Modelling cost-effective air pollution abatement:

a multi-period linear programming approach

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1 Introduction

Improvements in air quality for some criteria pollutants in Sydney, Wollongong and the Lower Hunter have been achieved, whilst further improvements are required for others.

> *"Air quality has improved over the past 10 years – many of the most dangerous pollutants are down by 30% and [NSW] consistently meet[s] national air quality standards for four of six major air pollutants (lead, carbon monoxide, sulfur dioxide and nitrogen dioxide). These reductions are a significant achievement, particularly as over the past 20 years Sydney's population has grown by 21% and the number of passenger vehicles, the main contributor of several significant air pollutants, has increased by 58%.*
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> *However, [NSW] still face[s] major challenges with ozone and particle pollution, and these are likely to be exacerbated by climate change. National standards for ozone are exceeded in Sydney as are particle standards in some regional areas. These exceedances generally occur between two and 20 days per year. Current and projected ozone and particle levels are a concern in view of growing evidence of the health impacts of air pollution"* (DECCW 2009).

Sydney Metropolitan air pollution levels exceed the daily national air quality standards for ozone, formed by the two ozone precursors oxides of nitrogen (NO_X) and volatile organic compounds (VOCs). Air quality management also aims to reduce emissions of particulate matter (PM_{10}). There is a variety of abatement actions available to reduce emissions of these pollutants. Actions differ by cost, abatement potential, timing and implementation. It is desirable to simultaneously choose the optimal portfolio of abatement actions which meets pre-specified objectives. Such objectives can include least cost abatement, emission reduction targets and/or targeted timing of abatement. The appropriate selection of abatement actions must simultaneously address multiple pollutant targets across multiple periods. Where there is joint production of pollutants, pollutants may chemically interact, and abatement may differentially target individual pollutants.

Linear programming is a suitable modelling approach for selecting the optimal package of abatement actions to achieve specified air management objectives. In the first instance, a single period linear programming model incorporates the interactions between abatement actions to solve for a multi-pollutant solution. Expansion to a multiple period model dynamically captures timing and implementation factors. The multi-period and multi-pollutant model solves for both the optimal selection and optimal timing of abatement actions.

This paper discusses the application of linear programming to air quality management, including the advantages and limitations of such an approach. The paper then discusses an air pollution abatement linear programming model which incorporates the key factors of cost, abatement potential and implementation to determine a least cost solution which meets specified emission reduction targets within a specified timeframe.

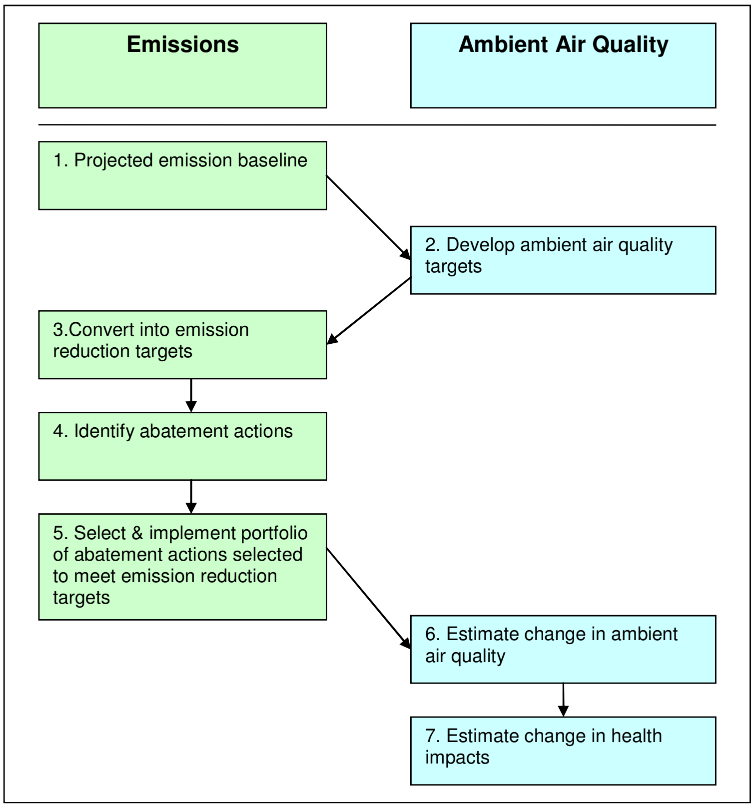
2 A framework for Air Quality Management

Air quality is a public good, managed by limiting pollutant emissions to reduce the negative externalities of air pollution. These include health impacts, visual dis-amenity and damage to the environment. National air quality standards determine emission limits for key pollutants (National Environment Protection Measure for Ambient Air Quality).

A framework for air quality management must assess the costs and benefits of implementing abatement actions. The framework should extend beyond a standard cost benefit analysis of individual abatement actions and encompass the multiple pollutant context of air quality management. Furthermore the cost benefit analysis should inform dynamic air quality management within an iterative and integrated framework.

