351,969,803	1.3x
WA	Perth	533,154,104	293,297,386	1.8x
TAS	Hobart	83,959,406	43,111,304	1.9x
NT	Darwin	119,129,303	30,370,666	3.9x
ACT	Canberra	137,652,125	191,480,393	0.7x
Total for all locations		**4,688,662,081**	**3,095,169,974**	**1.5x**

5.3.1 Results for all location and all years

The results of the impact pathway and damage cost methods over all years of the analysis were estimated (expressed as a present value sum) and compared (**Table 5.11**). Comparing the present value across all years, the impact pathway method still produced a higher estimate of benefits than the damage cost method overall, although the reverse was true for Victoria, Queensland and the ACT. On average, the impact pathway produced an estimate that was 1.5 times higher than using the damage cost method.

Table 5.11: Health benefits of 'all feasible measures' portfolio over all years

Jurisdiction	Impact pathway estimate ($m PV)	Damage cost estimate ($m PV)	Impact pathway as a multiple of damage cost
NSW	14,287,082,320	5,191,586,180	2.8x
VIC	2,185,130,985	3,185,065,788	0.7x
QLD	2,933,449,465	3,872,805,197	0.8x
SA	1,850,730,475	1,526,444,680	1.2x
WA	2,047,203,867	1,689,148,916	1.2x
TAS	258,440,604	333,482,334	0.8x
NT	650,854,778	176,684,139	3.7x
ACT	429,227,883	514,685,790	0.8x
All states	**24,642,120,378**	**16,489,903,025**	**1.5x**

5.3.2 Explaining differences between impact pathway and damage cost

With differences in population between the HRA analysis and the economic analysis taken into account, and when analysed over all years and all locations, the impact pathway method gave health benefits that were still around 50% higher than those obtained using the damage cost method. However, the difference varied considerably from location to location. Through discussion with international experts and our own analysis we have identified a number of factors that contribute to this result, and these include the following:

- The damage costs are based on marginal emissions, whereas the impact pathway is based on marginal concentrations.
- The damage costs are based on UK data, whereas the impact pathway approach is based on (at least in part) Australian data. There is an (unknown) degree of uncertainty relating to the application of the UK concentration-response functions (CRFs) in Australia. There are likely to be different mortality rates in the UK and Australia due to differences in health status, age, life expectancy, as well as other factors (incidence of smoking, *etc*.) **(Aust *et al.*, 2013)**.
- The external costs of air pollution vary according to a variety of environmental factors, including overall levels of pollution, geographic location of emission sources, and meteorology. These are different in the UK and Australia **(Aust *et al.*, 2013)**.
- The damage cost approach is based on years of life lost (YOLL) for mortality in the UK, albeit adjusted for the Australian VOLY, whereas impact pathway approach is based on deaths and VSL. This has the potential to cause differences between the two approaches for two reasons. Firstly, the VSL estimate (**ASCC, 2008**) assumes an average life remaining of 40 years (approximately the average across the entire population). In contrast, the damage cost approach is based on YOLL, which on average is likely to be lower than 40 years given the greater vulnerability of older populations to air pollution. Secondly, the VSL estimate from **ASCC (2008)** is derived using a discount rate of 3%. Consistent with previous Australian studies **(ENVIRON and SKM-MMA, 2011**; **BDA Group, 2013; MMA, 2009)** and Treasury guidelines, a discount rate of 7% has been applied in the economic analysis. The two cannot be easily compared as the former relates to the discount rate applied to years of the same life whereas the latter relates to the discount rate applied to life years from all individuals across the time period of the analysis. However, the difference contributes to the generally higher result seen using the impact pathway approach.
- Damage costs are calculated at the grid cell level, whereas impact pathway is calculated based on the population-weighted concentration.

Large discrepancies can arise between the damage cost and impact pathway approaches. For example the work in Europe (which used both YOLL and VSL) that the choice of method can lead to a factor-of-two difference in the results when all other assumptions are equivalent. This is simply because different assumptions are required for the analyses **(AEA, 2005)**.

We have concluded from this comparison that the health benefits based on the damage cost method show an agreement with the benefits based on the impact pathway method that is within a reasonable range. However, the damage costs results are likely to represent a conservative estimate of health benefits.

6 COSTS AND BENEFITS OF AIR QUALITY STANDARDS AND EXPOSURE-REDUCTION TARGET

6.1 Overview

This Chapter of the Report presents the full CBA of the hypothetical air quality standards and the exposure-reduction target. Whilst the MACCs provided a visual representation of the monetary costs of abatement measures that could benefit from a national approach, and a proxy for their monetary benefit (tonnes of emission), a CBA was required to calculate both the costs and benefits of measures more precisely.

The original intention of the project was to examine the incremental effects of different combinations of abatement measures on air quality, and to determine the least-cost routes to achieving compliance. However, due to the combined effects of evaluating only primary anthropogenic PM, the growth in population, and the growth in emissions up to 2036, it became apparent that many of the individual abatement measures did not have a large effect when treated in isolation. Consequently, a simpler approach was taken, whereby two portfolios of national abatement measures were considered:

- A portfolio containing all abatement measures which could be applied in combination[28] to give the largest possible emission reduction (termed 'all feasible measures').
- A portfolio that gave the largest possible emissions reduction, but only including measures with a benefit:cost ratio[29] (BCR) of greater than one (termed 'all economic measures').

The costs and benefits of a third portfolio ('all feasible with phase-out of wood heaters') were also provided for completeness. This portfolio included the phase-out of all wood heaters (as opposed to an emission standard), but was considered less practical as it required very significant changes to heating systems Australia-wide. It has therefore not been included as part of the core analysis.

The findings of a sensitivity analysis are presented at the end of the Chapter.

6.2 Method

6.2.1 Construction of portfolios

The 'all feasible measures' and 'all economic measures' portfolios were constructed by combining individual abatement measures, keeping in mind that some of the measures analysed were mutually exclusive. For example, there can only be one national wood heater standard in force at any given time. The following rules were applied:

- Not more than one measure applying to new non-road diesel engines could be included in a portfolio.
- Not more than one measure applying to new non-road spark-ignition engines could be included in a portfolio.
- Not more than one measure relating to wood heater standards and in-service measures could be included in a portfolio. However, the regulation of moisture content of wood fuel may be

[28] Measures can be implemented in combination (are complementary or supplementary) as long as they are not mutually exclusive. For example, if standards are to be introduced for wood heaters, only one standard can be in force at any one time.

[29] A BCR is defined as the economic value of benefits expected from implementation of a policy divided by the economic costs of implementation. A measure with a relatively higher BCR delivers greater dollar benefits per dollar of costs and therefore can be considered superior to a measure with relatively lower BCR (all else being equal).

considered to be complementary to wood heater standards, and therefore could be included in a portfolio which also includes a standard.

- A portfolio that included the phase-out of wood heaters could not include a measure relating to wood heater standards and in-service measures (but could include the regulation of moisture content of wood fuel).
- A portfolio could include standards for new diesel locomotives or a standard for new diesel trains as well as the replacement of the existing fleet, but not both.

Notwithstanding the above rules, all other measures could be included in portfolios in combination.

The costs and benefits of individual measures were additive (*i.e.* the costs and benefits of a portfolio were equal to the sums of the costs and benefits of the constituent individual measures). This is because the relationship between emission reduction and health costs (all else being equal) is linear. Therefore, the costs or benefits of the portfolios were derived by summating the effects of the individual measures.

For each abatement measure the following cost and benefit items were estimated based on the methodology described in **Chapters 4** and **5**:

- Costs
  - Costs incurred by government in implementing and administering the measure.
  - Capital investment or ongoing expenditure incurred by industry.
- Benefits
  - Savings in fuel consumption associated with the implementation of the measure.
  - Reductions in PM associated with the implementation of the measure.
  - Reductions in CO_2 associated with the implementation of the measure.
  - Reductions in NO_x associated with the implementation of the measure.

This analysis provided the monetary costs and benefits per year by measure. These were then aggregated across all years by calculating a 'present value'[30] (PV). From these PVs, two metrics were calculated for each measure:

- A benefit:cost ratio (BCR): This is the economic value of benefits expected from implementation of a policy divided by the economic costs of implementation. A measure with a relatively high BCR delivers greater dollar benefits per dollar of costs, and can therefore be considered to be superior to a measure with a lower BCR (all else being equal).
- A net present value (NPV): This is the economic cost of implementation expected from implementation of a policy subtracted from the economic benefit. This metric also provides information of the scale of costs and benefits.

By definition, all measures contained in the 'all economic' portfolio had a positive NPV. This was not the case for the 'all feasible measures' and 'all feasible measures with phase-out of wood heaters' portfolios. However, the overall NPV of these portfolios was still positive, and the portfolio as a whole could therefore be assessed as being economic.

[30] The PV of a stream of monetary values over time is a metric that provides an aggregate total figure over the whole time horizon taking into account that values in the future are worth less than values today (*e.g.* a dollar today is worth more than a dollar tomorrow).

6.2.2 Evaluation approach

6.2.2.1 Annual mean concentrations

The CBA method for determining the effects of the 'all feasible measures' portfolio on annual mean concentrations in NSW and Victoria in 2036 is shown in **Figure 6.1**. For each PM metric and hypothetical air quality standard the steps taken are described below.

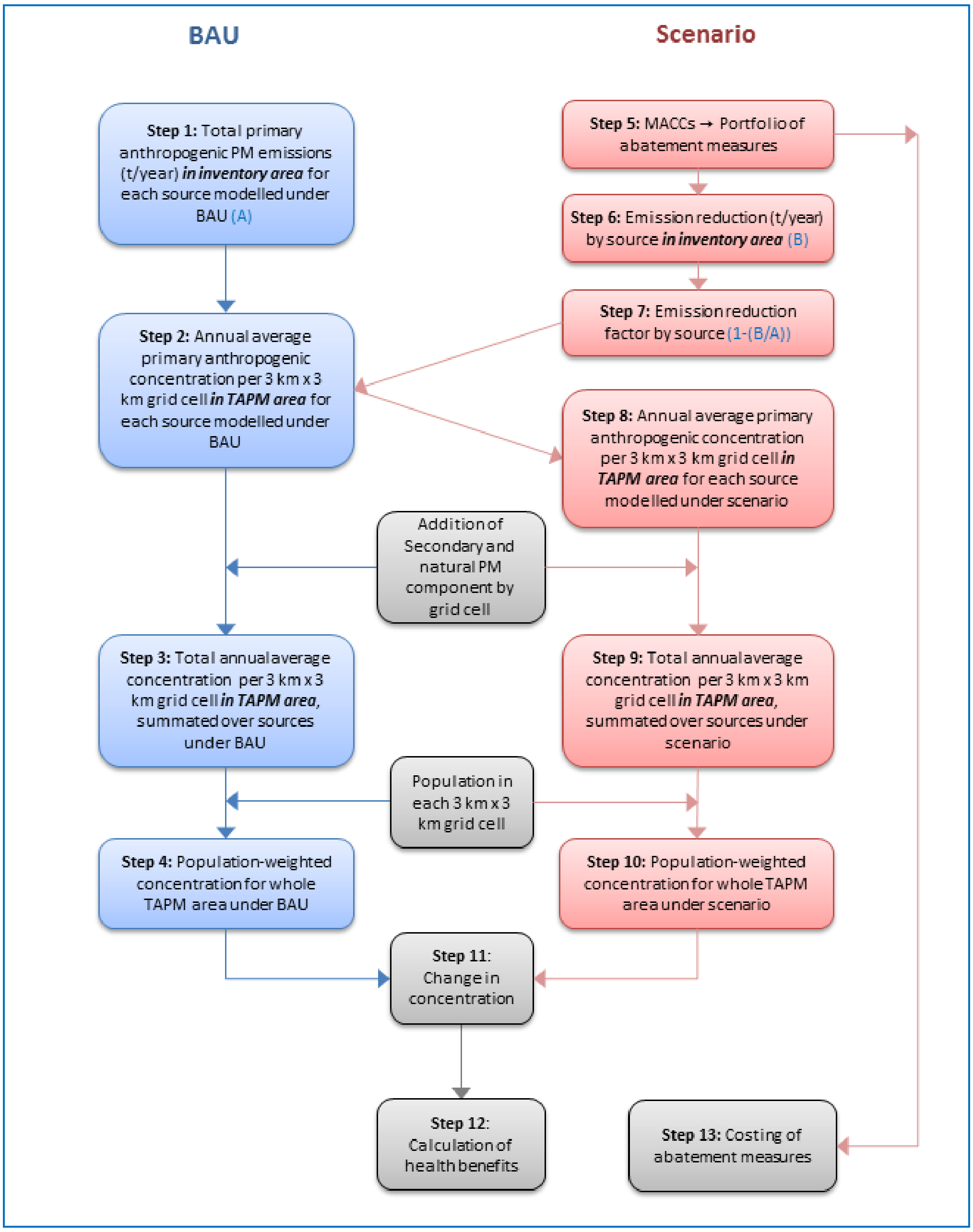

Figure 6.1: Method for NSW and Victoria – annual means

BAU case

Step 1: The total primary anthropogenic emissions **(A)** (in tonnes per year) from each source in the inventory area were obtained for the BAU scenario. The scaling factors that were used to determine emissions in future years were based on the projections described in **Chapter 3**.

Step 2: The annual mean primary anthropogenic PM concentrations (µg/m^3) per 3 km x 3 km grid cell and source group under the BAU scenario were obtained from TAPM (after model calibration).

Step 3: For each grid cell the primary anthropogenic PM contributions for all sources were summated, and the natural and secondary PM components were added to the result. This gave the total annual mean concentration for comparison with air quality standards.

Step 4: The total annual mean gridded PM concentrations were combined with gridded population data to give an average population-weighted concentration for the whole area modelled in TAPM.

Scenario (i.e. with abatement – all feasible measures)

Step 5: The costs, PM emissions reductions and co-benefits of all feasible abatement[31] measures was estimated.

Step 6: The reductions in emissions in the inventory area **(B)** (in tonnes per year) from different sources were determined for the abatement measures included in the portfolio.

Step 7: An emission-reduction factor for each emission source, defined as **1-(B/A)**, was determined.

Step 8: The emission-reduction factor for each source was applied to the corresponding primary anthropogenic concentration from the BAU scenario in Step 2.

Step 9: This repeated Step 3, but this time for the case with abatement.

Step 10: This repeated Step 4, but again for the case with abatement.

Step 11: The change in the population-weighted concentration was determined by subtracting the concentration with abatement from the concentration in the BAU case.

