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Evaluating Reduced-Form Tools for Estimating Air Quality Benefits

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EXECUTIVE SUMMARY

Quantifying and valuing the health impacts of changes in air quality can be a time- and resource-intensive endeavor that often requires large, detailed datasets and sophisticated computer models. The US Environmental Protection Agency (EPA) routinely undertakes these analyses as part of Regulatory Impact Analyses (RIAs) for major air pollution regulations. EPA strives to estimate the health benefits of air quality changes using a state-of-the-science "full-form" approach that couples a photochemical air quality model, such as the Community Multiscale Air Quality (CMAQ) model or the Comprehensive Air Quality Model with Extensions (CAMx), with its Environmental Benefits Mapping and Analysis Program – Community Edition (BenMAP-CE) health benefits tool. However, there are times when EPA has used "reduced-form" tools, which employ simpler models to approximate these more complex analyses with a lower computational burden. This can occur when time and resources are constrained, such as when rule development timelines are compressed, or air quality policy details required for full-form photochemical modeling are not available until very late in the rulemaking process.

The number of reduced form tools that quantify air quality benefits has grown over the last several years, giving EPA and other analysts of air policies more options to consider. To date, EPA has not formally explored the ability of these alternatives to estimate reliably full-form-based benefits of reducing emissions across a range of policies. The study described in this report demonstrates an approach to systematically comparing monetized health benefits estimated using reduced-form tools against those generated using full-form air quality models. The goal of this comparison was not to make any determinations as to whether any specific reduced-form tools are better-suited for use in regulatory applications than others, but rather to: 1) learn more about the reduced-form approaches available to regulatory analysts at EPA and elsewhere; and 2) provide an example of how one could conduct an evaluation of multiple approaches that could provide insights into relevant factors for choosing among alternative tools. The study did not evaluate the ability of each approach to characterize the distribution of PM2.5-related premature deaths according to the annual mean concentration at which they occurred. The need for the evaluation of reduced form techniques as described in this report was identified in the 2017 proposed rule to repeal the Clean Power Plan (FR 82 48035).

MODELS AND POLICY SCENARIOS

We compare results across four reduced-form tools, using each to quantify the impacts of five air quality policies. The tools we evaluated and associated sample references of model applications are listed in Exhibit ES-1.

EXHIBIT ES-1. REDUCED-FORM TOOLS EVALUATED

REDUCED-FORM TOOL	SAMPLE REFERNCE(S)
Source Apportionment (SA) Benefit Per Ton (BPT)	Fann, Baker, & Fulcher, 2012; Fann, Fulcher, & Baker, 2013; United States Environmental Protection Agency, 2013
Air Pollution Emission Experiment and Policy Analysis Model (APX)	Muller & Mendelsohn, 2006
Intervention Model for Air Pollution (InMAP)	Tessum, Hill, et al., 2017
Estimating Air Pollution Social Impacts Using Regression (EASIUR)	Heo et al., 2016

These tools vary in design, implementation, and ease-of-use. To ensure a reasonably fair comparison, we followed two guiding principles when applying these tools in this analysis:

1. Key model inputs should be standardized across reduced-form tools to the extent allowable by each tool to ensure that results are as comparable as possible.
2. The underlying model architecture should not be substantially altered so that the results still reflect the unique properties of each reduced-form tool.

The first principle ensured that differences would not be attributable to, for instance, use of an alternative concentration-response function or value of statistical life (VSL) value. The second principle helped ensure that the models we evaluated would be substantially similar to that downloaded or accessed by an analyst.

In some cases, we applied models directly to obtain monetized health benefit results from emissions inputs; in those cases, we append “Direct” to the model name (e.g., EASIUR Direct”) when describing the tool; in other cases we achieved the first principle by coupling the reduced-form air quality modeling aspect of the tool with EPA’s BenMAP-CE tool. This approach allowed us to specifically evaluate the air quality modeling aspect of some of the tools. In those cases, we append “BenMAP” to the tool name when we refer to the results (e.g., AP2-BenMAP). For the APEEP (versions 2 and 3; APX) models we applied them both directly and coupled with BenMAP.

We generated benefits estimates using the reduced form tools for the five example policies shown in Exhibit ES-2.