Generic steps of an integrated air quality management framework are outlined in Figure 1. As shown in Figure 1, throughout the framework the focus alternates between emissions and ambient air quality. From the beginning projected emission baselines inform management and the development of ambient air quality targets. These targets must subsequently be converted into emission reduction targets to relate to emission reductions from industry abatement actions. After identifying feasible abatement actions a portfolio of actions is selected, based on cost and emission reduction merit, to satisfy specified emission reduction targets. The change in ambient air quality arising from the proposed emission reductions is estimated and the corresponding change in health impacts determined. The change in health impacts is quantitatively valued and compared against the cost of implementing the abatement actions within a cost benefit framework. A limitation of this framework is the translation from emissions to ambient air quality.

Figure 1 Air Management Integrated Framework



This paper focuses on a method to select the portfolio of abatement actions to meet specified emission reduction targets. The associated complexities are documented below. The key issues are multiple independent pollutants, interacting pollutants, and time.

2.1 Single versus multiple pollutant framework

The attainment of air quality standards is an issue for environment protection agencies around the world, including European Union countries and the United States. Cohan et al. (2007) noted that previous attempts to meet national air quality standards have been restricted to a single pollutant framework in a context when a multiple pollutant framework is actually required. A single pollutant framework fails in the context of most air quality management. The diversity of emission sources, the range of available abatement actions, and the interactions between pollutants require a multiple pollutant framework.

Air quality management generally focuses on limiting the anthropogenic emissions as opposed to biogenic emissions (e.g. volatile organic compounds emitted by native vegetation such as eucalypts, especially at high ambient temperatures). Anthropogenic emissions include point source and non-point source emissions. These emissions are further categorised into various sectors of the economy, such as commercial, industrial and on-road mobile. To varying degrees, abatement actions are available across all these emissions sources. Multiple pollutants are simultaneously emitted by the emissions sources and similarly reduced by the abatement actions.

The limitation of the single pollutant framework is the failure to capture interactions between pollutants. The first dimension is the simultaneous emission of multiple pollutants and the second is the formation of secondary pollutants through atmospheric reactions between emitted pollutants (discussed in section 2.2). In an air quality context pollutants are rarely emitted in isolation. Table 1 presents a scenario where Pollutant A and Pollutant B are emitted and abatement actions X and Y are available to reduce emissions of these two pollutants. Assume only Pollutant A must be reduced and a single pollutant framework is used to determine which abatement action to select. Abatement action X and Y reduces pollutant A by 100 units and 50 units respectively. Assuming abatement actions X and Y have equivalent costs, abatement action X is clearly favourable and would be selected. In this scenario the single pollutant framework failed to capture the interaction between pollutants by ignoring the increased emissions of Pollutant B. This can lead to expensive and possibly misguided attempts to reach ambient air quality standards.

Table 1: Interactions between initiatives and pollutants

	Pollutant A	**Pollutant B**
Abatement Action X	↓ emissions by 100 units	↑ emissions by 25 units
Abatement Action Y	↓ emissions by 50 units	↓ emissions by 50 units

A second scenario requires simultaneous reductions of both Pollutant A and Pollutant B. In this case Initiative X is not the clear winner because it increases emissions of Pollutant B. The selection of abatement action is not obvious from Table 1 and will depend on the relative emission reduction targets for the two pollutants and the cost of each action.

This example shows that a method is required which simultaneously selects abatement actions based on relative emission reduction targets, relative cost and relative emission reductions achieved. The key focus of this method is ‘relative’. A multi-pollutant framework incorporates this focus whilst a single pollutant framework does not.

In a single pollutant framework the total cost of an abatement action is attributed to its emission reduction of a single pollutant. It may then be possible to select abatement actions based on cost effectiveness of emission reductions achieved. When emission reductions are required for multiple pollutants the total cost can not be attributed to a single pollutant. Then abatement actions can not be selected based on cost effectiveness because of the difficult question of how to attribute cost of an abatement action across emission reductions of multiple pollutants. The total cost of the abatement action can not be attributed solely to the reduction of one pollutant as this ignores the co-benefit the abatement action achieves of emission reduction for other key pollutants. Chestnut et al. (2006) noted that a single pollutant framework precludes cross-prioritisation that could enhance overall cost-effectiveness.

2.2 Secondary pollutants

A single pollutant framework is inadequate when air quality targets aim to reduce emissions of secondary pollutants as opposed to primary pollutants. Primary pollutants are released directly into the atmosphere, secondary pollutants are formed within the atmosphere through processes involving light, heat or other chemicals. Oxides of nitrogen (NO_X) and volatile organic compounds (VOCs) are examples of primary pollutants that are released into the atmosphere and through photochemical reactions in the atmosphere can form the secondary pollutant, ozone. Ozone can lead to numerous health impacts causing air quality management to focus on reducing emissions of the ozone precursors (NO_X and VOCs) to indirectly reduce formation of ozone. Hence air quality targets for ozone necessitate a multi-pollutant framework to achieve emission reductions of the two primary pollutants oxides of nitrogen and volatile organic compounds.