Step 12: The health benefits associated with the change in the population-weighted concentration were calculated for specific locations using the impact pathway approach. ***NB***: *The health benefits for all locations were primarily determined using the damage cost method based on changes in emissions, as described in* **Chapter 5**.

Step 13: The costs associated with implementation of the required abatement measures were calculated (see **Chapter 4**).

There was no feedback aspect to the analysis; for the portfolio of abatement measures investigated there was either compliance with an air quality standard or there was not. However, shortfalls in emission reductions were estimated in the gap analysis (see **Section 6.2.3**).

The general approach used for the other jurisdictions was similar to that presented in **Figure 6.1,** except that (i) the calculations were undertaken for the whole inventory area *en bloc* (*i.e*. gridded data were not used) and (ii) the BAU concentrations were based on monitoring data rather than model predictions. Although it would be desirable to understand the contribution of each source group to population-weighted exposure, no spatial information on emissions and concentrations was available for this purpose. It therefore had to be assumed that changes in exposure (to primary anthropogenic

[31] The all feasible portfolio was used as opposed to the all economic portfolio, as none of the standards that required abatement could be met through the all economic portfolio. The standards that required abatement could still not be met with the all feasible portfolio. However, this portfolio minimises the total emissions shortfall, which is then later bridged using state based measures.

PM) would be directly proportional to changes in emissions. In other words, emission reductions in all sectors had the same impact on concentrations.

6.2.2.2 24-hour mean concentrations

In NSW and Victoria the approach used for the 24-hour PM standards was directly analogous to that used for the annual mean standards. However, because the concentration peaks associated with each source group occur at different locations and at different times of the year, it is not appropriate to simply summate the 6th highest (in the case of PM_{10}) and 98th percentile (in the case of $PM_{2.5}$) 24-hour concentrations from each contributing source. A more complex treatment of Steps 2 and 3 in **Figure 6.1** was therefore required.

For each assessment year the 2011 concentration matrix (*i.e*. all grid cells and all days of the year) for each source group was taken in turn. Firstly, a scaling factor was applied to each element of the matrix to convert the 2011 concentrations into values for the assessment year. Secondly, an emission-reduction factor for abatement (Step 7 in **Figure 6.1**) was applied to all elements of the matrix. The results for each element of the matrix were summated over all sources. For each grid cell, the appropriate 24-hour metric for primary anthropogenic sources (*i.e.* 6th highest value for PM_{10}; 98th percentile value for $PM_{2.5}$) was then determined based on the 365 daily values.

Different options were considered for including the natural/secondary PM contribution on a 24-hour basis. It was concluded that an appropriate approach would be to use the mapped annual mean natural/secondary contributions. This reduced the likelihood of excessively high combined concentrations, and was deemed suitable for the intent of the exercise (*i.e.* to explore the potential primary anthropogenic PM emission-reduction scenarios that would enable compliance with the hypothetical 24-hour PM standards).

In the other jurisdictions the 24-hour concentration was treated in the same way as the annual mean concentration. This is clearly a gross simplification, but a more complex treatment was not possible.

6.2.2.3 Exposure-reduction

The rationale for an exposure-reduction framework was explained in the introduction. The concept of exposure reduction was especially pertinent where it was possible to achieve compliance with air quality standards. In this part of the work the implications of achieving compliance with the target defined by the Air TOG were determined. The target was a 10% reduction in measured long-term average $PM_{2.5}$ concentrations, being applicable to monitoring stations in populated regions.

For the purpose of our analysis we assumed that the population-weighted annual mean $PM_{2.5}$ concentration in a given jurisdiction was equivalent to the Air TOG definition. It was also assumed that the base year for this assessment was 2015, and therefore the 10% reduction in exposure would be required by 2025.

6.2.3 Gap analysis

6.2.3.1 Emission gaps

As noted earlier, even after the implementation of all feasible measures we estimated that some of the hypothetical air quality standards would not be met, and therefore further abatement would be required. Where a portfolio did not result in compliance with a hypothetical air quality standard an 'emissions gap' was calculated. This additional reduction was placed into context by quantifying it as a percentage of the 'residual' emissions (*i.e*. the total emissions in the inventory area minus the amount removed by the 'all feasible measures' portfolio).

In each case the following steps were taken:

A. Calculating the population-weighted concentration for the BAU scenario in 2036 (in µg/m^3).

B. Determining whether or not the standard was above the natural/secondary PM component. This determined whether the standard could be achieved in principle.

C. Calculating the reduction in concentration that would be required for compliance with the standard in 2036 (in µg/m^3).

D. Determing the reduction in concentration in 2036 that would be achieved with the available abatement for the feasible measures identified in the economic analysis (in µg/m^3).

E. Calculating the 'concentration gap' – in other words the difference between (C) and (D) (in µg/m^3).

F. Calculating the 'emissions gap' – the reduction in emissions in the inventory area that would be required to bridge the concentration gap (in tonnes per year). This was based upon the relationship between emissions and primary anthropogenic concentrations in the inventory area.

For the exposure reduction target a similar approach to that described above, except that the 'gaps' related to the additional reductions required by 2025 to achieve a 10% reduction in the population-weighted $PM_{2.5}$ concentration.

6.2.3.2 Costs and benefits of further abatement

Costs and benefits of implementing further abatement measures to bridge the emission gaps were estimated. For reasons that will become clear, this analysis was only required for Western Australia, Tasmania and ACT, and was facilitated through inspection of the inventory data in these states (to obtain the amount of emissions still expected from sources after implementation of all feasible measures). It should be noted that in the instances where this gap analysis has been conducted, the costs and benefits of further abatement measures are added to the 'all feasible' portfolio (as opposed to 'all economic' or 'all feasible with phase-out of wood heaters'). This is because in order to meet tighter standards all identified measures are needed (with the exception of a wood heater phase-out).

In Western Australia the emissions gap was allocated to industrial point sources (the largest remaining source of emissions in the inventory). **SKM (2010)** developed cost abatement curves for air emission reductions for the NSW Department of Environment, Climate Change and Water (DECCW). These included estimates of the costs and emissions reductions to industry from complying with NO_x and PM emissions standards (**Table 6.1**). The initiative assessed reductions and costs associated with industrial plant upgrades in the NSW GMR. Information from Appendix F of **SKM (2010)** has been used to develop a cost estimate of abatement of PM emissions from industrial point sources of \$11,158/tPM_{10}[32]. $PM_{2.5}$ was assumed to comprise 66% of PM_{10} for emissions from industrial point sources based on the 'Emissions-to-Area' report for the GMR in 2011, as supplied by NSW EPA.

Table 6.1: Costs and emissions reduction of emissions limits on industry

Implementation (capital)	\$74m
Annual operating/ongoing	\$0
Abatement	626 tonnes per annum

In terms of cost-effectiveness, this measure ranks mid-range compared with the core measures. The implementation of this measure is also expected to abate NO_x emissions. However, this has not been

[32] The Equivalent Annual Cost (EAC) method was used. This is a more appropriate method in the context of the gap analysis as it matches an annual cost to annual emissions reductions (see **Chapter 6**).

included in order to provide a more conservative assessment of the measure (for which there is considerable uncertainty as to the costs and benefits).

In Tasmania and ACT the emission gaps were allocated to wood heaters (the largest remaining source of emissions). The cost of the most economic wood heater standard was used as a basis for estimating costs (60% efficiency, 1.5 g/kg emission standards, and in-service measures). However, an increase of 20% in costs (see **Section 5.4.2.6**) has been applied to recognise that the abatement required is beyond the scope of this measures and that additional abatement is likely to come only at a higher cost; this equates to a cost of $2,048/tPM$_{2.5}$[33].

The benefits of emissions reductions were calculated using the damage cost approach already described.

With respect to timing, the measures are assumed to be active over a 20-year period ending in 2036 (*i.e.* 2017 to 2036), this being a time-horizon broadly similar to that of the core abatement measures.

6.3 Results

6.3.1 Portfolios of abatement measures

The costs and benefits for all individual abatement measures are presented in **Table 6.2**. The measures are ordered by BCR. The NPV[34] for the measures has also been provided. The 'all feasible measures' and 'all economic measures' portfolios are given in **Table 6.3** and **Table 6.4** respectively. Note that in the cost-benefit analysis non-road diesel standards are referred to as a single policy given the similarity of the results of the two variants assessed (Commonwealth regulation or a NEPM). CO_2 benefits have only been estimated for area-wide planting, although CO_2 reductions are likely (but uncertain) for a number of other measures (see **Appendix D**). This results in a conservative estimate of CO_2 benefits for the portfolios.

The concentration profiles with and without all feasible abatement measures are presented in **Appendix H**.

6.3.2 Gap analysis

The results for each hypothetical air quality standard for PM_{10} and $PM_{2.5}$ are presented in the following Sections. It is again worth noting the following:

- The assumption of a constant contribution from secondary PM will mean that the required concentration and emission reductions will be overestimated, but the current state of the knowledge does not allow us to quantify the extent of the overestimation.
- We have assumed that compliance with an air quality standard in an inventory area would also mean that there would be compliance in the rest of the state. It is not difficult to imagine a situation where this might not be the case (*e.g.* in populated areas near mines), but we have no data on emissions in these areas to allow this to be tested.
- It is challenging to assess compliance with short-terms standards, especially over larger geographical areas where there are multiple emission sources and effects. We therefore consider our analysis of the 24-hour standards to be indicative.

[33] The EAC method has been applied as this is the most appropriate in the context of the gap analysis.

[34] An alternative metric to BCR is NPV. NPV is defined as the economic costs of implementation expected from implementation of a policy subtracted from the economic value of benefits. This metric also provides information of the scale of costs and benefits.

Table 6.2: Costs and benefits of all measures

Abatement measure	Government	Industry	PM	NOx	CO_2	Fuel efficiency	NPV (2011 $m)	BCR
Regulating moisture content of wood fuel to be less than 20%	-$0	-$1	$1,035				$1,034	1,176
Requiring wood heaters to be removed or rendered inoperable on sale of house	-$0	-$24	$10,587				$10,563	436
Wood heaters 60% efficiency, 3 g/kg emission standards	-$16	-$3	$3,741				$3,722	195
Wood heaters 60% efficiency, 3 g/kg emission standards and in-service measures	-$27	-$3	$4,031				$4,001	132
Wood heaters 65% efficiency, 3 g/kg emission standards and in-service measures	-$26	-$4	$3,906				$3,876	131
Wood heaters emissions labelling, star-rating, education, audit and 60% efficiency standard	-$16	-$1	$2,044				$2,027	120
Wood heaters 60% efficiency, 1.5 g/kg emission standards and in-service measures	-$24	-$13	$4,215				$4,178	114
Wood heaters emissions labelling, star-rating, education and audit	-$16	-$0	$1,758				$1,742	106
Wood heaters emissions labelling, education and audit	-$15	-$0	$1,515				$1,500	100
Wood heaters national audits and education	-$11	-$0	$836				$825	75
Wood heaters national audits, education and replacement initiatives	-$20	-$0	$1,180				$1,159	57
MOU to reduce shipping vessel speed for ocean transits	-$5	-$109	$435	$31			$352	4.1
US 2006 and 2010, outboard and watercraft, and US phase 2 gardening emissions standards	-$44	-$223	$540			$347	$620	3.3
US2010 outboard and watercraft, and US phase 2 gardening emissions standards	-$44	-$233	$544			$349	$616	3.2
Diesel trains driver assistance software for line haul locomotives	-$2	-$53	$63	$39		$33	$80	2.5
Retrofitting high-polluting (urban) non-road diesel engines & equipment with DPFs	-$4	-$1	$11				$6	2.3
Adoption of international best practice PM control measures at coal mines	-$5	-$2,437	$3,085				$643	1.3
US non-road diesel standards in Australia (excluding < 19kW)	-$22	-$6,484	$5,611	$579		$2,239	$1,922	1.3
Requiring new locomotives to meet US Tier 4 standards	-$2	-$234	$170	$68			$1	1.0
Mandatory low-sulfur fuel use by ships while at berth	-$4	-$642	$583	$2			-$61	0.9
Retrofitting non-road diesel engines at mine sites with DPFs (emissions reduction program)	-$2	-$575	$432				-$145	0.8
Targeted maintenance of high-polluting LCVs using remote sensing	-$2	$0	$1				-$1	0.6
Penalty and incentive scheme for high polluting vehicles	-$7	-$12	$9				-$9	0.5
Replacing old line locomotive and requiring new locomotives to meet US Tier 4 standards	-$2	-$2,393	$352	$209			-$1,835	0.2
Area-wide planting to remove PM from the atmosphere	-$628	$0	$114	$1	$4		-$510	0.2

Table 6.3: Costs and benefits of 'all feasible measures' portfolio

Abatement measure	Government	Industry	PM	NOx	CO_2	Fuel efficiency	NPV (2011 $m)	BCR
Regulating moisture content of wood fuel to be less than 20%	-$0	-$1	$1,035				$1,034	1,176
Wood heaters 60% efficiency, 1.5 g/kg emission standards and in-service measures	-$24	-$13	$4,215				$4,178	114
MOU to reduce shipping vessel speed for ocean transits	-$5	-$109	$435	$31			$352	4.1
US2010 outboard and watercraft, and US phase 2 gardening emissions standards	-$44	-$233	$544			$349	$616	3.2
Diesel trains driver assistance software for line haul locomotives	-$2	-$53	$63	$39		$33	$80	2.5
Retrofitting high-polluting (urban) non-road diesel engines & equipment with DPFs	-$4	-$1	$11				$6	2.3
Adoption of international best practice PM control measures at coal mines	-$5	-$2,437	$3,085				$643	1.3
US non-road diesel standards in Australia (excluding < 19kW)	-$22	-$6,484	$5,611	$579		$2,239	$1,922	1.3
Mandatory low-sulfur fuel use by ships while at berth	-$4	-$642	$583	$2			-$61	0.9
Retrofitting non-road diesel engines at mine sites with DPFs (emissions reduction program)	-$2	-$575	$432				-$145	0.8
Targeted maintenance of high-polluting LCVs using remote sensing	-$2	$0	$1				-$1	0.6
Penalty and incentive scheme for high-polluting vehicles	-$7	-$12	$9				-$9	0.5
Replacing old line locomotive and requiring new locomotives to meet US Tier 4 standards	-$2	-$2,393	$352	$209			-$1,835	0.2
Area-wide planting to remove PM from the atmosphere	-$628	$0	$114	$1	$4		-$510	0.2
Total	**-$752**	**-$12,951**	**$16,490**	**$859**	**$4**	**$2,621**	**$6,271**	**1.5**