EXHIBIT ES-2 AIR QUALITY POLICIES ANALYZED

POLICY SCENARIO	POLICY YEARS (BASE/FUTURE)	SOURCE SECTOR
Clean Power Plan (CPP) Proposal	2011/2025	Electricity generating units (EGUs)
Tier 3 Rule	2005/2030	On-road vehicles
Cement Kilns*	2011/2025	Cement kilns
Refineries*	2011/2025	Oil refineries
Pulp and Paper*	2011/2025	Pulp and paper processing
*These policies apply hypothetical across-the-board emissions reductions rather than a detailed policy representation with spatially- and temporally-varying emissions impacts		

These example air quality policies vary in the magnitude and composition of their emissions changes and in the emissions source affected (e.g., mobile, industrial point, or electricity generating units [EGUs]). They also differ in the spatial distribution of emissions and concentration changes and in their impacts on primary particulate matter (prPM$_{2.5}$) emissions and secondary PM$_{2.5}$ precursors (e.g., nitrous oxides and sulfur dioxide). Finally, they differ in complexity, with some representing uniform emissions changes to all facilities in a particular sector while others represent more realistic cases where the policy results in emissions changes that vary both spatially and temporally.

We compared all reduced form tool results for the scenarios in Exhibit ES-2 against full-form results that were generated using a combination of the CMAQ air quality model and BenMAP-CE. For four of the five scenarios (all except Tier 3) we also had results generated using a combination of CAMx and BenMAP. We compared the CMAQ-based results against CAMx where available to identify any potential biases associated with using CMAQ alone as our full-form comparator.

ANALYSIS

We evaluated the reduced-form tools across two dimensions:

- A quantitative analysis at the national and regional level to explore the deviation of reduced-form tool results from full-form BenMAP results (this comparison was performed for total benefits as well as the fraction of benefits attributed to each PM$_{2.5}$ component), and
- A qualitative comparison of the computational complexity of each reduced-form tool and level of technical expertise needed to operate it.

The SA Direct, APX Direct, and EASIUR Direct results all use the tool itself to directly quantify the benefits of each air quality policy scenario. Results for the full-form models as well as the APX BenMAP and InMAP BenMAP reduced-form tools were generated by using the tools/models to create air quality surfaces that were then run through BenMAP-CE version 1.5.0.4 using the parameters in Exhibit ES-3.

EXHIBIT ES-3. BENMAP-CE PARAMETERS BY POLICY

BENMAP-CE INPUT	2025 POLICIES: CPP PROPOSAL, CEMENT KILNS, REFINERIES, PULP AND PAPER	2030 POLICY: TIER 3
Population[A]	County-level US Census population estimate for 2025	County-level US Census population estimate for 2030
Health Incidence[A]	County-level death rates projected to 2025	County-level death rates projected to 2030
Concentration-Response Relationship[B]	All-cause mortality, ages 30-99 (Krewski et al., 2009)	All-cause mortality, ages 30-99 (Krewski et al., 2009)
Valuation[B]	VSL based on 26 value-of-life studies with an inflation adjustment to $2015 and an income growth adjustment to 2025. A 3% discount rate and a 20-year cessation lag were applied to all estimated benefits.	VSL based on 26 value-of-life studies with an inflation adjustment to $2015 and an income growth adjustment to 2026 (the latest value provided in BenMAP-CE). A 3% discount rate and a 20-year cessation lag were applied to all estimated benefits.

[A] These population and incidence datasets are also reflected in the SA Direct and APX Direct BPT values. The only model that does not reflect these inputs is the EASIUR Direct reduced-form tool.

[B] This is the same concentration-response function and VSL estimate used to estimate the economic value of avoided premature deaths across all reduced-form tools. See https://www.epa.gov/environmental-economics/mortality-risk-valuation for more information.

We generated results for each full-form model and reduced-form tool expressed in terms of monetized benefits of avoided premature mortality ($2015). Results were compared at the national- and regional-level for primary $PM_{2.5}$ ($prPM_{2.5}$; defined as the results attributed to changes in elemental carbon [EC] emissions only), NO_3 (results attributed to changes in NO_X emissions), SO_4 (results attributed to changes in SO_2 emissions), and $PM_{2.5}$ (results attributed to EC, NO_X, and SO_2 emissions as well as NH_3 and VOC emissions, where applicable).