2.3 Multi-period

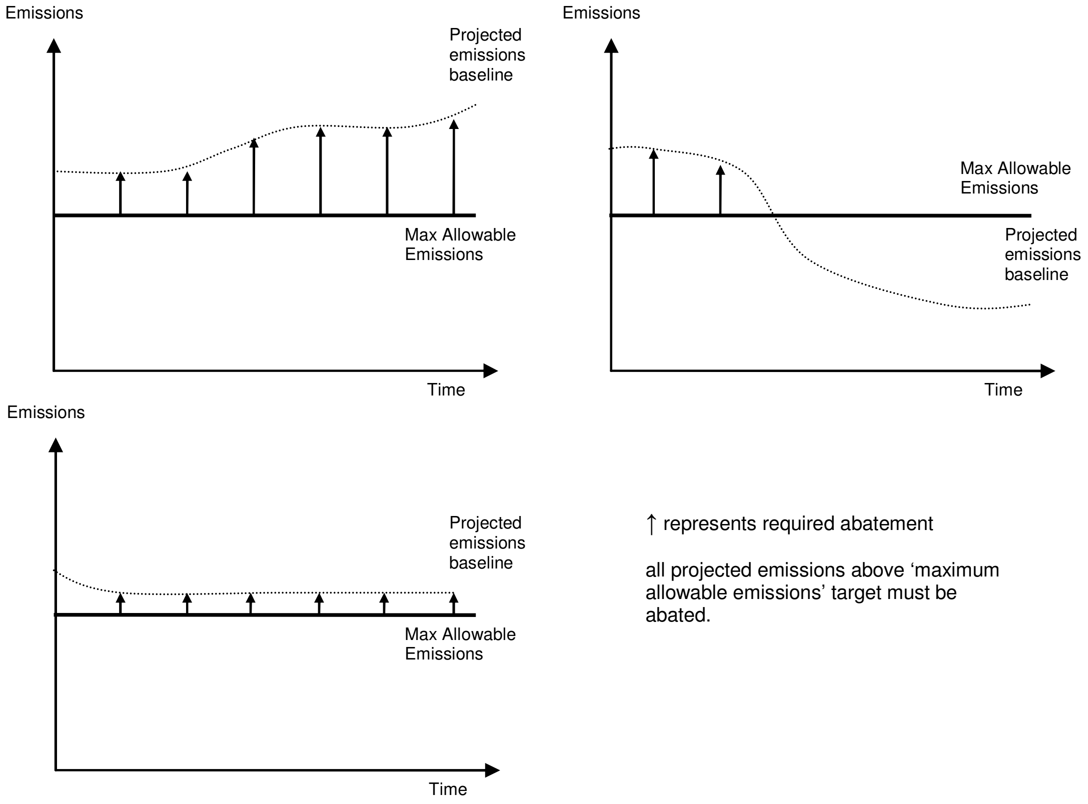
Many government agencies project emission trends for various key pollutants. These projections incorporate anticipated trends in economic activity, population growth and various factors. Air quality targets are specified relative to projected emission baselines but these targets rarely can be reached instantaneously. The timing of the targets relative to the project emission baselines should be considered when abatement actions are selected. The selection of abatement actions should also consider the availability of the actions with respect to time. The implementation of abatement actions is often restricted by availability of technology, duration required to implement, and timing of proposed and existing regulations.

The different possible emission baselines, emission reduction targets and availability of abatement actions require a multi-period management framework. A multi-period framework simultaneously accounts for decisions made in each time period to achieve a final outcome capturing changes in the optimal mix of abatement actions and switching between actions.

In dynamic modelling of abatement actions, emission reduction targets are relative to a projected emissions baseline. Emission reduction targets have previously been set as proportional targets, e.g. 30% reduction in emissions. Such proportional emission reduction targets are problematic when they are relative to a dynamic emission baseline. It is unclear what time period a proportional target should be pegged to, the first or the last, or instead adjusted for each time period. Each of these three options will lead to very different emission reduction outcomes, and in some cases will lead to perverse outcomes. For example, the emission reduction achieved by a proportional target pegged to the first year on an increasing emission baseline may eventually be outstripped by the growth in emissions.

A better approach is an absolute target which specifies the maximum allowable emissions within each time period. With a dynamic emission baseline the maximum allowable emissions remains constant and the emission reductions required changes in each time period, maintaining an artificial emissions ‘cap’. Examples of three different emission baselines are provided in Figure 2. The bold horizontal line represents the maximum allowable emissions. When the emission baseline exceeds the maximum allowable emissions the required annual emission reduction is represented by the area between the two curves.

Figure 2 Absolute emission target for different emission baselines



↑ represents required abatement

all projected emissions above ‘maximum allowable emissions’ target must be abated.