Table 6.4: Costs and benefits of 'all economic measures' portfolio

Abatement measure	Government	Industry	PM	NOx	CO_2	Fuel efficiency	NPV (2011 $m)	BCR
Regulating moisture content of wood fuel to be less than 20%	-$0	-$1	$1,035				$1,034	1,176
Wood heaters 60% efficiency, 1.5 g/kg emission standards and in-service measures	-$24	-$13	$4,215				$4,178	114
MOU to reduce shipping vessel speed for ocean transits	-$5	-$109	$435	$31			$352	4.1
US2010 outboard and watercraft, and US phase 2 gardening emissions standards	-$44	-$233	$544	$0		$349	$616	3.2
Diesel trains driver assistance software for line haul locomotives	-$2	-$53	$63	$39		$33	$80	2.5
Retrofitting high-polluting (urban) non-road diesel engines & equipment with DPFs	-$4	-$1	$11				$6	2.3
Adoption of international best practice PM control measures at coal mines	-$5	-$2,437	$3,085				$643	1.3
US non-road diesel standards in Australia (excluding < 19kW)	-$22	-$6,484	$5,611	$579		$2,239	$1,922	1.3
Requiring new locomotives to meet US Tier 4 standards	-$2	-$234	$170	$68			$1	1.0
Total	**-$109**	**-$9,563**	**$15,169**	**$716**	**$0**	**$2,621**	**$8,834**	**1.9**

Table 6.5: Costs and benefits of all 'all feasible measures (with phase-out of wood heaters)'

Abatement measure	Government	Industry	PM	NOx	CO_2	Fuel efficiency	NPV (2011 $m)	BCR
Regulating moisture content of wood fuel to be less than 20%	-$0	-$1	$1,035				$1,034	1,176
Requiring wood heaters to be removed or rendered inoperable on sale of house	-$0	-$24	$10,587	$0	$0	$0	$10,563	436
MOU to reduce shipping vessel speed for ocean transits	-$5	-$109	$435	$31			$352	4.1
US2010 outboard and watercraft, and US phase 2 gardening emissions standards	-$44	-$233	$544			$349	$616	3.2
Diesel trains driver assistance software for line haul locomotives	-$2	-$53	$63	$39		$33	$80	2.5
Retrofitting high-polluting (urban) non-road diesel engines & equipment with DPFs	-$4	-$1	$11				$6	2.3
Adoption of international best practice PM control measures at coal mines	-$5	-$2,437	$3,085				$643	1.3
US non-road diesel standards in Australia (excluding < 19kW)	-$22	-$6,484	$5,611	$579		$2,239	$1,922	1.3
Mandatory low-sulfur fuel use by ships while at berth	-$4	-$642	$583	$2			-$61	0.9
Diesel retrofit at mine sites (emissions reduction program) (diesel retrofit)	-$2	-$575	$432				-$145	0.8
Targeted maintenance of high-polluting LCVs using remote sensing	-$2	$0	$1				-$1	0.6
Penalty and incentive scheme for high-polluting vehicles	-$7	-$12	$9				-$9	0.5
Replacing old line locomotive and requiring new locomotives to meet US Tier 4 standards	-$2	-$2,393	$352	$209			-$1,835	0.2
Area-wide planting to remove PM from the atmosphere	-$628	$0	$114	$1	$4		-$510	0.2
Total	**-$728**	**-$12,963**	**$22,862**	**$859**	**$4**	**$2,621**	**$12,656**	**1.9**

6.3.2.1 Annual mean air quality standards for PM_{10}

PM_{10} standard of 20 µg/m³

Table 6.6 shows the results for the annual mean PM_{10} standard of 20 µg/m³. In all states except Western Australia the standard would already be met in the target year of 2036 in the BAU scenario. In Western Australia a reduction of 1.0 µg/m³ in 2036 would be required for compliance. The introduction of all feasible abatement measures would lead to a reduction of 0.6 µg/m³ in Western Australia, leaving a concentration gap (allowing for rounding) of 0.4 µg/m³, equating to an emissions gap of 609 tonnes per year in the inventory area (the Perth airshed) (around 7% of the residual emissions following the implementation of all feasible measures).

Table 6.6: Compliance with annual mean PM_{10} standard of 20 µg/m³ in 2036 ('all feasible measures' portfolio)

Criterion	Jurisdiction							
	NSW	VIC	QLD	SA	WA	TAS	NT	ACT
(A) Conc. in BAU scenario in 2036 (µg/m³)	19.7	18.5	18.1	16.4	**21.1**	13.5	17.8	11.1
(B) Standard above natural/secondary component?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
(C) Required conc. reduction(µg/m³)	-	-	-	-	1.0	-	-	-
(D) Reduction in conc. with max. abatement (µg/m³)	1.4	0.5	0.9	0.6	0.6	0.4	1.2	0.6
(E) Concentration gap (µg/m³)	-	-	-	-	0.4	-	-	-
(F) Emissions gap (tonnes per year)	-	-	-	-	**609**	-	-	-

These results imply that further measures and policies would be required to control PM emissions in Western Australia. The fact that base year PM_{10} concentrations in the Perth airshed are below 20 µg/m³ does not ensure compliance in the future given the growth projections for Western Australia. If the projected increases in emissions and concentrations actually ensue, then compliance with this standard could represent a significant challenge in Western Australia.

The inventory data suggest that it would be appropriate to target the industrial sector when considering the options for further emission reductions. The costs and benefits of the further (industrial point source) measures that would be required to bridge the emissions gap in Western Australia are shown in **Table 6.7**. The costs and benefits of implementing these further measures are estimated to be small relative to those for the 'all feasible measures' portfolio.

Table 6.7: Costs and benefits of meeting annual mean PM_{10} standard of 20 µg/m³ in Western Australia

Abatement measure	Costs (2011 $m)	Benefits (2011 $m)	BCR	NPV (2011 $m)
'All feasible measures' portfolio	$13,703	$19,974	1.46	6,271
Measures required to reduce PM_{10} emissions by a further 609 tonnes in Western Australia	$48	$166	3.46	$118
Total Portfolio	**$13,751**	**$20,140**	**1.46**	**$6,389**

PM_{10} standard of 16 µg/m³

Only Tasmania and ACT would comply with an annual mean PM_{10} standard of 16 µg/m³ in the BAU scenario in 2036 (**Table 6.8**). The introduction of all feasible abatement measures would also result in compliance in South Australia, but there would be concentration gaps in the other jurisdictions of between 0.5 µg/m³ and 4.4 µg/m³. These concentration gaps equate to large further reductions in emissions in the corresponding jurisdictions. For example, in the NSW GMR the emissions gap of 72,257 tonnes per year corresponds to approximately four fifths of the residual emissions after the introduction of all feasible abatement measures in the economic analysis. In Victoria the natural/secondary PM concentration is only slightly below 16 µg/m³, and the emission gap of 17,517 tonnes per year equates to 93% of the remaining emissions in the inventory area. In Western Australia the corresponding proportion is 77%. Such reductions in emissions will not be feasible. Based on these findings we consider it highly unlikely that an annual mean PM_{10} standard of 16 µg/m³ will be achievable nationally. Therefore, no further analysis of the costs and benefits of compliance with this hypothetical standard was undertaken.

Table 6.8: Compliance with annual mean PM_{10} standard of 16 µg/m³ in 2036 ('all feasible measures' portfolio)

Criterion	Jurisdiction							
	NSW	VIC	QLD	SA	WA	TAS	NT	ACT
(A) Conc. in BAU scenario in 2036 (µg/m³)	**19.7**	**18.5**	**18.1**	**16.4**	**21.1**	13.5	**17.8**	11.1
(B) Standard above natural/secondary component?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
(C) Required conc. reduction(µg/m³)	3.7	2.5	2.1	0.4	5.1	-	1.8	-
(D) Reduction in conc. with max. abatement (µg/m³)	1.4	0.5	0.9	0.6	0.6	0.4	1.2	0.6
(E) Concentration gap (µg/m³)	2.4	2.0	1.2	-	4.4	-	0.5	-
(F) Emissions gap (tonnes per year)	**72,257**	**17,517**	**4,917**	-	**6,331**	-	**27**	-

PM_{10} standard of 12 µg/m³

The results for the annual mean PM_{10} standard of 12 µg/m³ (**Table 6.9**) show that compliance would not be possible in all but two jurisdictions (Tasmania and ACT). This is because the standard is below the concentration associated with natural and secondary PM. We therefore gave no further consideration to this standard in the economic analysis.

Table 6.9: Compliance with annual mean PM_{10} standard of 12 µg/m³ in 2036 ('all feasible measures' portfolio)

Criterion	Jurisdiction							
	NSW	VIC	QLD	SA	WA	TAS	NT	ACT
(A) Conc. in BAU scenario in 2036 (µg/m³)	**19.7**	**18.5**	**18.1**	**16.4**	**21.1**	**13.5**	**17.8**	11.1
(B) Standard above natural/secondary component?	No	No	No	No	No	Yes	No	Yes
(C) Required conc. reduction(µg/m³)	Not possible by reducing primary PM alone	Not possible by reducing primary PM alone	Not possible by reducing primary PM alone	Not possible by reducing primary PM alone	Not possible by reducing primary PM alone	1.5	Not possible by reducing primary PM alone	-
(D) Reduction in conc. with max. abatement (µg/m³)						0.4		0.6
(E) Concentration gap (µg/m³)						1.1		-
(F) Emissions gap (tonnes per year)						**1,249**		-

6.3.2.2 Annual mean air quality standards for $PM_{2.5}$

Annual mean $PM_{2.5}$ standard of 10 µg/m³

Table 6.10 shows that all jurisdictions would achieve compliance with the annual mean $PM_{2.5}$ standard of 10 µg/³ in 2036. No gap analysis was therefore required in this case.

Table 6.10: Compliance with annual mean $PM_{2.5}$ standard of 10 µg/m³ in 2036 ('all feasible measures' portfolio)

Criterion	Jurisdiction							
	NSW	VIC	QLD	SA	WA	TAS	NT	ACT
(A) Conc. in BAU scenario in 2036 (µg/m³)	7.2	6.1	6.5	8.4	6.9	9.2	9.2	7.4
(B) Standard above natural/secondary component?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
(C) Required conc. reduction(µg/m³)	-	-	-	-	-	-	-	-
(D) Reduction in conc. with max. abatement (µg/m³)	0.9	0.4	0.3	0.6	0.3	0.5	1.5	0.8
(E) Concentration gap (µg/m³)	-	-	-	-	-	-	-	-
(F) Emissions gap (tonnes per year)	-	-	-	-		-	-	-

Annual mean $PM_{2.5}$ standard of 8 µg/m³

Table 6.11 shows that In the BAU case five jurisdictions complied with the annual mean $PM_{2.5}$ standard of 8 µg/³ (the current NEPM advisory value) in 2036. In two of the remaining three jurisdictions (South Australia and Northern Territory) we estimate that the introduction of the 'all feasible measures' portfolio would also result in compliance. Further state-based measures would be required in Tasmania.

Table 6.11: Compliance with annual mean $PM_{2.5}$ standard of 8 µg/m³ in 2036 ('all feasible measures' portfolio)

Criterion	Jurisdiction							
	NSW	VIC	QLD	SA	WA	TAS	NT	ACT
(A) Conc. in BAU scenario in 2036 (µg/m³)	7.2	6.1	6.5	**8.4**	6.9	**9.2**	**9.2**	7.4
(B) Standard above natural/secondary component?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
(C) Required conc. reduction(µg/m³)	-	-	-	0.4	-	1.2	1.2	-
(D) Reduction in conc. with max. abatement (µg/m³)	0.9	0.4	0.3	0.6	0.3	0.5	1.5	0.8
(E) Concentration gap (µg/m³)	-	-	-	-	-	0.7	-	-
(F) Emissions gap (tonnes per year)	-	-	-	-	**-**	**553**	-	-

For the Hobart airshed the gap analysis indicated that a further reduction of 553 tonnes of $PM_{2.5}$ per year (18% of the remainder after abatement) would be required for compliance. According to the Hobart inventory the dominant source of $PM_{2.5}$ is wood heater emissions. As there is a substantial residual emission following the application of the abatement portfolio there may be an inconsistency in the data (*e.g.* the emission reduction for wood heaters in Hobart may be underestimated). This requires further investigation.

The costs and benefits of implementing further measures in Tasmania to bridge the emissions gap are summarised in **Table 6.12**. The costs and benefits of implementing these further measures are estimated to be small relative to those for the 'all feasible measures' portfolio.

Table 6.12: Costs and benefits of meeting annual mean $PM_{2.5}$ standard of 8 µg/m³

Abatement measure	Costs (2011 $m)	Benefits (2011 $m)	BCR	NPV (2011 $m)
'All feasible measures' portfolio	$13,703	$19,974	1.46	6,271
Measures required to reduce $PM_{2.5}$ emissions by a further 533 tonnes in Tasmania	$8	$201	24.27	$193
Total Portfolio	**$13,711**	**$20,176**	**1.47**	**$6,464**

6.3.2.3 Annual mean $PM_{2.5}$ standard of 6 µg/m³

For the annual mean $PM_{2.5}$ standard of 6 µg/m³ the introduction of the 'all feasible measures' portfolio would lead to compliance in Victoria but not in the other jurisdictions (**Table 6.13**). Compliance in some of the other jurisdictions should be feasible. For example, in NSW, Queensland and Western Australia the emission gaps are equivalent to 11%, 6% and 18% of the residual emissions respectively. However, in South Australia and Tasmania it seems that achieving compliance would be much more difficult, as the gaps represent 60% and 69% of the residual emissions respectively. Therefore, we undertook no further analysis of the costs and benefits of compliance with this hypothetical standard.

Table 6.13: Compliance with annual mean $PM_{2.5}$ standard of 6 µg/m³ in 2036 ('all feasible measures' portfolio)

Criterion	Jurisdiction							
	NSW	VIC	QLD	SA	WA	TAS	NT	ACT
(A) Conc. in BAU scenario in 2036 (µg/m³)	**7.2**	**6.1**	**6.5**	**8.4**	**6.9**	**9.2**	**9.2**	**7.4**
(B) Standard above natural/secondary component?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
(C) Required conc. reduction(µg/m³)	1.2	0.1	0.5	2.4	0.9	3.2	3.2	1.4
(D) Reduction in conc. with max. abatement (µg/m³)	0.9	0.4	0.3	0.6	0.3	0.5	1.5	0.8
(E) Concentration gap (µg/m³)	0.2	-	0.2	1.8	0.6	2.7	1.7	0.6
(F) Emissions gap (tonnes per year)	**3,238**	-	**631**	**3,027**	**1,405**	**2,167**	**68**	**242**

6.3.2.4 24-hour air quality standards for PM_{10} (6th highest value)

PM_{10} standard of 50 µg/m³

With the introduction of the 'all feasible measures' portfolio all jurisdictions would comply with a 24-hour PM_{10} standard of 50 µg/m³ on a population-weighted basis by 2036, as shown in **Table 6.14**. No gap analysis was therefore required in this case.