For comparisons of $PM_{2.5}$ at the national level, we use $prPM_{2.5}$ benefits that have been scaled up to better represent the fraction of $PM_{2.5}$ benefits that would be attributed to total $prPM_{2.5}$ emissions (i.e., EC, crustal and prOC). We multiplied the $prPM_{2.5}$ benefit per ton based on EC by the total amount of primary $PM_{2.5}$ emissions to estimate benefits related to all primary $PM_{2.5}$ emissions. Model comparison at the national-level is limited to: a) an overall comparison of total estimated benefits and b) ratios of total reduced-form tool benefits to CMAQ-derived benefits. At the regional-level, we compared full- and reduced-form tool results using a wider set of statistical metrics including:

- Total estimated benefits

- Mean bias (MB)
- Mean error (ME)
- Normalized mean bias (NMB)
- Normalized mean error (NME)
- Coefficient of determination (r^2)

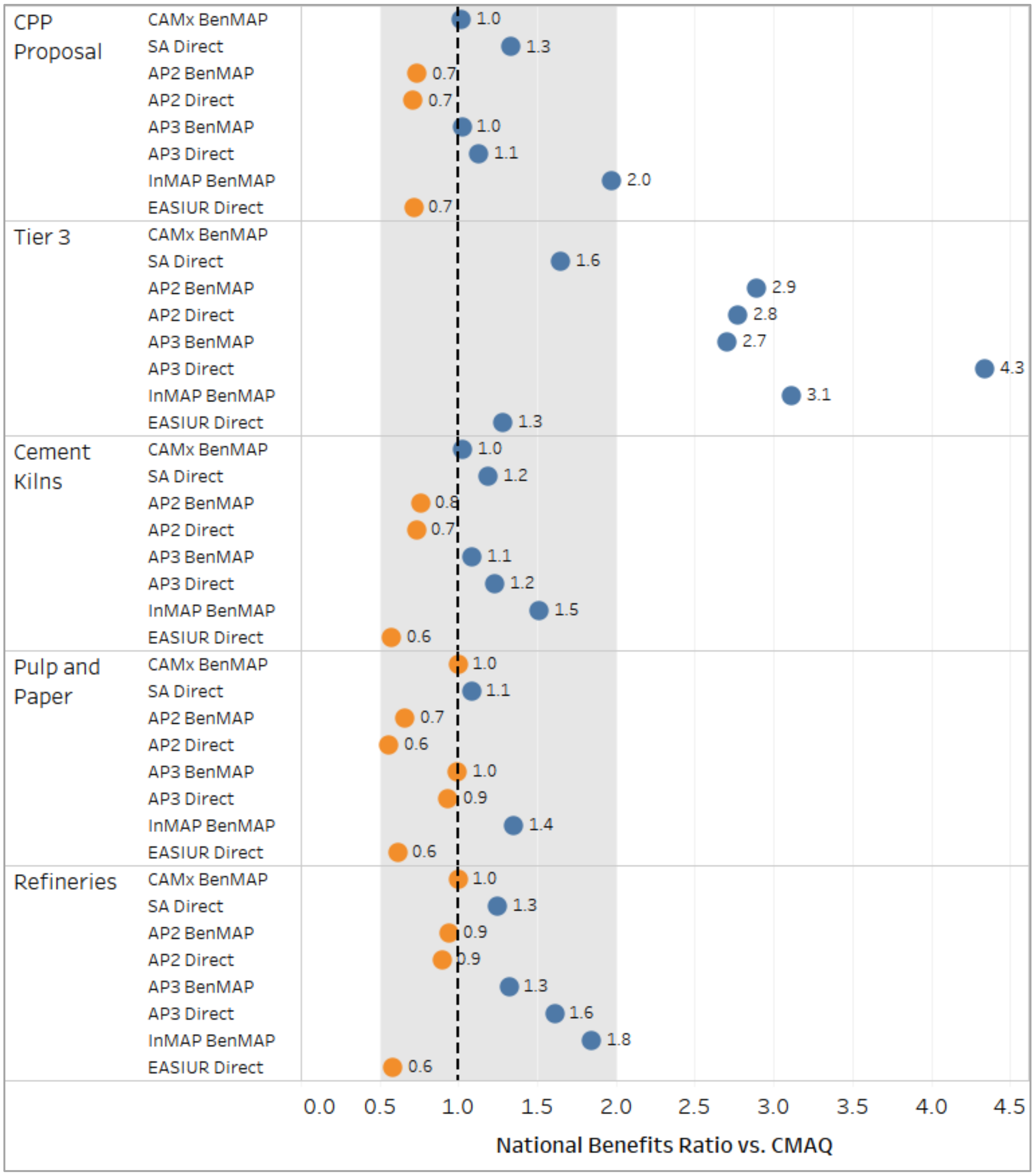
This set of statistics is both widely reported in the literature and is consistent with the recommendations provided in Simon et al. (2012). It is important to note that while this document sometimes uses a factor of two to differentiate relative performance against the full-form models, the factor of two delineation is not a measure of acceptability for any particular type of assessment.