2.4 A portfolio approach

Air quality management is complicated due to multiple pollutants, various emission sources and abatement actions, and emission reduction targets relative to dynamic emission baselines. From a cost perspective the goal is to select a portfolio of cost-effective abatement actions which meet specified multi-pollutant and multi-period emission reduction targets. Linear programming modelling is an analytical tool which can solve a multi-pollutant and multi-period problem. To demonstrate its applicability, linear programming was used in a case study of air quality management in the Sydney Metropolitan Area.

3 Linear Programming

A linear programming problem has three key components: an objective, activities and constraints. The objective specifies something to be maximised or minimised, for example, maximise profit or minimise cost. The activities are the options available for use by the decision maker, for example, types of crops to grow. The constraints are the restrictions on the selection of activities. These restrictions can be specified as minimum, maximum or exact level of the activities to be used in the solution (Pannell, 1997). A constraint is said to be ‘binding’ when all available units of an activity are used.

A solution to a linear programming problem must satisfy all the constraints specified. Optimal solutions to a linear programming problem are described as locally or globally optimal. The ideal is a globally optimal solution. Depending on the specified constraints there may be multiple ‘feasible’ solutions to a problem of which linear programming identifies the single feasible solution that is optimal in terms of the objective (Pannell, 1997). Constraints should be carefully specified by the decision maker to avoid unnecessarily prohibiting beneficial optimal solutions.

3.1 Shadow price and shadow cost

A linear programming solution describes the sensitivity of the solution in terms of shadow prices and shadow costs. A shadow price is given for each constraint and describes the value of relaxing the constraint, specifically how much the solution would improve if the constraint was relaxed by one unit. When a constraint is binding its shadow price will be positive. When a constraint is non-binding its shadow price will be zero. The other descriptor, shadow cost, is given for each activity and describes how much its price (for maximisation) or cost (for minimisation) must change before it enters the optimal solution.

3.2 Multiple optimal solutions

It is possible that multiple optimal solutions exist for a single scenario where each solution in the set of solutions gives the best feasible value of the objective function. This scenario is possible when there is great flexibility within the problem in terms of the activities available and the constraints implied. The presence of multiple optimal solutions suggests there is flexibility available to the decision maker (Pannell 1997). Evidence of multiple optimal solutions is a zero shadow cost for an activity which has a zero level (i.e. not selected in the solution) and/or a zero shadow price for a constraint which is binding (Pannell 1997).

4 Case study: Sydney Metropolitan Area

In the Sydney Metropolitan Area air quality management relates to standards for six criteria pollutants including particles, carbon monoxide, sulfur dioxide, nitrogen dioxide, lead and ozone. Emissions in the Sydney metro exceed the daily national air quality standards for ozone, formed by the primary pollutants, oxides of nitrogen and volatile organic compounds. Emission reductions of particulate matter are also desirable. Achieving emission reductions requires additional abatement actions. There are two questions that need to be answered:

1. What level of emission reduction should be achieved in the Sydney Metropolitan Area?
2. What is the cost-effective portfolio of abatement actions which will meet specified emission reduction targets?

A pilot linear programming model was developed for air quality management in the Sydney Metropolitan Area. The purpose of the pilot model was to identify a cost-effective portfolio of abatement actions given projected emissions, available abatement actions, cost and specified multi-pollutant emission reductions targets. At the time of development there were numerous data limitations for the cost data on abatement actions and also the potential emissions reduced for abatement actions.

The three key components of a linear programming methodology in the context of air quality management are as follows:

- **Objective function:** to define an objective functional (i.e. cost) that is properly represents fixed and variable costs of abatement
- **Activities:** abatement actions available across numerous emission sources
- **Constraints:**
    1. Emission reduction target for each pollutant
    2. Time period when emission reduction target must be met
    3. Annual emission reduction potential of each abatement action

Implementing such a model presents some mathematical challenges that are also relevant to problem specification and data gathering. The linear programming approach works most effectively when the model is linear in all inputs and outputs – if not, more sophisticated software is needed, the model takes longer to solve, and there is no guarantee that any solution is a global cost minimum. Considerable care is needed to specify cost inputs in a (piecewise) linear way, which has implications for how cost data should be collected. Care is also needed to specify constraints in a linear fashion, which has implications for what targets can be modelled.

The pilot model was a multi-pollutant model targeting three primary pollutants, oxides of nitrogen (NO_X), volatile organic compounds (VOCs) and particulate matter (PM_{10}).

The objective function does not include any objective related to benefits of reducing air pollution.

The activities included over thirty abatement actions which targeted emissions across the five categorised anthropogenic emission sources in the DECCW Air Emission Inventory.[5] These five emission source categories are:

- Commercial businesses (e.g. quarries, service stations and smash repairers)
- Domestic activities (e.g. house painting, lawn mowing and wood heaters)
- Industrial premises (e.g. oil refineries, power stations and steelworks)
- Off-road mobile (e.g. aircraft, railways and recreational boats)
- On-road mobile (e.g. buses, cars and trucks).