Table 6.14: Compliance with a 24-hour PM_{10} standard of 50 µg/m³ in 2036 ('all feasible measures' portfolio)

Criterion	Jurisdiction							
	NSW	VIC	QLD	SA	WA	TAS	NT	ACT
(A) Conc. in BAU scenario in 2036 (µg/m³)	27.5	27.4	33.9	32.6	40.3	44.2	41.3	34.1
(B) Standard above natural/secondary component?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
(C) Required conc. reduction(µg/m³)	-	-	-	-	-	-	-	-
(D) Reduction in conc. with max. abatement (µg/m³)	4.8	2.3	1.7	1.2	1.2	1.2	2.9	2.0
(E) Concentration gap (µg/m³)	-	-	-	-	-	-	-	-
(F) Emissions gap (tonnes per year)	-	-	-	-	-	-	-	-

PM_{10} standard of 40 µg/m³

In the case of the 24-hour PM_{10} standard of 40 µg/m³, the introduction of the 'all feasible measures' portfolio would result in compliance in all jurisdictions except Tasmania. Compliance in Tasmania would involve a reduction of 19% of the residual emissions.

Table 6.15: Compliance with a 24-hour PM_{10} standard of 40 µg/m³ in 2036 ('all feasible measures' portfolio)

Criterion	Jurisdiction							
	NSW	VIC	QLD	SA	WA	TAS	NT	ACT
(A) Conc. in BAU scenario in 2036 (µg/m³)	27.5	27.4	33.9	32.6	**40.3**	**44.2**	**41.3**	34.1
(B) Standard above natural/secondary component?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
(C) Required conc. reduction(µg/m³)	-	-	-	-	0.3	4.2	1.3	-
(D) Reduction in conc. with max. abatement (µg/m³)	4.8	2.3	1.7	1.2	1.2	1.2	2.9	2.0
(E) Concentration gap (µg/m³)	-	-	-	-	-	3.0	-	-
(F) Emissions gap (tonnes per year)	-	-	-	-	-	**1,024**	-	-

The costs and benefits of implementing further measures in Tasmania to bridge the emissions gap are summarised in **Table 6.16**. The costs and benefits of the 'all feasible measures' portfolio are largely unaffected by the implementation of the further measures.

Table 6.16: Costs and benefits of meeting 24-hour mean PM_{10} standard of 40 µg/m³

Abatement measure	Costs (2011 $m)	Benefits (2011 $m)	BCR	NPV (2011 $m)
'All feasible measures' portfolio	$13,703	$19,974	1.46	6,271
Measures required to reduce PM_{10} emissions by a further 1,024 tonnes in Tasmania	$15	$361	24.27	$346
Total Portfolio	**$13,718**	**$20,335**	**1.48**	**$6,616**

PM_{10} standard of 30 µg/m³

The results for the 24-hour PM_{10} standard of 30 µg/m³ are provided in **Table 6.17**. Only NSW and Victoria were compliant with the standard in the BAU case. It is worth noting that these two jurisdictions were compliant with all three 24-hour standards for PM_{10} in the BAU case. This may be a consequence of the more detailed population-weighting that was possible for NSW and Victoria. That is to say, if the same gridded approach could be applied to the other jurisdictions it may well be observed that they are also compliant with these standards. In two jurisdictions – Tasmania and Northern Territory – it was not possible to achieve compliance as the natural/secondary PM contribution was higher than the standard. Moreover, compliance in Western Australia would require a reduction of 83% in the residual emissions. Consequently, we conducted no further analysis of the costs and benefits of compliance with this hypothetical standard.

Table 6.17: Compliance with a 24-hour PM_{10} standard of 30 µg/m³ in 2036 ('all feasible measures' portfolio)

Criterion	Jurisdiction							
	NSW	VIC	QLD	SA	WA	TAS	NT	ACT
(A) Conc. in BAU scenario in 2036 (µg/m³)	27.5	27.4	**33.9**	**32.6**	**40.3**	**44.2**	**41.3**	**34.1**
(B) Standard above natural/secondary component?	Yes	Yes	Yes	Yes	Yes	No	No	Yes
(C) Required conc. reduction(µg/m³)	-	-	3.9	2.6	10.3	Not possible by reducing primary PM alone	Not possible by reducing primary PM alone	4.1
(D) Reduction in conc. with max. abatement (µg/m³)	4.8	2.3	1.7	1.2	1.2			2.0
(E) Concentration gap (µg/m³)	-	-	2.2	1.4	9.1			2.1
(F) Emissions gap (tonnes per year)	-	-	**4,765**	**1,277**	**6,811**			**216**

6.3.2.5 24-hour air quality standards for $PM_{2.5}$ (98th percentile value)

$PM_{2.5}$ standard of 25 µg/m³

Table 6.18 shows that this standard was achieved in the BAU scenario and with all feasible abatement measures in 2036 in all jurisdictions except Tasmania and ACT, where additional reductions in residual emissions of 51% and 3% would be required.

Table 6.18: Compliance with a 24-hour $PM_{2.5}$ standard of 25 µg/m³ in 2036 ('all feasible measures' portfolio)

Criterion	Jurisdiction							
	NSW	VIC	QLD	SA	WA	TAS	NT	ACT
(A) Conc. in BAU scenario in 2036 (µg/m³)	10.3	11.1	17.3	18.0	15.1	**34.2**	19.0	**30.1**
(B) Standard above natural/secondary component?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
(C) Required conc. reduction(µg/m³)	-	-	-	-	-	9.2	-	5.1
(D) Reduction in conc. with max. abatement (µg/m³)	2.3	1.9	0.8	1.2	0.7	1.9	1.0	4.7
(E) Concentration gap (µg/m³)	-	-	-	-	-	7.4	-	0.4
(F) Emissions gap (tonnes per year)	-	-	-	-		**1,594**	**-**	**39**

The costs and benefits of implementing further measures in Tasmania and ACT to bridge the emissions gap are summarised in **Table 6.19**. This standard required the greatest emission reduction of all the standards assessed, and the greatest shortfall to be bridged with state-based measures. Therefore, the total costs and benefits are somewhat different from the 'all feasible measures' portfolio.

Table 6.19: Costs and benefits of meeting annual mean $PM_{2.5}$ standard of 25 µg/m³

Abatement measure	Costs (2011 $m)	Benefits (2011 $m)	BCR	NPV (2011 $m)
'All feasible measures' portfolio	$13,703	$19,974	1.46	6,271
Measures required to reduce $PM_{2.5}$ emissions by a further 1,594 tonnes in Tasmania	$24	$581	24.27	$557
Measures required to reduce $PM_{2.5}$ emissions by a further 39 tonnes in ACT	$1	$113	193.80	$112
Total Portfolio	**$13,727**	**$20,668**	**1.50**	**$6,940**

$PM_{2.5}$ standard of 20 µg/m³

If the 'all feasible measures' portfolio is introduced we estimate that the standard of 20 µg/m³ would be met by 2036 in all jurisdictions except Tasmania and ACT (**Table 6.20**). The large reduction in emissions (85% of the residual) that would be required in Tasmania appears to render this hypothetical standard impractical.

Table 6.20: Compliance with a 24-hour $PM_{2.5}$ standard of 20 µg/m³ in 2036 ('all feasible measures' portfolio)

Criterion	Jurisdiction							
	NSW	VIC	QLD	SA	WA	TAS	NT	ACT
(A) Conc. in BAU scenario in 2036 (µg/m³)	10.3	11.1	17.3	18.0	15.1	**34.2**	19.0	**30.1**
(B) Standard above natural/secondary component?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
(C) Required conc. reduction(µg/m³)	-	-	-	-	-	14.2	-	10.1
(D) Reduction in conc. with max. abatement (µg/m³)	2.3	1.9	0.8	1.2	0.7	1.9	1.0	4.7
(E) Concentration gap (µg/m³)	-	-	-	-	-	12.4	-	5.4
(F) Emissions gap (tonnes per year)	-	-	-	-	-	**2,677**	-	**544**

$PM_{2.5}$ standard of 15 µg/m³

The standard of 15 µg/m³ would be lower than the natural/secondary $PM_{2.5}$ component in Tasmania and ACT, and therefore compliance would not be possible at the national level (**Table 6.21**). No further analysis of costs and benefits was carried out.

Table 6.21: Compliance with a 24-hour $PM_{2.5}$ standard of 15 µg/m³ in 2036 ('all feasible measures' portfolio)

Criterion	Jurisdiction							
	NSW	VIC	QLD	SA	WA	TAS	NT	ACT
(A) Conc. in BAU scenario in 2036 (µg/m³)	10.3	11.1	**17.3**	**18.0**	**15.1**	**34.2**	**20.0**	**30.1**
(B) Standard above natural/secondary component?	Yes	Yes	Yes	Yes	Yes	No	Yes	No
(C) Required conc. reduction(µg/m³)	-	-	2.3	3.0	0.1	Not possible by reducing primary PM alone	4.0	Not possible by reducing primary PM alone
(D) Reduction in conc. with max. abatement (µg/m³)	2.3	1.9	0.8	1.2	0.7		1.0	
(E) Concentration gap (µg/m³)	-	-	1.5	1.8	-		3.0	
(F) Emissions gap (tonnes per year)	-	-	**1,868**	**1,369**	**-**		**59**	

6.3.2.6 Exposure-reduction target

Figure 6.2 shows the change in population exposure to $PM_{2.5}$ in each jurisdiction between 2015 and 2030 (percentage change relative to 2015) with all feasible abatement measures in place, and the reduction achieved by the target year 2025. The profile for each jurisdiction reflects the net effect of increasing emissions and concentrations due to economic growth[35], and decreasing concentration associated with abatement measures. Where there is an increase in exposure over this period, the former outweighs the latter.

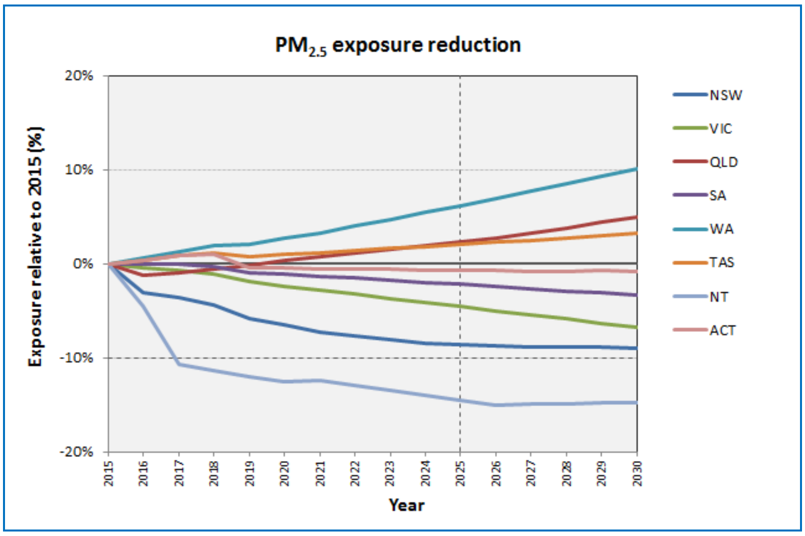

Figure 6.2: Reduction in population exposure to $PM_{2.5}$ between 2015 and 2030 with all feasible abatement measures (target year 2025)

The target of a 10% reduction by 2025 would only be achieved in the Northern Territory; the initial decrease in concentration in this jurisdiction is largely due to shipping-related measures. NSW would be close to compliance. There would also be net reductions in exposure between 2015 and 2025 in ACT, Victoria and South Australia, but net increases in Western Australia, Queensland and Tasmania. The gap

[35] Changes in population have not been factored into these calculations.

analysis for this case is given in **Table 6.22**. In NSW the emission gap equated to 4% of residual emissions in the inventory. In the other jurisdictions the proportion was around 20-30%.

Table 6.22: Compliance with an exposure-reduction target of 10% reduction in population-weighted $PM_{2.5}$ concentration between 2015 and 2025 ('all feasible measures' portfolio)

Criterion	Jurisdiction							
	NSW	VIC	QLD	SA	WA	TAS	NT	ACT
(A) Pop.-weighted concentration in BAU in 2015 (µg/m³)	6.9	6.1	5.6	8.2	5.7	8.3	8.7	6.6
(B) Conc. required for10% reduction between 2015-2025 (µg/m³)	6.2	5.5	5.1	7.3	5.1	7.5	7.8	6.0
(C) Target above natural/secondary PM component?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
(D) Reduction in conc.to meet target in 2025 (µg/m³)	0.7	0.6	0.6	0.8	0.6	0.8	0.9	0.7
(E) Reduction in conc. 2015-2025 with full abatement (µg/m3)[(a)]	0.6	0.3	-0.1	0.2	-0.4	-0.2	1.3	0.0
(F) Abatement gap (µg/m³)	0.1	0.3	0.7	0.6	0.9	1.0	-	0.6
(G) Emissions gap (tonnes per year in inventory area)	1,189	2,947	2,360	1,047	2,067	806	-	253
Emissions gap as % of residual emissions in inventory	4%	28%	23%	21%	26%	26%	-	22%

(a) A negative value represents an increase.

We also compared the stringency of the 10% exposure-reduction target with the current NEPM advisory reporting standard for annual mean $PM_{2.5}$ of 8 µg/m³, in this case with the latter applied to a target year of 2025. Whilst the exposure-reduction target requires further reductions in emissions over and above those generated by all feasible measures in all but one jurisdiction (Northern Territory), the further reduction required in Tasmania was actually lower than that required to comply with the air quality standard.

After implementation of the 'all feasible measures' portfolio, all states (except Northern Territory) had an emissions gap. A 10% exposure reduction target could be met with a combination of national and state-based measures. Further analysis of costs was not undertaken. However, the health benefits in the states other than Northern Territory were estimated. It was assumed that emission reductions would be primarily associated with urban areas, where the concentration gaps are expected to be most pronounced, and the reductions would be achieved through measures in place for the 20 years between 2017 and 2036 (as with the gap analysis for the air quality standards). The total potential health benefits were estimated as $17.2 billion, as shown in **Table 6.23**.