RESULTS AND CONCLUSIONS

Our quantitative analysis led to several observations relevant for analysts considering using reduced form tools:

- Across all comparators examined in this analysis, CMAQ and CAMx produce very similar estimates of both total $PM_{2.5}$ benefits and benefits related to specific components of $PM_{2.5}$. They are also in agreement on the spatial distribution of those benefits at the region-level. This finding, which was consistent across all policies for which both results were available, gives us confidence that we are not introducing significant uncertainty into our analysis of reduced-form tools by relying on a single full-form model as our sole comparator.
- The difference between reduced-form and full-form models can vary substantially across different policy scenarios. For example, in Exhibit ES-4, which groups national results by policy, we can see that the two policies that resulted in the best alignment between CMAQ results and reduced-form tool results were the CPP Proposal and Pulp and Paper scenarios. On the other hand, differences between the two model types were largest for the mobile-source Tier 3 scenario. In general, point source scenarios with non-ground-level emissions showed much better agreement with CMAQ-based estimates across reduced-form tools.
- We also observed differences in tools when comparing national-level benefits by precursor. Across components, we observed that reduced-form tools generally matched CMAQ more closely for primary $PM_{2.5}$ (estimated using EC only) and for sulfate than for nitrate. With just a few exceptions, most estimates for the first two components fell within a factor of two of the CMAQ estimates. However, estimates for nitrate were much more variable, with only SA Direct and EASIUR Direct having estimates within a factor of two of the CMAQ estimates for all scenarios. In general, estimates of nitrate were much higher for the reduced form tools than for CMAQ. This appears to be a significant contributor to the large variances seen for Tier 3.

EXHIBIT ES-4. RATIO OF NATIONAL AVOIDED PREMATURE MORTALITY BENEFITS ESTIMATES COMPARED AGAINST CMAQ ESTIMATES, BY POLICY SCENARIO. ORANGE DOTS REPRESENT RATIOS LESS THAN 1 AND BLUE DOTS RATIOS GREATER THAN 1.



- A drawback of the benefit-per-ton (BPT) based reduced-form tools (SA Direct, EASIUR Direct, and APX Direct) is that because they assign benefits to locations with emissions changes rather than air quality changes, they are not able to provide estimates that could substitute for full-scale modeling at fine spatial scales such as county-level. We conducted an analysis at a regional scale to see if this effect was less pronounced when results are aggregated to larger areas. Our initial analysis of regional estimates is somewhat inconclusive as to which model types might perform better at this scale at matching CMAQ, with varying results by policy and type of statistic. Additional research is warranted to further explore variances at sub-national levels and assess if there are consistent biases in particular locations that may affect these results.

- As far as ease of use, SA Direct and EASIUR Direct had the lowest time requirements and require minimal special skills or software. All APEEP models run directly have a moderate time requirement but require MATLAB expertise and a MATLAB license. InMAP and any model paired with BenMAP-CE would have a higher time requirement than APX Direct, EASIUR Direct, or SA Direct.
- Overall, we believe there continues to be value in evaluating how reduced-form tools compare to full-form air quality model estimates in emission reduction scenarios. Several of the reduced-form tools considered in this analysis produced results that were reasonably comparable to those derived from full-form models and offer a quicker approach to generating ballpark estimates of the health-related benefits or costs associated with an air quality policy. However, none of the reduced-form tools in the form evaluated here should be considered a substitute for a full-form analysis, particularly in situations with large changes in precursor emissions and where a non-linear response is anticipated (e.g., NO_X to $PM_{2.5}$ nitrate).