The majority of the abatement actions reduce emissions of multiple pollutants. Some abatement actions reduce emissions of all three pollutants (oxides of nitrogen, volatile organic compounds and particulate matter), others a combination of the three, and a few actions which only reduce emissions of one pollutant. Discussed above was the importance of understanding the interactions between pollutants for each abatement action, as an abatement action may reduce emissions of one pollutant whilst increasing the emissions of another pollutant (see Table 1). A couple of abatement actions included in the pilot model are examples of this, reducing emissions of volatile organic compounds and particulate matter whilst increasing emissions of oxides of nitrogen. In a single pollutant framework targeting emissions of volatile organic compounds, these abatement actions may be selected over other abatement actions for their ability to reduce volatile organic compounds which may be detrimental to the achievement of emission reduction targets for oxides of nitrogen.

The emissions reduction targets were relative to the projected emissions baseline for each pollutant (see Figure 3). The projected emission baselines are modelled within the DECCW Air Emission Inventory.[5] The projected emission baseline for oxides of nitrogen, volatile organic compounds and particulate matter in the Sydney Metropolitan Area for the period between 2010 and 2030 were incorporated into the pilot model.

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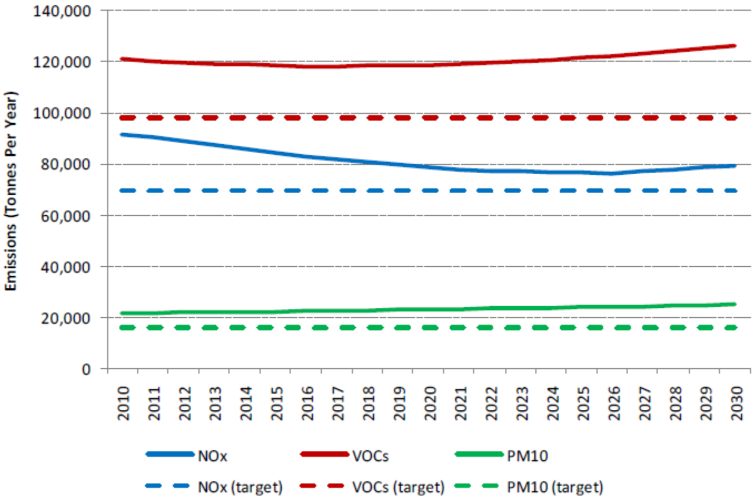
[5] NSW Department of Environment, Climate Change and Water (DECCW) Air Emission Inventory for the Greater Metropolitan Region in NSW
http://www.environment.nsw.gov.au/air/airinventory.htm

Figure 3 Projected emissions baseline and emission reduction targets



Source AECOM based on data provided by DECCW

The time period constraint specifies the year (between 2010 and 2030) when the emission reduction target must be met. For instance the target year may be set at 2020. The earlier the target year the more expensive it is to meet the emission reduction targets. The objective of the model is to minimise the cost of meeting specified targets. The model will delay the discounted costs for as long as possible to minimise the present value of cost.

The emission reduction constraint for each abatement action specifies the maximum emission reduction available in current and subsequent periods once the action is implemented. Where possible, the model may select to partially implement an action or stage the uptake of implementation to minimise the cost of meeting the targets.

4.1 Model outputs

The pilot model for the Sydney Metropolitan Area was developed by AECOM Australia. The model was programmed in an Excel add-in called What's*Best!*.[6] The three main model outputs are:

1. Timeline of emission reduction relative to the target and emission baseline for each pollutant (Figure 4)
2. Time profile of the abatement action portfolio detailing when individual abatement actions start and the degree to which they are implemented in each period (Figure 5)