Table 6.23: Expected health benefits of an exposure-reduction framework

Jurisdiction	2011 damage cost $/t$PM_{2.5}$ (capital city damage cost)	Emissions reductions necessary (t$PM_{2.5}$)	Expected health benefit (2011 $m)
NSW	280,000	1,189	$3,340
VIC	190,000	2,947	$5,615
QLD	110,000	2,360	$2,603
SA	170,000	1,047	$1,784
WA	140,000	2,067	$2,902
TAS	46,000	806	$372
NT	100,000	-	$0
ACT	230,000	253	$583
Total		**10,669**	**$17,200**

Combining this overall health benefit ($17.2 billion) with the total estimated health benefits of the 'all feasible measures' portfolio ($17.3 billion) provided a total national health benefit for the exposure-reduction target of $34.5 billion.

6.4 Sensitivity analysis

Five types of sensitivity analyses were performed in order to test how results would vary based on alternative sets of assumptions. Specifically, we tested the sensitivity of the results to the following:

- The cost and emissions assumptions for the abatement measures.
- The discount rate.
- The assumptions relating to growth in emissions under the BAU scenario (Western Australia was taken to be representative of a jurisdiction with higher growth).
- The assumption relating to the value of a life year.
- The method used to monetise the benefits of emission reductions.

The portfolios of measures performed well in the sensitivity tests and carried the benefit of diversifying the risk of individual measures. The performance of the 'all economic measures' portfolio was shown to be superior to that of the 'all feasible measures' portfolio.

The rationale for, and results of, the sensitivity analysis are presented in **Appendix I**.

7 CONCLUSIONS

7.1 Context

The economic analysis was complex and comprehensive; it brought together much of the available data on emissions, air quality, air pollution abatement and health impacts in Australia. The best possible use was made of the data, taking into account their limitations. Significant advances were made in some areas to allow the evaluation of options by policymakers.

Before presenting the conclusions of the economic analysis, it is important to reiterate the context within which they are framed. The most important points are as follows:

- The analysis focussed on the reduction of emissions of primary anthropogenic particles. The results indicate that these are responsible for around 20-25% of PM_{10} and around 40-50% of $PM_{2.5}$ (depending on the season and location). A significant proportion is therefore natural or secondary in origin. For example, the contribution of sea salt to $PM_{2.5}$ ranges from around 10% to 25% on average. This has important implications in terms of the emission reductions required for compliance, and suggests that the processes for defining air quality standards and monitoring compliance have limitations which should be considered thoroughly in the future.

- The level of an air quality standard relative to the level of the natural/secondary PM component at a given location is very important. To a large extent it determines whether compliance will be possible and, if so, the emission reduction that will be required. However, whilst there are significant contributions to airborne PM from natural and secondary anthropogenic particles we could not fully account for their impact given the limitations of the models and data in Australia. In particular, the reduction of primary PM emissions will often be associated with a reduction in emissions of other pollutants that are precursors of secondary PM, thus leading to a reduction in secondary PM formation. The required concentration and emission reductions that we have calculated are therefore probably overestimates (*i.e.* our approach is conservative). The current state of the knowledge does not allow us to quantify the extent of the overestimation with a high level of confidence.

- The emission and concentration projections are based on forecasts for growth in population, historical growth in industrial/commercial activity, and projected emissions from ABS and BITRE. In some jurisdictions the projected values for some sectors are relatively high. If the rate of growth decreases in the future, then smaller emission reductions than those stated in the Report will be required for compliance with the hypothetical air quality standards.

- The analysis dealt primarily with abatement measures that could benefit from a national approach. The emission reductions are based on a package of feasible abatement measures. A gap analysis approach was used where only one or more jurisdictions were not compliant with a hypothetical standard. This assumed that some additional economic abatement alternatives were available in these jurisdictions based on existing Australian air pollution abatement studies.

These issues highlight some of the complexities of setting (and evaluating) air quality standards for PM_{10} and $PM_{2.5}$, especially where the prevailing PM concentrations are relatively low so that natural and secondary PM components become very important. The exposure-reduction approach bypasses these problems to some extent, as it does not involve compliance with a fixed concentration.

7.2 Responses to project objectives

Our responses to the questions posed in the project objectives are provided below. It is worth reiterating that all estimates of economic benefit (and hence net benefit) are based on the damage cost approach and take into account the distribution of emissions and population across Australia.

What total reductions in PM emissions would be required to meet the hypothetical air quality standards?

We estimated the reductions in emissions that would be required to achieve compliance with each of the hypothetical air quality standards in the target year of 2036. In all jurisdictions we used the relationship between total emissions across all sectors and the population-weighted primary anthropogenic concentration to convert a concentration gap into an emissions gap. In fact, it is never possible to state a definitive total reduction in emissions to ensure compliance with a standard. This is because the effect of a given total reduction in emissions on the population-weighted concentration depends upon the sources that are affected, and the extent to which emissions from each source are reduced. Where multiple emission sources are affected, any calculation of a single emissions gap can only ever be a broad estimate.

The estimated emission reductions that would be required in the BAU case (*i.e.* with no new abatement measures) are shown in **Table 7.1**. The green cells show where an air quality standard was met in 2036 in the BAU scenario, and the burgundy cells show the estimated reduction in emissions that would be necessary to achieve compliance. The orange cells show where compliance would not be possible by reducing primary anthropogenic emissions alone.

Table 7.1: Emission reductions in 2036 (no new abatement measures)

Jurisdiction	PM_{10} annual mean AQ standard (µg/m³)			$PM_{2.5}$ annual mean AQ standard (µg/m³)			PM_{10} 24-hour 6th highest AQ standard (µg/m³)			$PM_{2.5}$ 24-hour 98th %ile AQ standard (µg/m³)		
	20	16	12	10	8	6	50	40	30	25	20	15
NSW		113,832				15,463						
VIC		21,501				823						
QLD		8,674				1,684			8,522			2,921
SA		658			686	3,980			2,365			2,323
WA	1,502	7,224				2,116		235	7,704			147
TAS			1,674		959	2,573		1,449		2,000	3,083	
NT		90			47	129		29				99
ACT						576			414	513	1,018	

Key:

Concentration below standard in BAU case in 2036

Standard lower than natural/secondary PM component

34 Emission gap (tonnes per year)

What are the abatement measures that are feasible at the national level?

MACCs were developed to compare the long-run costs and emission reductions of measures that were feasible at the national level. As an example, the data for the national $PM_{2.5}$ MACC are provided in **Table 7.2**. The incremental abatement is defined as the additional abatement delivered by a variant[36] over and above the variant in the same sector immediately preceding it (in order of cost-effectiveness).

[36] Policies to reduce emissions from a given sector using the same mechanism (e.g. standards) can be implemented in a number of ways or levels of standard. Each alternative is a 'variant'.

Table 7.2: PM$_{2.5}$ data for national MACC

Measure	Marginal cost ($/tPM$_{2.5}$)	Abatement (tPM$_{2.5}$/year)	Incremental abatement (tPM$_{2.5}$/year)
US 2006 & 2010 outboard and watercraft, and US phase 2 gardening emissions standards	-11,963	388	388
US2010 outboard and watercraft, and US phase 2 gardening emissions standards	-10,815	390	2
Regulating moisture content of wood fuel to be less than 20%	99	851	851
Wood heaters 60% efficiency, 3 g/kg emission standards	499	3,242	3,242
Wood heaters 65% efficiency, 3 g/kg emission standards and in-service measures	739	3,416	173
Wood heaters 60% efficiency, 3 g/kg emission standards and in-service measures	742	3,485	69
Wood heaters 60% efficiency, 1.5 g/kg emission standards and in-service measures	850	3,664	179
Diesel trains driver assistance software for line haul locomotives	5,426	110	110
Adoption of international best-practice PM control measures at coal mines	9,115	17,302	17,302
US non-road diesel standards in Australia (excluding <19kW)	9,191	13,699	13,699
MOU to reduce shipping vessel speed for ocean transits	10,632	638	638
Retrofitting non-road diesel engines at mine sites with DPFs (emissions reduction program)	15,893	2,426	2,426
Requiring new locomotives to meet US Tier 4 standards	21,598	297	297
Retrofitting high-polluting (urban) non-road diesel engines & equipment with DPFs	22,455	22	22
Mandatory low-sulfur fuel use by ships while at berth	50,066	969	969
Replacing old locomotives and requiring new locomotives to meet US Tier 4 standards	105,841	614	317
Targeted maintenance of high-polluting LCVs using remote sensing	158,922	1	1
Penalty and incentive scheme for high polluting vehicles	202,673	10	10
Area-wide planting to remove PM from the atmosphere	407,418	66	66

What would be the effects on emissions and air quality of introducing all feasible abatement measures?

The emission reductions that would still be required after the introduction of all feasible national measures are shown in **Table 7.3**. The purple cells show where the standard would be met with the 'all feasible measures' portfolio in place. It can be seen that further (state-based) abatement would still be required to comply with some air quality standards. It was also considered important to frame these further state-based emission reductions in the context of the residual emissions in the inventory (*i.e.* the total emissions in the inventory in 2036 minus the emission reductions for all feasible national measures, as shown in **Table 7.4**).

Table 7.3: Emission reductions 2036 ('all feasible measures' portfolio)

Jurisdiction	PM$_{10}$ annual mean AQ standard (µg/m³)			PM$_{2.5}$ annual mean AQ standard (µg/m³)			PM$_{10}$ 24-hour 6th highest AQ standard (µg/m³)			PM$_{2.5}$ 24-hour 98 %ile AQ standard (µg/m³)		
	20	16	12	10	8	6	50	40	30	25	20	15
NSW		72,257				3,238						
VIC		17,517										
QLD		4,917				631			4,765			1,868
SA						3,027			1,277			1,369
WA	609	6,331				1,405			6,811			
TAS			1,249		553	2,167		1,024		1,594	2,667	
NT		27				68						59
ACT						242			216	39	544	

Key:

- Concentration below standard in BAU case in 2036
- Standard lower than natural/secondary PM component
- 34 Emission gap (tonnes per year)
- Compliant with abatement

Table 7.4: Emission gaps as a percentage of residual emissions in 2036

Jurisdiction	PM_{10} annual mean AQ standard (µg/m³)			$PM_{2.5}$ annual mean AQ standard (µg/m³)			PM_{10} 24-hour 6th highest AQ standard (µg/m³)			$PM_{2.5}$ 24-hour 98th %ile AQ standard (µg/m³)		
	20	16	12	10	8	6	50	40	30	25	20	15
NSW		74%				11%						
VIC		93%										
QLD		27%				6%			26%			19%
SA						60%			24%			27%
WA	7%	77%				18%			83%			
TAS			37%		18%	69%		19%		51%	85%	
NT		18%				64%						1%
ACT						21%			18%	3%	48%	

Key:

- Concentration below standard in BAU case in 2036
- Standard lower than natural/secondary PM component
- 20% Emission gap as % of residual emissions
- Compliant with abatement

Under the BAU scenario there will be overall increases in the population-weighted PM concentrations over the period 2011-2036 due to the combined effects of increased emissions and population growth. For example, the population-weighted annual mean PM_{10} concentration would increase by between 0.2 µg/m³ and 2.4 µg/m³, depending on the jurisdiction, and $PM_{2.5}$ would increase by up to 1.5 µg/m³ (the exception being Victoria, where there would be a slight reduction in the $PM_{2.5}$ concentration). In **Figure 7.1** the state-level $PM_{2.5}$ concentrations have been combined using a population weighting to give national projections. Projections are shown for the BAU case and for the situation with all feasible abatement measures in place. These values are strongly influenced by the results for the most populous states (NSW and Victoria).

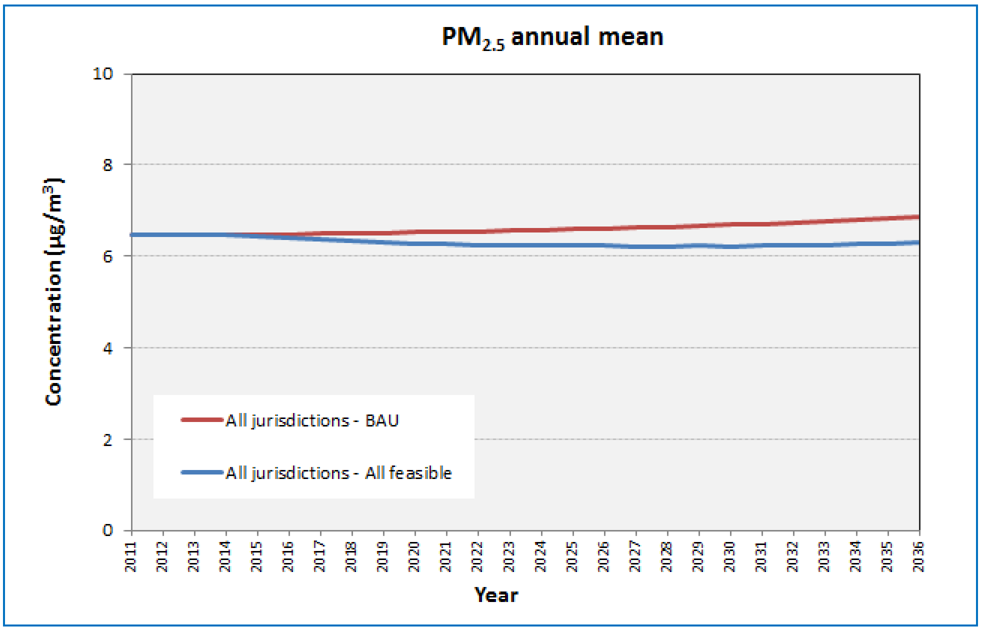

Figure 7.1: National population-weighted annual mean $PM_{2.5}$ concentration for BAU scenario and all feasible measures

We estimate that the introduction of all feasible national abatement measures will result in a relatively modest reduction in PM concentrations relative to the BAU case. There would be a reduction in the population-weighted annual mean PM_{10} concentration of between 0.4 and 1.4 μg/m^3 by 2036, depending on the airshed, and a reduction in the annual mean $PM_{2.5}$ concentration of between around 0.3 and 1.5 μg/m^3. The fact that there is a larger upper limit for $PM_{2.5}$ is probably an artefact of the assumptions used in the analysis. Nevertheless, there would be substantial monetised health benefits in the airsheds considered in the analysis (*i.e.* the inventory areas).

What would be the net economic benefit of compliance with the hypothetical air quality standards?

The net benefits[37] of compliance with the hypothetical air quality standards are shown in **Table 7.5**. The benefits are a function of the magnitude of the emission reductions and their spatial distribution (with emission reductions in more polluted areas carrying more net benefit). Given that all standards primarily rely on the same portfolio of national measures (augmented with state-based measures on a much smaller scale), the net benefit of compliance with each standard is similar (around \$6.4 to \$7 billion). Standards should not be considered additive. That is, if two standards are set simultaneously (*e.g.* one for $PM_{2.5}$ and one for PM_{10}), the one which requires the greater emission reduction will drive costs and benefits.