Chapter 1 | INTRODUCTION

Quantifying and valuing the health impacts of changes in air quality can be a time- and resource-intensive endeavor that often requires large, detailed datasets and sophisticated computer models that predict the formation and transport of air pollutants. The US Environmental Protection Agency (EPA) routinely undertakes these analyses as part of Regulatory Impact Analyses (RIAs) for major air pollution regulations. EPA often employs a traditional "full-form" analysis linking emission inventories, photochemical transport models and a benefits tool. This approach captures the complexities of environmental processes (e.g., atmospheric reactions, chemical processes, diffusion and dispersion of pollutants) and associated health outcomes. In the last decade, both EPA and independent researchers have developed simpler models or "reduced-form tools" to approximate these more complex analyses with a lower computational burden. The primary purpose of this assessment was to 1) learn more about reduced-form approaches, and 2) provide an intercomparison of currently available tools, including discussing how they perform relative to one another as well as to full-form models. It is anticipated that the evaluation framework, and model input and output data, generated as part of this project could be used to test updates to these models and other similar tools. Given these broad objectives, a decision was made to apply each tool as consistently as possible in terms of emissions, meteorology (where possible), and domain structure. This report presents a review and evaluation of several of these publicly available reduced-form tools. Both full-form and reduced-form approaches are in a continual cycle of evaluation and update. It is important to note that the purpose of this comparison was not to make any determinations as to whether any specific reduced-form tools are better-suited for use in regulatory applications than others.

1.1 BACKGROUND AND STUDY MOTIVATION

EPA strives to estimate the health benefits of air pollutant emissions changes using a state-of-the-science full-form photochemical air quality model coupled with its Environmental Benefits Mapping and Analysis Program – Community Edition (BenMAP-CE) health benefits tool. Air quality models such as the Community Multiscale Air Quality (CMAQ[1]) model or the Comprehensive Air Quality Model with Extensions (CAMx[2]) simulate the emission, production, decay, deposition, and transport of gas and particle phase pollutants in the atmosphere to produce air pollutant

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[1] https://www.epa.gov/cmaq

[2] http://www.camx.com

concentration surfaces typically at a spatial resolution of 12km by 12km for national assessments in the US. Surfaces generated for different policy scenarios can then be input into BenMAP-CE to quantify and monetize changes in mortality and morbidity incidence resulting from the modeled changes in air pollution.

However, there are times when EPA has used reduced-form tools. This can occur when time and resources are constrained, such as when rule development timelines are compressed; the air quality policy details required for full-form photochemical modeling are not available until very late in the rulemaking process; or when public health benefits related to changes in air quality are “co-benefits” of the policy rather than benefits from reducing the pollutant targeted by the policy.

EPA has employed reduced-form tools in support of RIAs by calculating the value of reducing one ton of emissions from individual emission sectors. More recently, EPA estimated “benefit-per-ton” (BPT) values using CAMx source apportionment modeling. Several recent national rules, including the Mercury and Air Toxics Standards and the Ozone Cross-State Air Pollution Rule Update, have used BPT values to quantify the health benefits of reducing fine particulate matter concentrations ($PM_{2.5}$) (US EPA, 2011a; US EPA 2011b). However, to date, EPA has not formally explored the ability of the BPT values to estimate reliably the benefits of reducing emissions across all sectors. In addition, the proliferation of other reduced-form tools that quantify air quality benefits over the last several years has produced more choices for EPA and other analysts to consider. The multi-scenario comparison we conducted of various analytical approaches will help EPA to better understand how health benefit estimates from reduced-form tools can differ from their full-form counterparts across an array of policies and spatial scales.