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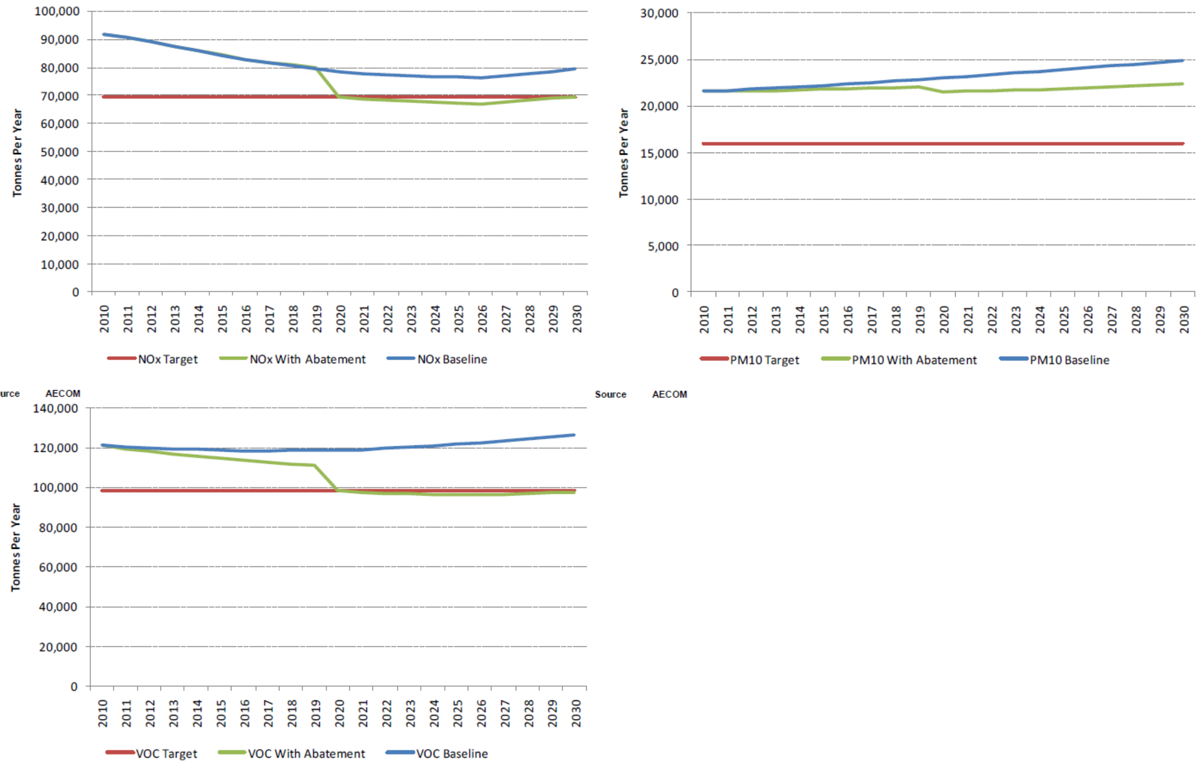
[6] What's*Best!* is an add-in to Excel that allows you to build large scale optimisation models within a spreadsheet (http://www.lindo.com/index.php?option=com_content&view=article&id=3&Itemid=11)

3. Emission reduction of each pollutant by abatement action, showing the proportion of reduction each abatement action contributes in each time period (Figure 6).

The output provided in Figure 4, Figure 5 and Figure 6 is illustrative only. Due to existing data limitations, particular solutions are not provided in this paper as the purpose of this paper is to demonstrate a method to model and select a cost-effective portfolio of abatement actions to meet specified targets within the multi-pollutant and multi-period context of air quality management.

Figure 5 shows a generic solution for meeting targets in 2020. The majority of abatement actions start in 2020. The abatement actions which start earlier than 2020 were modelled differently to the other actions as they accumulate the annual emission reduction potential over time. The earlier they are implemented the larger the annual emission reduction achieved in subsequent years. In Figure 5 most are started as early as possible to accumulate the emission reduction potential available in the target year 2020. Further work is required to reduce the data limitations which will probably result in more abatement actions starting earlier than the target year.