Table 7.5: Net benefits of compliance with air quality standards in 2036

Pollutant	Averaging period and metric	Concentration (μg/m^3)	Net benefit (2011 \$m)
PM_{10}	1 year	20.0	**\$6,389**
		16.0	Not feasible to meet through primarily national measures
		12.0	Not possible to meet due to natural/secondary component
$PM_{2.5}$	1 year	10.0	Already met in BAU
		8.0	**\$6,464**
		6.0	Not feasible to meet through primarily national measures
PM_{10}	24 hours (6th highest value)	50.0	Already met in BAU
		40.0	**\$6,616**
		30.0	Not possible to meet due to natural/secondary component
$PM_{2.5}$	24 hours (98th percentile)	25.0	**\$6,940**
		20.0	Not feasible to meet through primarily national measures
		15.0	Not possible to meet due to natural/secondary component

What would be the net economic benefit of implementing all feasible national abatement measures?

The 'all feasible measures' portfolio is shown in **Table 7.6**. Here, the net benefit was calculated using the damage cost approach. This portfolio is expected to deliver a significant net benefit (\$6.3 billion) in excess of cost to the Australian community. This is due to the relatively low cost of emission reduction compared with the avoidance of health costs (primarily life expectancy extended) for the Australian community. The gross monetised health benefit of the 'all feasible measures' portfolio is estimated to be \$17.3 billion (63% of which is due to measures currently that are being progressed through national assessment processes[38]).

[37] In addition to health benefits of avoided PM and NO_x, benefits include fuel savings and abatement of CO_2.

[38] Referred to as 'existing measures' in this analysis and includes standards for non-road diesel engines, wood heaters and non-road spark ignition engines.

Table 7.6: Net benefits of 'all feasible measures' portfolio

Abatement measure	BCR	NPV (2011 $m)
Regulating moisture content of wood fuel to be less than 20%	1,175	$1,034
Wood heaters 60% efficiency, 1.5 g/kg emission standards and in-service measures	114	$4,178
MOU to reduce shipping vessel speed for ocean transits	4.1	$352
US2010 outboard and watercraft, and US phase 2 gardening emissions standards	3.2	$616
Diesel trains driver assistance software for line haul locomotives	2.4	$80
Retrofitting high-polluting (urban) non-road diesel engines & equipment with DPFs	2.3	$6
Adoption of international best practice PM control measures at coal mines	1.3	$643
US non-road diesel standards in Australia (excluding < 19kW)	1.3	$1,922
Mandatory low-sulfur fuel use by ships while at berth	0.9	-$61
Retrofitting non-road diesel engines at mine sites with DPFs (emissions reduction program)	0.7	-$145
Targeted maintenance of high-polluting LCVs using remote sensing	0.6	-$1
Penalty and incentive scheme for high-polluting vehicles	0.5	-$9
Replacing old line locomotive and requiring new locomotives to meet US Tier 4 standards	0.2	-$1,835
Area-wide planting to remove PM from the atmosphere	0.2	-$510
Total	**1.5**	**$6,271**

What would be the economic benefit of implementing all economic national abatement measures?

All feasible measures with a benefit:cost ratio greater than one are contained in the 'all economic measures' portfolio (**Table 7.7**). This portfolio is expected to deliver net benefits (again based on damage costs) in excess of costs of $8.8 billion (higher than the 'all feasible' portfolio) to the Australian community. The higher NPV results through the exclusion of measures with negative NPVs. The gross monetised health benefit of the all economic portfolio is estimated to be $15.9 billion (69% of which is contributed to by measures currently being progressed through national assessment processes).

Table 7.7: Net benefits of 'all economic measures' portfolio

Abatement measure	BCR	NPV (2011 $m)
Regulating moisture content of wood fuel to be less than 20%	1,176	$1,034
Wood heaters 60% efficiency, 1.5 g/kg emission standards and in-service measures	114	$4,178
MOU to reduce shipping vessel speed for ocean transits	4.1	$352
US2010 outboard and watercraft, and US phase 2 gardening emissions standards	3.2	$616
Diesel trains driver assistance software for line haul locomotives	2.5	$80
Retrofitting high-polluting (urban) non-road diesel engines & equipment with DPFs	2.3	$6
Adoption of international best practice PM control measures at coal mines	1.3	$643
US non-road diesel standards in Australia (excluding < 19kW)	1.3	$1,922
Requiring new locomotives to meet US Tier 4 standards	1.0	$1
Total for portfolio	**1.9**	**$8,834**

Exposure-reduction framework

What reductions in PM emissions would be required to meet the exposure-reduction target?

With the 'all feasible measures' portfolio in place, the target of a 10% reduction the population-weighted annual mean $PM_{2.5}$ concentration between 2015 and 2025 would be achieved in the Northern Territory, largely as a consequence of abatement measures relating to shipping. NSW would be close to compliance. There would also be net reductions in exposure between 2015 and 2025 in ACT, Victoria and South Australia, but net increases in Western Australia, Queensland and Tasmania.

The gap analysis is given in **Table 7.8**. The Table shows the emission gaps in both the BAU case and with the 'all feasible measures' portfolio, and the percentage reduction in residual emissions in 2025 that would be required in each jurisdiction. In NSW the emission gap equated to 4% of residual emissions in the inventory. In the other jurisdictions the proportion was around 20-30%. Meeting the target of a 10% reduction in the annual mean $PM_{2.5}$ concentration between 2015 and 2025 would therefore require additional state-based measures in most jurisdictions. The overall emission reduction at the national level would be larger than that required for compliance with the (achievable) air quality standards.

Table 7.8: Emission reductions required to meet exposure-reduction target 2025

Jurisdiction	$PM_{2.5}$ annual mean BAU gap (t/y)	All feasible measures gap (t/y)	% of residual emissions in 2025
NSW	9,496	1,189	4%
VIC	4,691	2,947	28%
QLD	3,113	2,360	23%
SA	1,528	1,047	21%
WA	2,476	2,067	26%
TAS	1,004	806	26%
NT	40		
ACT	416	253	22%

Key:

34 Emission gap (tonnes per year)

Compliant with abatement

What would be the monetised health benefit of implementing a new exposure-reduction framework for PM?

After implementation of the national 'all feasible measures' portfolio, no jurisdiction except Northern Territory will meet the exposure-reduction target of a 10% decrease in annual mean $PM_{2.5}$ between 2015 and 2025. The target could be met with a combination of national and state-based measures.

Further analysis of the cost of complying with the target was not undertaken. However, the health benefits associated with compliance were calculated for the jurisdictions other than Northern Territory. Compliance with the exposure-reduction target would require substantial state-based reductions in emissions, with correspondingly large further benefits. The overall health benefit of bridging the emission gaps was estimated to be $17.2 billion. Combining this with the total estimated health benefits of the 'all feasible measures' portfolio ($17.3 billion) provided a total estimated health benefit in Australia of $34.5 billion.

Sensitivity analysis

The portfolios of measures performed well in the sensitivity tests and carried the benefit of diversifying the risk of individual measures. The performance of the 'all economic measures' portfolio was shown to be superior to that of the 'all feasible measures' portfolio.

It is important to reiterate that a damage cost approach was used to determine health benefits in the economic analysis. However, for selected locations the impact pathway approach resulted in health benefit estimates that were approximately 1.5 times higher than those based on damage costs. To estimate the effect of potentially higher health benefits a factor of 1.5 was applied to the total damage cost estimates across Australia. The resulting benefits were $8.6-$8.8 billion higher than those based on damage costs.

7.3 Guidance on air quality standards

Our conclusions from the economic analysis - in relation to each of the hypothetical air quality standards - are given in **Table 7.9**.

Table 7.9: Conclusions in relation to hypothetical air quality standards incorporating feasible national measures (assessment for 2036)

Pollutant	Averaging period and metric	Concentration (µg/m³)(a)	Conclusion from economic analysis		
			Feasible in principle?(b)	Further emission reduction required (by state)?(c)	Emission reductions likely to be achievable?
PM_{10}	1 year	20.0	Yes	WA	Yes
		16.0	Yes	NSW, VIC, QLD, WA, NT	No
		12.0	No	-	-
$PM_{2.5}$	1 year	10.0	Yes	None	No reduction required
		8.0	Yes	TAS	Yes
		6.0	Yes	NSW, QLD, SA, WA, TAS, NT, ACT	No
PM_{10}	24 hours (6th highest value)	**50.0**	Yes	None	No reduction required
		40.0	Yes	TAS	Yes
		30.0	No	-	-
$PM_{2.5}$	24 hours (98th percentile)	**25.0**	Yes	TAS, ACT	Possible
		20.0	Yes	TAS, ACT	No
		15.0	No	-	-

a) Current Australian standards and advisory reporting levels are shown in bold.
b) 'Feasible' cases are those where the air quality standard is not lower than the contribution of natural and secondary PM.
c) Following the application of all feasible national measures.

We have assessed that the annual mean standards for PM_{10} and $PM_{2.5}$ of 20 µg/m³ and 8 µg/m³ respectively could be achievable in Australia. In the case of PM_{10} some state-based abatement measures would be required in Western Australia to ensure national compliance if the current rate of economic growth in the state continues. Compliance with an annual mean standard for $PM_{2.5}$ of 8 µg/m³ would be possible to achieve in all jurisdictions in principle, but would require some further state-based abatement in Tasmania.

For 24-hour PM_{10} both the 50 µg/m³ and 40 µg/m³ standards are assessed as achievable. A standard of 50 µg/m³ would be achieved in the BAU case, and so the adoption of a lower value could drive environmental improvement. A value of 40 µg/m³ would require state-based abatement in Tasmania, but should be achievable. For 24-hour $PM_{2.5}$ only a standard of 25 µg/m³ (as a 98th percentile) is assessed as being achievable, although this would require further abatement action in both Tasmania and ACT.

7.4 Guidance on exposure-reduction target

A 10% exposure-reduction target over ten years could be met with a combination of national and state-based measures. However, alternative targets and timeframes may need to be considered to address the high industry growth rates for some jurisdictions.

It is important to emphasise again the likely benefits of an exposure-reduction target. As noted in the introduction, long-term exposure to the prevailing background PM concentration is the most important determinant of health outcomes. Even where a NEPM standard is not exceeded there is a health benefit associated with reducing concentrations, and an exposure-reduction framework provides an appropriate mechanism for this.

8 ACKNOWLEDGEMENTS

The authors would like to thank the following individuals and organisations for their kind assistance during this project:

- The following individuals at Pacific Environment, for their assistance with the work on air pollution modelling and health impacts: Khalia Hill, Tom Robertson, Nathan Aust and Lyn Dension.
- Prof Duncan Laxen of Air Quality Consultants and Mr Paul Watkiss of Paul Watkiss Associates for advice and experience from previous UK and European cost-benefit analyses.
- Mr Kerry Lack of NSW EPA, for input and guidance throughout the project.
- Mr Nick Agapides and Mr Gareth Jones of NSW EPA, for the provision on emission inventory data for the NSW EPA and general guidance.
- Mr Sean Walsh of EPA Victoria, for the provision on emission inventory and population data for Victoria, and well as guidance on particle measurement and PM composition.
- Dr Martin Cope of CSIRO, for advice on PM composition and the use of TAPM.
- The separate Australian jurisdictions for the provision of air pollution monitoring data and advice on emission projections, and in particular:
  - Mr Stefan Gabrynowicz of the South Australian Environment Protection Authority.
  - Mr Peter Bek of the Queensland Department of Environment and Heritage Protection.
  - Peter Musk, Department of Environment and Conservation, Western Australia.
  - Mr Alasdair Wells, Dr Elzbieta Chelkowska and Mr Bob Hyde, Department of Primary Industries, Parks, Water and Environment, Tasmania.

9 REFERENCES

ABARE (2006). Australian Energy, National and State Projections to 2029-30. ABARE Research Report 06.26. Australian Bureau of Agricultural and Resource Economics, Canberra.

ABARES (2010). Australian commodity statistics 2010. Australian Bureau of Agricultural and Resource Economics and Sciences, Canberra.

ABARES (2011a). Energy Update 2011. Australian Bureau of Agricultural and Resource Economics and Sciences, Canberra.

ABARES (2011b). Australian Mineral Statistics 2011 - March quarter 2011 Australian Bureau of Agricultural and Resource Economics and Sciences, Canberra, Australia.

Abelson P (2003). The value of life and health for public policy. The Economic Record, 79, pp. S2-S13.

Abelson P (2008). Establishing a Monetary Value for Lives Saved: Issues and Controversies. Office of Best Practice Regulation, Department of Finance and Deregulation, Canberra.

ABS (2006). Australian Social Trends, 2006. Environmental Impact of Household Energy Use. Australian Bureau of Statistics, Canberra. http://www.abs.gov.au/Ausstats/abs@.nsf/7d12b0f6763c78caca257061001cc588/a300c2a2b4e0b91fca2571b000197552!OpenDocument#foot%206#foot%206

ABS (2008). Population Projections, Australia, 2006 to 2101. ABS Publication 3222.0. Australian Bureau of Statistics, Canberra. http://www.abs.gov.au/AUSSTATS/abs@.nsf/DetailsPage/3222.02006%20to%202101?OpenDocument#Time

ABS (2012a). Historical Population Estimates by Australian Statistical Geography Standard, 1971 to 2011. Australian Bureau of Statistics, Canberra. http://www.abs.gov.au/AUSSTATS/abs@.nsf/DetailsPage/3218.02011?OpenDocument

ABS (2012b). Australian National Accounts: State Accounts. 5220.0. Australian Bureau of Statistics, Canberra.

AEA (2005). Service contract for carrying out cost-benefit analysis of air quality related issues, in particular in the Clean Air for Europe (CAFE) Programme. AEA Technology Environment, Oxfordshire, UK.

AECOM (2009). Economic Viability of Electric Vehicles. AECOM Australia, Sydney.

AECOM (2011). Economic Appraisal of Wood Smoke Control Measures. AECOM Australia, Sydney.

AIHW (2012). Australian hospital statistics 2010–11. Australian Institute of Health and Welfare, Canberra.