1.2 STUDY OBJECTIVE

The objective of this study is to demonstrate an approach to systematically compare monetized health benefits estimated using full-form air quality models against those generated using reduced-form tools. We compare results across four reduced-form tools, using each to quantify impacts of five air quality policies. These example air quality policies vary in the magnitude and composition of their emissions changes and in the emissions source affected (e.g., mobile, industrial point, or electricity generating units [EGUs]). They also differ in the spatial distribution of emissions and concentration changes and in their impacts on primary particulate matter emissions ($prPM_{2.5}$) and secondary $PM_{2.5}$ precursors (e.g., nitrous oxides and sulfur dioxide). Finally, they differ in complexity, with some representing uniform changes to entire sectors while others represent more realistic cases where the policy results in emissions changes that vary both spatially and temporally.

Specifically, we statistically evaluate the deviation of reduced-form tool estimated benefits from full-form model derived benefits for each of the five policy scenarios. Performance statistics are quantified at the regional scale for total $PM_{2.5}$ and for each major component of $PM_{2.5}$ (i.e., $prPM_{2.5}$ represented by elemental carbon (EC) only, nitrate, and sulfate). The goal of the analysis is to compare differences in model results and note the conditions under which different reduced-form tools perform similarly to the full-form approach. In addition, we provide a sense of the overall complexity of each model formulation, such as whether it involves straightforward mathematics or an understanding of and experience with specific tools and models, and the level of effort required to operate it.

1.3 ORGANIZATION OF THIS DOCUMENT

The remainder of this report is organized into four chapters. Chapter 2 describes our analytical approach to performing the comparative analysis, including descriptions of the reduced-form tools and air quality policies, the methods used to run each of the reduced-form tools, and the statistical comparisons used to quantify model differences. Chapter 3 presents the results of the comparative analysis for each reduced-form tool by policy scenario and $PM_{2.5}$ component. Chapter 4 discusses and compares the relative performance of each reduced-form tool. Finally, Chapter 5 presents broad conclusions as well as limitations of the analysis and suggestions for future research. In addition, there are three Appendices to this document. Appendix A provides additional detail on our approach to generating results for each of the reduced-form tools we evaluated. Appendix B provides a table of states grouped by National Climate Assessment (NCA) region in the continental US. Appendix C provides tables of national benefits estimates for each model as well as the calculated regional statistics.

Chapter 2 | ANALYTICAL APPROACH

This chapter describes the analytical approach we used to compare reduced-form tool results against full-form model results. The goal was to assess how well each reduced-form tool replicated the air quality changes and associated health benefits derived from full-form photochemical models (hereafter referred to as “full form-BenMAP results”) across five different policy scenarios. We evaluated the reduced-form tools across two dimensions:

- A quantitative analysis at the national and regional level to explore the deviation of reduced-form tool results from full-form BenMAP results (this comparison was performed for total benefits as well as the fraction of benefits attributed to each $PM_{2.5}$ component), and
- A qualitative comparison of the computational complexity of each reduced-form tool and level of technical expertise needed to operate it.

The goal of these comparisons was to assess whether there were types of questions that each model may be better suited to answer and the conditions under which it might serve as a possible surrogate for full-form analysis of a policy assessment. Appendix A at the end of this report supplements this chapter and provides more detailed information on how each tool was used in this analysis.

2.1 AIR QUALITY POLICY SCENARIOS

We used a set of five policy scenarios to compare reduced-form tools to full-form BenMAP results across the contiguous US. (Exhibit 2-1). These policy scenarios were chosen as illustrative examples intended to capture an array of spatial and sectoral differences. Importantly, these were examples for which EPA had conducted full-form modeling, so that we had a target against which to compare results from reduced form tools. These policies were projected to impact $PM_{2.5}$ emissions from sources that have varying geographic distributions within the US (and consequently proximity to population centers); as well as variations in the relative magnitudes of $prPM_{2.5}$ and $PM_{2.5}$ precursor species emissions, temporal patterns of emissions, and effective stack heights. These differences enable us to explore model performance across a range of policy characteristics and examine the impact of specific model differences such as the emissions species included in each reduced-form tool.