Figure 4 Emission profile for the three key pollutants



Source AECOM

Source AECOM

Source AECOM

Figure 5 Portfolio of abatement actions

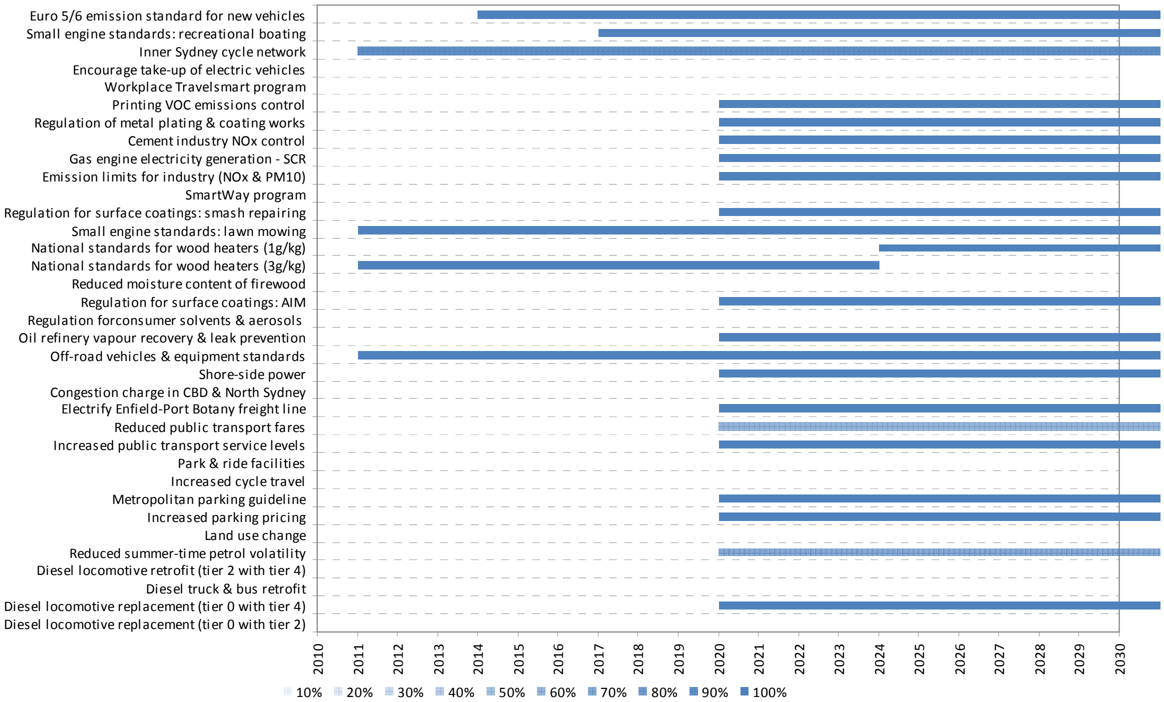
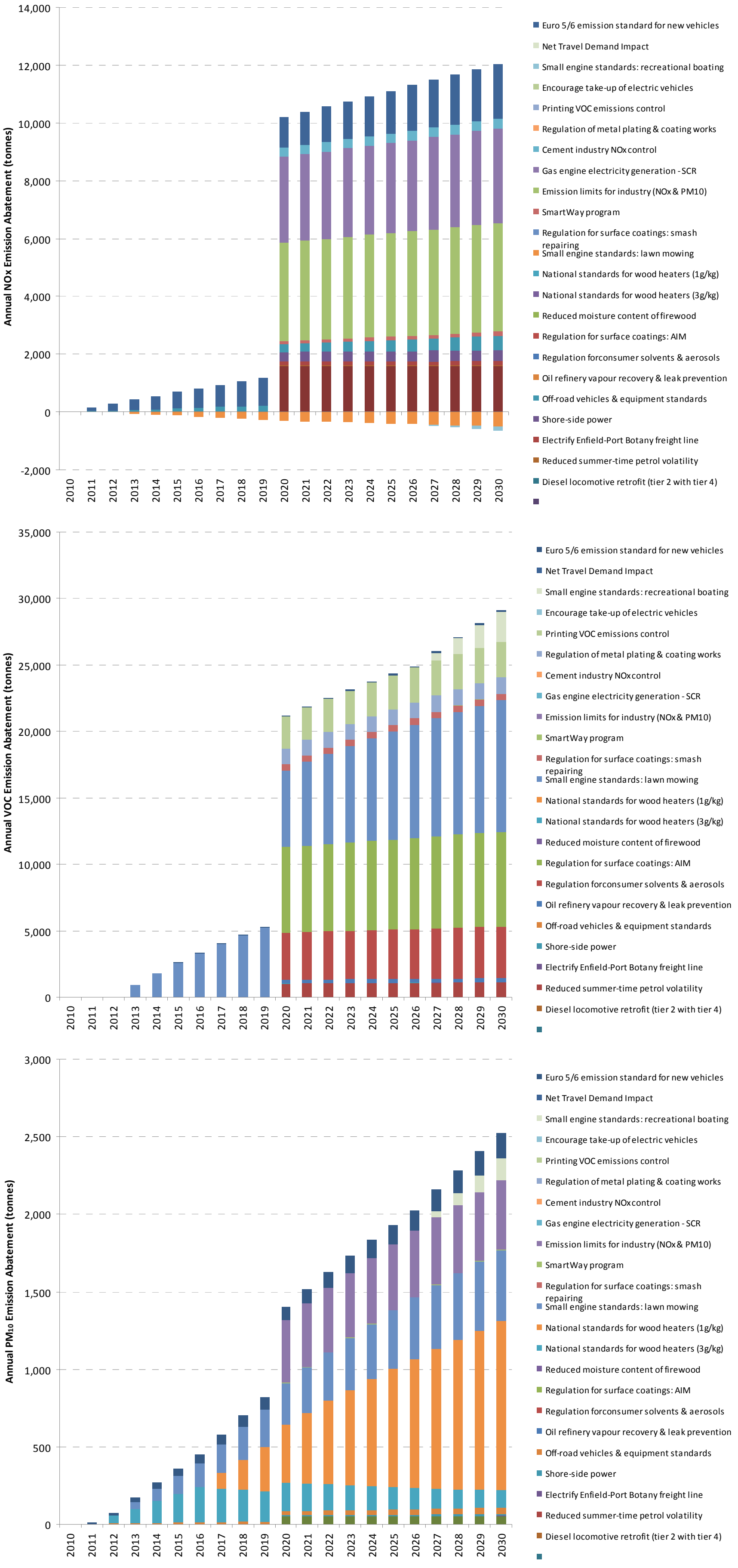


Figure 6 Emission reductions by pollutant and abatement action



4.2 Model limitations

An efficient linear programming model requires a sufficient number of activities, in this case a sufficient number of abatement actions. A limitation with the modelling software, What'sBest!, is that no usable output is provided when the model cannot find a feasible solution. A lack of abatement actions necessary to meet the specified emission reduction targets limits the range of emission reduction targets which can be analysed. When a feasible solution is not found the model does not provide output describing how far away from a feasible solution it is, i.e. how many additional units of abatement are required to meet the emission reduction targets. In such a case What's*Best!* simply reports that the problem is infeasible.