ANSTO (2008). Fine Particle Aerosol Sampling Newsletter, Number 38, July 2008. http://www.ansto.gov.au/__data/assets/pdf_file/0019/39313/Newsletter38.pdf

ANSTO (2010). Fine Particle Aerosol Sampling Newsletter, Number 40, May 2010. http://www.ansto.gov.au/__data/assets/pdf_file/0018/47133/Newsletter40.pdf

ASCC (2008). The Health of Nations: The Value of a Statistical Life. Australian Safety and Compensation Council, July 2008. http://www.safeworkaustralia.gov.au/AboutSafeWorkAustralia/WhatWeDo/Publications/Documents/330/TheHealthOfNations_Value_StatisticalLife_2008_PDF.pdf

Aust N, Watkiss P, Boulter P and Bawden K (2013). Methodology for valuing the health impacts of changes in particle emissions – Final Report. PAEHolmes Report 6695.

Australian Government (2010). Best Practice Regulation Handbook, June 2010, Commonwealth of Australia. Canberra 2010.

Australian Treasury (2011). Strong Growth, Low Pollution: Modelling a Carbon Price. Commonwealth of Australia, 2011, Canberra.

Bawden K, Aust N, Moorcroft S, Laxen D and Williams M (2012). Evaluating Options for an Exposure Reduction Framework in Australia. PAEHolmes Report 6808. PAEHolmes, Brisbane.

BCI (2008) - source used in IMWG for Diesel emissions (Isuzu NPR 300 model).

BDA Group (2006). Wood heater Particle Emissions and Operating Efficiency Standards - Cost Benefit Analysis - Prepared for the Department of the Environment and Heritage. BDA Group, Manuka, ACT.

BDA Group (2013). Consultation regulation impact statement for reducing emissions from wood heaters. Report for National Environment Protection Council Service Corporation, 11 April 2013. BDA Group, Manuka, ACT.

Beer T (2002). Valuation of pollutants emitted by road transport into the Australian atmosphere, Proceedings of the 16th International Clean Air & Environment Conf, Christchurch, New Zealand.

Betts A (2012). Personal communication from Alan Betts at the NSW Environment Protection Agency to Paul Boulter at Pacific Environment.

BITRE (2010). Long-term Projections of Australian Transport Emissions: Base Case 2010. Bureau of Infrastructure, Transport and Regional Economics, Canberra.

BITRE(2011). Australian Sea Freight 2009-2010. Bureau of Infrastructure, Transport and Regional Economics, Canberra

BITRE (2012). State and Capital City vehicle kilometres travelled, 1990–2012. Bureau of Infrastructure, Transport and Regional Economics, Canberra

BOM (2012). Record-breaking La Niña events: An analysis of the La Niña life cycle and the impacts and significance of the 2010–11 and 2011–12 La Niña events in Australia. Australian government Bureau of Meteorology, Melbourne. http://www.bom.gov.au/climate/enso/history/ln-2010-12/

Brook R D, Rajagopalan S, Pope C A, Brook J R, Bhatnagar A, Diez-Roux A V, Holguin F, Hong Y, Luepker R V, Mittleman M A, Peters A, Siscovick D, Smith S C Jr, Whitsel L and Kaufman J D (2010). Particulate matter air pollution and cardiovascular disease: An update to the scientific statement from the American Heart Association. *Circulation*, 2010, 121, pp. 2331-2378.

BTRE (2005). Health Impacts of Transport Emissions in Australia: Economic Costs. BTRE Working Paper 63, Bureau of Transport and Regional Economics, Canberra. http://www.bitre.gov.au/publications/2005/files/wp_063.pdf

BTRE (2006). Container and Ship Movements Through Australian Ports 2004-05 to 2024-25: Working Paper 65. Bureau of Transport and Regional Economics, Canberra.

Cachier H, Brémond M-P and Buat-Ménard P (1989). Carbonaceous aerosols from different tropical biomass burning sources, *Nature*, 340, pp. 371–373.

Chan Y C, Simpson R W, Mctainsh G H, Vowles P D, Cohen D D, Bailey G M (1997). Characterization of chemical species in $PM_{2.5}$ and PM_{10} aerosols in Brisbane, *Atmospheric Environment*, 31, 2061–2080.

Chan Y C, Simpson R W, Mctainsh G H, Vowles P D, Cohen D D and Bailey G M (1999). Source apportionment of $PM_{2.5}$ and PM_{10} aerosols in Brisbane (Australia) by receptor modelling. Atmospheric Environment, Vol. 33, Issue 19, pp. 3251–3268.

Chan Y C, Vowles P D, Mctainsh G H, Simpson R W, Cohen D D, Bailey G M and McOrist G D (2000). Characterisation and source identification of PM_{10} aerosol samples collected with a high volume cascade impactor in Brisbane (Australia). The Science of the Total Environment, Vol. 262, pp. 5-19.

Chan Y C, Cohen D D, Hawas O, Stelcer E, Simpson R, Denison L, Wong N, Hodge M, Comino E and Carswell S (2008). Apportionment of sources of fine and coarse particles in four major Australian cities by positive matrix factorisation. Atmospheric Environment, Vol. 42, Issue 2, pp. 374–389.

Chan Y C, Hawas O, Hawker D, Vowles P, Cohen D D, Stelcer E, Simpson R, Golding G and Christensen E (2011). Using multiple type composition data and wind data in PMF analysis to apportion and locate sources of air pollutants. Atmospheric Environment, Vol. 45, Issue 2, pp. 439–449.

Chelkowska E (2013). Personal communication from Elzbieta Chelowska to Paul Boulter at Pacific Environment.

CIE (2005). Sydney's transport infrastructure - the real economics. Centre for International Economics, Canberra. http://www.thecie.com.au/content/publications/cie-sydneys_transport_infrastructure.pdf

Ciuk J (2002), South Australian NPI Summary Report - Adelaide and regional airsheds air emissions study 1998-99, Published by South Australia Environmental Protection Authority, Adelaide. http://www.npi.gov.au/publications/pubs/sa-airsheds.pdf

Climate Works (2010). Low Carbon Growth Plan for Australia. March 2010.

COAG (2012). Public statement on the development of the National Plan for Clean Air. The Council of Australian Governments Standing Council on Environment and Water, 31 May 2012. http://www.scew.gov.au/strategic-priorities/national-plan-for-clean-air.html

Coffey (2003). Fuel quality and vehicle emissions standards Cost benefit analysis prepared for MVEC Review of Vehicle Emissions and Fuel Standards Post 2006. Coffey Geosciences Pty Ltd. October 2003. Available at: http://www.ephc.gov.au/ltec/pdfs/CBAFinalReport23October.pdf

COMEAP (2009). Long-term exposure to air pollution: effect on mortality. A report by the Committee on the Medical Effects of Air Pollutants. London, Department of Health, United Kingdom. ISBN 978-0-85951-640-2.

Commonwealth of Australia (2011). State of the Air in Australia 1999–2008. Department of Sustainability, Environment, Water, Population and Communities, Canberra, Australia.

Cope M (2012). Reflections on Domestic Wood Smoke Emissions – Effects, Concerns, Progress and Opportunities. Presentation to NSW/ACT Branch Technical Meeting, Monday, 10 September, 2012, Macquarie University.

Cope M and Lee S (2009). Chemical Transport Model - User Manual. Centre for Australian Weather and Climate Research. October 2009.
CSIRO (2011). Polglase P, Reeson A, Hawkins C, Paul K, Siggins A, Turner J, Crawford D, Jovanovic T, Hobbs T, Opie K, Carwardine J and Almeida A. Opportunities for carbon forestry in Australia: Economic assessment and constraints to implementation.

Defra (2007). An Economic Analysis to inform the Air Quality Strategy- Updated Third Report of the Interdepartmental Group on Costs and Benefits. July 2007. Department for Environment, Food and Rural Affairs, London.
http://archive.defra.gov.uk/environment/quality/air/airquality/publications/stratreview-analysis/index.htm

Defra (2010). Air Quality Appraisal – Valuing Environmental Limits. Interdepartmental Group on Costs and Benefits, Air Quality Subject Group. Department for Environment, Food and Rural Affairs, London.
http://archive.defra.gov.uk/environment/quality/air/airquality/panels/igcb/documents/100303-aq-valuing-env-limits.pdf

Defra (2011). Air Quality Appraisal – Damage Cost Methodology. Interdepartmental Group on Costs and Benefits, Air Quality Subject Group February 2011. Department for Environment, Food and Rural Affairs, London.

Delaney W and Marshall A (2011). Victorian Air Emissions Inventory for 2006. Proceedings of the 20th International Clean Air and Environment Conference, Auckland, 31 July – 2 August 2011. Clean Air Society of Australia & New Zealand, Eastwood, NSW.

Dennis R L, Bhave P V and Pinder R W (2007). Observable indicators of the sensitivity of $PM_{2.5}$ nitrate to emission reductions—Part II: Sensitivity to errors in total ammonia and total nitrate of the CMAQ-predicted non-linear effect of SO_2 emission reductions. Air Resources Laboratory, Atmospheric Sciences Modeling Division, National Oceanic and Atmospheric Administration, United States Environmental Protection Agency, Research Triangle Park, NC 27711, USA.

DSITIA (2012a). Response to Project Questionnaire - Queensland Questionnaire, Department of Science, Information Technology, Innovation and the Arts, GPO Box 2454, City East, Queensland, 4002

DSITIA (2012b). Queensland air monitoring report 2011National Environment Protection (Ambient Air Quality) Measure. Department of Science, Information Technology, Innovation and the Arts, GPO Box 2454, City East, Queensland, 4002.
http://www.ehp.qld.gov.au/air/pdf/reports/2011-air-monitoring-report.pdf

Duan F K, He K, Ma Y, Jia Y, Yang F, Lei Y, Tanaka S and Okuta T (2005). Characteristics of carbonaceous aerosols in Beijing, China. *Chemosphere*, 60 (3), pp. 355–364.

Dunteman G H (1989). Principal Components Analysis, Little Green Books, ISBN: 9780803931046.

ENVIRON (2012). Potential Measures to Reduce Emissions from New and In-service Locomotives in NSW and Australia - Prepared for NSW EPA. September 2012

ENVIRON and SKM-MMA (2011). Cost Benefit Analysis of Options to Manage Non-road Diesel Engine Emissions - Prepared for NEPC Service Corporation and NSW Office of Environment and Heritage. October 2011.

EPA South Australia (2010). Air Monitoring Report for South Australia 2009. Compliance with the National Environment Protection (Ambient Air Quality) Measure. Environment Protection Authority, Adelaide.

EPA Victoria (2007). Air monitoring report 2006 – Compliance with the National Environment Protection (Ambient Air Quality) Measure.
http://epanote2.epa.vic.gov.au/EPA/publications.nsf/2f1c2625731746aa4a256ce90001cbb5/d6edcdeecf7d8ecdca2572d0000c4ca1/$FILE/1137.pdf

EPHC (2005). Expansion of the multi-city mortality and morbidity study. Final report. Volume 3. Tabulated results, Environment Protection and Heritage Council (EPHC).

EPHC (2010). Reducing Emissions from Non-Road Spark Ignition Engines and Equipment - Consultation Regulation Impact Statement. May 2010. Prepared by Non-Road Engines Working Group on behalf of Environment Protection and Heritage Council.

European Commission (2005). ExternE. Externalities of Energy: Methodology 2005 Update. P. Bickel and R. Friedrich, Luxemburg, European Commission.

Fann N, Fulcher C M and Hubbell B J (2009). The influence of location, source, and emission type in estimates of the human health benefits of reducing a ton of air pollution. *Air Qual Atmos Health* (2009) 2:169–176.

Frangos J and DiMarco P (2012). Draft exposure assessment and risk characterisation to inform recommendations for updating ambient air quality standards for $PM_{2.5}$, PM_{10}, O_3, NO_2, SO_2. Report number 127643066-001-R-RevA. Golder Associates, Richmond, Victoria.

Gelencsér A, May B, Simpson D, Sánchez-Ochoa A, Kasper-Giebl A, Puxbaum H, Caseiro A, Pio C and Legrand M (2007). Source apportionment of $PM_{2.5}$ organic aerosol over Europe: Primary/secondary, natural/anthropogenic, and fossil/biogenic origin. *Journal of Geophysical Research*, Vol. 112, D23S04, doi:10.1029/2006JD008094, 2007.

Grover B D, Kleinman M, Eatough N L, Eatough D J, Hopke P K, Long R W, Wilson W E, Meyer M B and Ambs J L (2005). Measurement of total $PM_{2.5}$ mass (nonvolatile plus semivolatile) with the Filter Dynamic Measurement System tapered element oscillating microbalance monitor, *Journal of Geophysical Research*, 110, D07S03, doi:10.1029/2004JD004995.

Hinds W C (1999). Aerosol Technology Properties, Behaviour and Measurement of Airborne Particles. Second Addition. John Wiley & Sons, USA. Page 311.

Hohnen L, Godden D, Balding J and Adams D (2011). Modelling cost-effective air pollution abatement: a multi-period linear programming approach. Paper presented at the Annual Conference of the Australia Agricultural and Resource Economics Society.

Hurley P J (2008). TAPM V4. Part 1: Technical Description. CSIRO Marine and Atmospheric Research Paper No. 25. 59 pp.

IAWG (2012). National Plan for Clean Air – Exposure Assessment and Risk Characterisation to Inform Recommendations for Updating Standards for PM_{10}, $PM_{2.5}$, NO_2, O_3 and SO_2.

Jalaludin B and Cowie C (2012). Health Risk Assessment – Preliminary Work to Identify Concentration-Response Functions for Selected Ambient Air Pollutants. Report prepared for EPA Victoria. Respiratory and Environmental Epidemiology, Woolcock Institute of Medical Research. 30 June 2012.

Jalaludin B, Khalaj B, *et al.* (2008). Air pollution and ED visits for asthma in Australian children: a case-crossover analysis. International Archives of Occupational and Environmental Health 81(8): 967-974.

Jalaludin B, Salkeld G Morgan G, Beer T and Bin Nasir Y (2009). A methodology for cost-benefit analysis of ambient air pollution health impacts. Canberra, Australian Government Department of the Environment, Water, Heritage and the Arts, Commonwealth of Australia.

Jalaludin B, Morgan G, Salkeld G and Gaskin C (2011). Health benefits of reducing ambient air pollution levels in the Greater Metropolitan Region. Report for the NSW Ministry of Health and the NSW Office of Environment and Heritage (unpublished). December 2011.

Katestone Environmental (2011). NSW Coal Mining Benchmarking Study: Measures to Prevent and/or Minimise Emissions of Particulate Matter from Coal Mining - Prepared for Office of Environment & Heritage. June 2011.

Kelly P M, Jones P D, Sear C B, Cherry B S G and Tavakol R K (1982). Variations in Surface Air Temperatures: Part 2. Arctic Regions, 1881-1980, Monthly Weather Review, 110, 71-83.