Additional limitations with the current pilot model are that emissions are included at the highly aggregated level of annual emissions and the spatial distribution of emissions is not included. These both limit the transferability of the output to subsequent atmospheric modelling and health benefit estimation which are components of the air quality management framework described in Figure 1.

Emissions data are available by year, month, day and hour. The emissions data included in the pilot model is highly aggregated annual data. The timing of emissions is an important factor for primary pollutants which form secondary pollutants affected by sunlight, heat and other time related factors. Currently the pilot model selects abatement actions based on absolute annual reductions. This ignores the seasonal and daily elements of emissions and formation of secondary pollutants. For example, primary pollutants oxides of nitrogen and volatile organic compounds are targeted primarily to reduce the secondary pollutant, ozone. The pilot model will select an abatement action portfolio to achieve the annual emission reduction targets for oxides of nitrogen and volatile organic compounds. When the timing and spatial distributions of these annual reductions of oxides of nitrogen and volatile organic compounds are accounted for in atmospheric modelling, the reduction in ozone may not be as significant as a less optimal portfolio not selected by the pilot model. This occurs because disaggregated spatial and timing aspects of emissions and emission reductions are not represented in the model.

The spatial unit for air quality management is an airshed. The pilot model was developed as a single region model for the Sydney Metropolitan airshed. The activities and constraints of the model were specified for this airshed, including the emission reduction targets. Expanding the model to include activities and constraints for multiple airsheds would significantly increase the size and complexity of the model.

As part of the integrated framework discussed in Figure 1, the input into subsequent atmospheric modelling and health benefit estimation needs to align with the output of a cost abatement model. Given the pilot model can not capture all spatial and temporal factors of emissions and emissions reduction, the integrated framework must enable an iterative process in which the outputs at each stage can iteratively inform each other.

4.3 Scenario analysis

A linear programming model such as the pilot model discussed in this paper strongly lends itself to scenario analysis. Possible scenario analyses by this pilot model include:

- Varying the target year constraint to analyse the impact on cost of bringing forward or delaying
- Varying the emission reduction target constraint to analyse the impact on cost of increasing or decreasing the target
- Including an additional constraint which restricts the start year of an abatement action
- Include additional abatement actions that can be added as they become available
- Solve for a subset of pollutants, for instance restrict emission reduction targets to oxides of nitrogen and volatile organic compounds to assess how the portfolio and total cost change

Additional functionalities for scenario analyses which are currently not included in the pilot model but could be added at a later date include:

- progressive targets
- ‘must have’ abatement actions
- amend baseline to reflect exogenous events

Progressive targets would specify increasing sub-targets to be met leading up to the final target in the target year. For example, over *n* years an X unit target must be achieved followed by an X+Y unit target in the subsequent *n* years.

The flexibility to force ‘must have’ abatement actions can account for exogenous factors which require an abatement action even when the model does not select the action in the optimal portfolio. This allows useful scenario analysis for policy makers by demonstrating the change in cost from exogenously forcing an abatement action into the optimal portfolio when otherwise it would not be selected.

There are factors exogenous to air quality management which influence air pollution. For instance town planning, transport planning, and adaptation and mitigation to climate change could all influence air pollution. The influence of these exogenous factors could be indirectly analysed in the context of air quality management by incorporating an amended emission baseline into the linear programming model. For example transport planning may lead to a significant decrease in passenger cars on the road as people switch to public transport. This travel demand shift may, on aggregate, decrease air pollution. Although transport planning is not an air pollution abatement action,[7] the expected decrease in air pollution could be modelled by amending the emission baseline. An abatement action portfolio selected in the model with an amended baseline could be compared to a portfolio selected without the amended baseline. This comparison would demonstrate the change in the total cost to achieve emission reduction targets when transport planning is occurring alongside air quality management. A similar approach could amend the emissions baselines to incorporate the effect climate change policies have on air pollution.

5 Conclusion

Previously attempts to achieve air quality targets have been limited by the use of a single pollutant framework. The framework presented in this paper selects a cost-effective portfolio of abatement actions to meet specified multi-pollutant and multi-period emission reduction targets using linear programming. Beyond addressing the data limitations in the pilot model, further work is required to improve the link between optimising for the cost-effective portfolio and maximising health benefits from ambient air quality improvements.

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[7] This pilot model did attempt to include a suite of initiatives which fit under the umbrella of travel demand management. The difficulty with these travel demand abatement actions is the total cost can not be attributed to air quality management. The benefit of reducing air pollution is an indirect co-benefit and not the primary motivation for implementation of these initiatives.

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