Keywood M and Cope M (2008). Development of Tools for the Identification of Secondary Organic Aerosol in Australian Cities. Final Report Prepared for Department of the Environment, Water, Heritage and the Art. Work carried out under the Clean Air Research Program (CARP) Project No. 15.

Keywood M, Guyes H, Selleck P and Gillett R (2011). Quantification of secondary organic aerosol in an Australian urban location. *Environmental Chemistry*, 8, pp. 115-126.

Krewski D, Jerrett M *et al.* (2009). Extended follow-up and spatial analysis of the American Cancer Society study linking particulate air pollution and mortality Boston, MA, HEI Research Report 140: Health Effects Institute.

Kutzbach J E (1967). Empirical Eigenvectors of Sea-Level Pressure, Surface Temperature and Precipitation Complexes over North America, *J. Applied Meteorology*, 6, 791-802.

Laxen D, Moorcroft S, Marner B, Laxen K, Boulter P, Barlow T, Harrison R and Heal M (2010). $PM_{2.5}$ in the UK: Enhancing the general understanding of the issues relating to the regulation of fine particulate matter. Published by the Scotland and Northern Ireland Forum for Environmental Research (SNIFFER), Edinburgh. http://www.sniffer.org.uk/Resources/ER12/Layout_Default/0.aspx?backurl=http

Liu X, Zhang W, Wang Z, Zhao W, Tao L and Yang X (2009). Chemical composition and size distribution of secondary organic aerosol formed from the photooxidation of isoprene. J. Environ. Sci (China), Vol. 21(11), pp. 1525-31.

Mathers C, Vos T and Stevenson C (1999). The Burden of Disease and Injury in Australia, Australian Institute of Health and Welfare, AIHW Cat. No. PHE 17, Canberra.

MMA (2008). Cost Benefit Analysis of Options to Manage Emissions From Selected Non-Road Engines. August 2008.

MMA (2009). Cost Benefit Analysis of Options to Manage Emissions From Selected Non-Road Engines - Additional Scenarios. November 2009.

NEPC (2001). National Environment Protection (Ambient Air Quality) Measure Technical Paper No. 10 – Collection and Reporting of TEOM PM_{10} Data. Peer Review Committee, National Environment Protection Council, May 2001.
http://www.ephc.gov.au/sites/default/files/AAQPRC_TP__10_Collection_and_Reporting_200105_Final.pdf

NEPC (2002). Impact statement for $PM_{2.5}$ Variation – Setting a $PM_{2.5}$ standard in Australia. National Environmental Protection Council, Adelaide.

NEPC (2009). An Australian approach to setting air quality standards: consultation draft, National Environment Protection Council, Canberra.

NEPC (2011a). National Environment Protection (Ambient Air Quality) Measure Review. National Environment Protection Council Service Corporation, Level 5 81 Flinders Street, Adelaide, South Australia. http://www.ephc.gov.au/sites/default/files/AAQ%20NEPM%20review%20report_0.pdf

NEPC (2011b). Methodology for Setting Air Quality Standards in Australia, Part A, February 2011. National Environment Protection Council, Canberra.

NetBalance (2010). Domestic/Commercial Report: Future Air Projections: Contribution to Scenario Definition 2030 and 2070. Consultancy report to EPA Victoria.

NIWA (2008). Assessing Vehicle Air Pollution Emissions. NIWA Client Report: CHC2008-001July 2008. Prepared for Department of the Environment, Water, Heritage and the Arts. National Institute of Water & Atmospheric Research Ltd.

NSW DEC (2004). Measures to Encourage the Supply and Uptake of Cleaner Lawnmowers and Outdoor Handheld Equipment. Department of Environment and Conservation, Sydney.

NSW DEC (2005). Air Pollution Economics - Health Costs of Air Pollution in the Greater Sydney Metropolitan Region, NSW. Department of Environment and Conservation, Sydney. http://www.environment.nsw.gov.au/resources/air/airpollution05623.pdf

NSW DPI (2010). 2009 New South Wales Coal Industry Profile Statistical Supplement. NSW Department of Primary Industries.

NSW EPA (1997). Proposed Clean Air (Motor Vehicles and Motor Vehicle Fuels) Regulation 1997 – Regulatory Impact Statement, NSW EPA, Chatswood, NSW.

NSW EPA (2012a). Air Emissions Inventory for the Greater Metropolitan Region in New South Wales - 2008 Calendar Year. Technical Report No. 1 - Consolidated Natural and Human-Made Emissions: Results. NSW Environment Protection Authority, Sydney South.

NSW EPA (2012b). Air Emissions Inventory for the Greater Metropolitan Region in New South Wales - 2008 Calendar Year. Technical Report No. 2 - Biogenic and Geogenic Emissions: Results. NSW Environment Protection Authority, Sydney South.

NSW EPA (2012c). Air Emissions Inventory for the Greater Metropolitan Region in New South Wales - 2008 Calendar Year. Technical Report No. 3 - Commercial Emissions: Results. NSW Environment Protection Authority, Sydney South.

NSW EPA (2012d). Air Emissions Inventory for the Greater Metropolitan Region in New South Wales - 2008 Calendar Year. Technical Report No. 4 - Domestic-Commercial Emissions: Results. NSW Environment Protection Authority, Sydney South.

NSW EPA (2012e). Air Emissions Inventory for the Greater Metropolitan Region in New South Wales - 2008 Calendar Year. Technical Report No. 5 - Industrial Emissions: Results. NSW Environment Protection Authority, Sydney South. http://www.environment.nsw.gov.au/resources/air/120049AEITR5Industrial.pdf

NSW EPA (2012f). Air Emissions Inventory for the Greater Metropolitan Region in New South Wales - 2008 Calendar Year. Technical Report No. 6 - Off-Road Mobile Emissions: Results. NSW Environment Protection Authority, Sydney South. http://www.environment.nsw.gov.au/resources/air/120050AEITR6OffRoadMobile.pdf

NSW EPA (2012g). Air Emissions Inventory for the Greater Metropolitan Region in New South Wales - 2008 Calendar Year. Technical Report No. 7 - On-Road Mobile Emissions: Results. NSW Environment Protection Authority, Sydney South.
http://www.environment.nsw.gov.au/resources/air/120256AEITR7OnRoadMobile.pdf
http://www.environment.nsw.gov.au/resources/air/120256AEITR7OnRoadMobileAppendix.pdf

NSW EPA (2013). Hunter Valley Annual Air Quality 2012 - Fine Particles. NSW Environment Protection Authority, Sydney. http://www.environment.nsw.gov.au/resources/aqms/20130037HunterAir2012.pdf

NZMFE (2004). Good Practice Guide for Atmospheric Dispersion Modelling. New Zealand Ministry for the Environment, Wellington.

Orbital and CSIRO (2008). Evaluating the Health Impacts of Ethanol Blend Petrol, June 2008, Canberra.

PAE Holmes (2011). Potential Measures for Air Emissions from NSW Ports - Prepared for NSW Office of Environment & Heritage. June 2011.

Pankow J F (1994). An adsorption model of the gas/aerosol partitioning involved in the formation of secondary organic aerosol. *Atmospheric Environment*, Vol. 28, pp. 189–193.

Pope C A III, Thun M J, *et al*. (1995). Particulate air pollution as a predictor of mortality in a prospective study of US adults. American Journal of Respiratory and Critical Care Medicine 151(3): 669-674.

Pope C A III and Dockery D W (2006). Health effects of fine particulate air pollution: lines that connect. J Air Waste Manag Assoc 2006, 56:709-742.

Putaud J P, Van Dingenen R, Alastuey A, Bauer H, Birmili W, Cyrys J, Flentje H, Fuzzi S, Gehrig R, Hansson H C, Harrison R M, Herrmann H, Hitzenberger R, Hüglin C, Jones A M, Kasper-Giebl A, Kiss G, Kousa A, Kuhlbusch T A J, Löschau G, Maenhaut W, Molnar A, Moreno T, Pekkanen J, Perrino C, Pitz M, Puxbaum H, Querol X, Rodriguez S, Salma I, Schwarz J, Smolik J, Schneider J, Spindler G, ten Brink H, Tursic J, Viana M, Wiedensohler A and Raes F (2010). A European aerosol phenomenology - 3: Physical and chemical characteristics of particulate matter from 60 rural, urban, and kerbside sites across Europe. Atmospheric Environment, Vol. 44, pp. 1308-1320.

Queensland EPA (2004). Air Emissions Inventory – South East Queensland Region, Queensland Environmental Protection Agency and Brisbane City Council, Brisbane Qld.
http://www.ehp.qld.gov.au/air/pdf/reports/air-emissions-inventory-seq.pdf

Queensland Rail (2012). 2011/12 Annual and Financial Report. Queensland Rail limited, Brisbane.

RWDI (2006). South Fraser Perimeter Road Regional Air Quality Assessment: Technical Volume 16 of the Environmental Assessment Application. BC Ministry of Transportation (www.gov.bc.ca/tran/).

Seguel R A, Morales R G E and Leiva M A (2009). Estimations of primary and secondary organic carbon formation in $PM_{2.5}$ aerosols of Santiago, Chile, Atmospheric Environment, Vol. 43, Issue 13, pp. 2125–2131.

Sellers W D (1968). Climatology of Monthly Precipitation Patterns in the Western United States, 1931-1966, Monthly Weather Review, 96, 585-595.

SKM (2006). Perth Airshed Diffuse Emissions Study 2004/2005. Sinclair Knight Merz, Perth.

SKM (2010). Cost Abatement Curves for Air Emissions Reduction Actions. Sinclair Knight Merz.

Southard M, Essink-Bot M, Bonsel G, Barendregt J, Kramer P, van de Water H, Gunnin-Schepers, L and van der Maas P (1997). Disability weights for diseases in the Netherlands, Department of Public Health, Rotterdam.

Stern N (2006). Stern Review: The Economics of Climate Change, October 2006, HM Treasury, London.

Stone R (1989). Weather types at Brisbane, Queensland: An example of the use of principal components and cluster analysis, *International Journal of Climatology*, 9, 3-32.

TDC (2009). TDC Forecasts for Population and VKT 2006 to 2036 Ref: 09/088, Transport Data Centre, GPO Box 1620, Sydney, NSW 2001, Australia.

Thompson S (1994). Residence Time of Contaminants Released in Surface Coal Mines -- A Wind Tunnel Study. Proceedings Eighth Joint Conference on Applications of Air Pollution Meteorology, January 23-28, Nashville, TN.

Todd J (2003). Wood-Smoke Handbook: Wood heaters, Firewood and Operator Practice.

Tsimpidi A P, Karydis VA and Pandis S N (2008). Response of fine particulate matter to emission changes of oxides of nitrogen and anthropogenic volatile organic compounds in the eastern United States. J Air Waste Manag Assoc., 2008, 58(11), pp.1463-73.

Uherek E, Halenka T, Borken-Kleefeld J, Balkanski Y, Berntsen T, Borrego C, Gauss M, Hoor P, Juda-Rezler K, Lelieveld J, Melas D, Rypdal K, Schmid S (2010). Transport impacts on atmosphere and climate: land transport. Atmospheric Environment, 44:4772–4816.

UK Office for National Statistics (2012). 2011 Census: Population Estimates for the United Kingdom, 27 March 2011.

URS (2000). Mount Arthur North Coal Project. EIS produced for COAL Australia Pty Ltd by URS Australia Pty Ltd, Level 22, and 127 Creek Street, Brisbane, Queensland 4000.

USEPA (1994). Industrial Source Complex (ISC3) Dispersion Model User's Guide. EPA-454/B-95-003b. United States Environmental Protection Agency, Research Triangle Park, NC.

USEPA (2004). Final Regulatory Analysis: Control of Emissions from Nonroad Diesel Engines. EPA420-R-04-007. United States Environmental Protection Agency, Research Triangle Park, NC.

USEPA (2008). Integrated Science Assessment for Oxides of Nitrogen – Health Criteria (Final Report). EPA/600/R-08/071. United States Environmental Protection Agency, Research Triangle Park, NC.

USEPA (2009). Integrated Science Assessment for Particulate Matter. EPA/600/R-08/139F. United States Environmental Protection Agency, Research Triangle Park, NC. Available at: http://cfpub.epa.gov/ncea/cfm/recordisplay.cfm?deid=216546

USEPA (2012). Regulatory Impact Analysis for the Proposed Revisions to the National Ambient Air Quality Standards for Particulate Matter. EPA-452/R-12-003, June 2012. United States Environmental Protection Agency, Research Triangle Park, NC.

USEPA (2013). Federal Register, Vol. 78, No. 10 January 15, 2013 – Part II – Environmental Protection Agency – 40 CFR Parts 50, 51,52 et al. National Ambient Air Quality Standards for Particulate Matter; Final Rule. United States Environmental Protection Agency, Research Triangle Park, NC.

Vutukuru S, Griffin R J and Dabdub D (2006). Simulation and analysis of secondary organic aerosol dynamics in the South Coast Air Basin of California. *Journal of Geophysical Research*, Vol. 111, D10S12, doi:10.1029/2005JD006139.

WA DEC (2008). CleanRun Behaviour Change, Initiative Evaluation of Phase II. July 2008. Department of Environment and Conservation, Perth, Western Australia.

WA DEC (2012). 2011 Western Australia Air Monitoring Report. Department of Environment and Conservation, Perth, Western Australia.

WA DEP (2003) National Pollutant Inventory – Perth Airshed Emissions Study 1998/1999 – Revised 2003, Department of Environment Protection, Western Australia, Australia. http://www.npi.gov.au/publications/pubs/perth-aedreport.pdf

Walsh S (2012a). Personal communication from Sean Walsh of Victoria EPA to Paul Boulter of Pacific Environment.

Walsh S (2012b). Personal communication from Sean Walsh of Victoria EPA to Kelsey Bawden of Pacific Environment.

Watkiss P, Holland M, Hurley F and Pye S (2008). Damage Costs for Air Pollution. Report to the Department for Environment, Food and Rural Affairs, UK. Published on the Defra website.

Watkiss P (2013). Personal communication from Paul Watkiss of Paul Watkiss Associates to Paul Boulter of Pacific Environment.

Wilson C, Chiodo J and Grey F (2011a). National Environment Protection (Ambient Air Quality) Measure – Draft Cost Benefit Analysis Methodology, April 2011.

Wilson C, Chiodo J and Grey F (2011b). National Environment Protection (Ambient Air Quality) Measure – Draft Preliminary Cost Benefit Analysis, April 2011.

Winges K D and Cole C F (1986). Continued analysis and derivation of a method to model pit retention. Research Triangle Park, N.C., U.S. Environmental Protection Agency, Office of Air and Radiation, Office of Air Quality Planning and Standards.