We focused our analysis on three $PM_{2.5}$ components: $prPM_{2.5}$ derived from EC emissions only, $PM_{2.5}$ sulfate particles derived from SO_2 emissions, and $PM_{2.5}$ nitrate particles derived from NO_X emissions. While there are three main components of $prPM_{2.5}$ (EC, organic carbon and crustal material), the $prPM_{2.5}$ results in this analysis focus on EC for multiple reasons: 1) CAMx was not configured to incorporate the same crustal emissions species as CMAQ for these simulations, and 2) organic aerosol in CAMx and CMAQ includes some components of secondary organic aerosols that are not attributable solely to $prPM_{2.5}$ emissions. Since the major physical processes that impact the various $prPM_{2.5}$ components are the same (i.e. dispersion and deposition), EC was used as surrogate for all $prPM_{2.5}$ emissions. The EASIUR tool also represents all $prPM_{2.5}$ impacts with the EC component. In addition, some of the tools estimate changes in PM2.5 from changes in ammonia (NH_3) and volatile organic compound (VOC) emissions. The tools that predict benefits associated with these precursors are noted in Exhibit 2-9 and scenarios with changes these precursors are shown in Exhibit 2-2. Each policy scenario is described in more detail below.

Because EPA generally evaluates impacts of policies that are targeted to take effect in the future, modeling is generally carried out for both a base year and a future year. The base year is the most recent year with detailed emissions and meteorological inputs available. The future year represents a year in which policy impacts are expected to occur. The future-year modeling captures two scenarios: a baseline scenario using emissions that are projected to occur without any policy in place; and a policy case or control scenario using emission that would occur if the policy in question were implemented. The impact of the policy in the future year is calculated as the difference between the future year policy case air pollution levels and the future year baseline pollution levels.

EXHIBIT 2-1. AIR QUALITY POLICIES ANALYZED

POLICY SCENARIO	POLICY YEARS (BASE/FUTURE)	SOURCE SECTOR
Clean Power Plan (CPP) Proposal	2011/2025	Electricity generating units (EGUs)
Tier 3 Rule	2005/2030	On-road vehicles
Cement Kilns*	2011/2025	Cement kilns
Refineries*	2011/2025	Oil refineries
Pulp and Paper*	2011/2025	Pulp and paper processing
*These policies apply hypothetical across-the-board emissions reductions rather than a detailed policy representation with spatially- and temporally-varying emissions impacts		

EXHIBIT 2-2. AIR QUALITY POLICY EMISSIONS CHANGES BY PRECURSOR (TONS [% OF TOTAL CHANGE])

POLICY SCENARIO	PRIMARY $PM_{2.5}$ A	NO_X	SO_2	NH_3	VOCS
CPP Proposal	2,481 (0.29%)	414,479 (48.59%)	422,670 (49.55%)	3,318 (0.39%)	9,992 (1.17%)
Tier 3 Rule	1,322 (0.25%)	345,333 (64.05%)	13,002 (2.41%)	-	179,531 (33.30%)
Cement Kilns	557 (0.37%)	96,468 (63.29%)	55,398 (36.34%)	-	-
Refineries	424 (0.82%)	34,967 (67.49%)	16,421 (31.69%)	-	-
Pulp and Paper	278 (0.39%)	34,616 (48.51%)	36,464 (51.10%)	-	-

A For all scenarios Primary $PM_{2.5}$ is represented by EC emissions only.

2.1.1 CPP PROPOSAL

The Standards of Performance for Greenhouse Gas Emissions from New, Modified, and Reconstructed Stationary Sources: EGUs, more commonly known as the Clean Power Plan (CPP) was published in the Federal Register in October 2015. It established standards for emissions of carbon dioxide (CO_2) for newly constructed, modified, and reconstructed fossil-fuel-fired EGUs. The CPP proposal included several potential policy options and was published in the Federal Register on June 18, 2014.[3] The final rule went into effect on October 23, 2015.[4] Repeal of the CPP was subsequently proposed by EPA on October 10, 2017. The CPP was eventually replaced with the Affordable Clean Energy (ACE) rule that was signed on July 8, 2019.[5] While the CPP was aimed at reducing emissions of CO_2 specifically, it was expected to also yield significant co-benefits in the form of $PM_{2.5}$ reductions. We specifically analyzed the $PM_{2.5}$ changes associated with proposed CPP Option 1 State (Exhibit 2-3; blue shading represents an emissions decrease and orange an emissions increase) whose emissions were modeled using the Integrated Planning Model (IPM) version 5.13, as described in Chapter 3 of EPA’s regulatory impact analysis document.[6]

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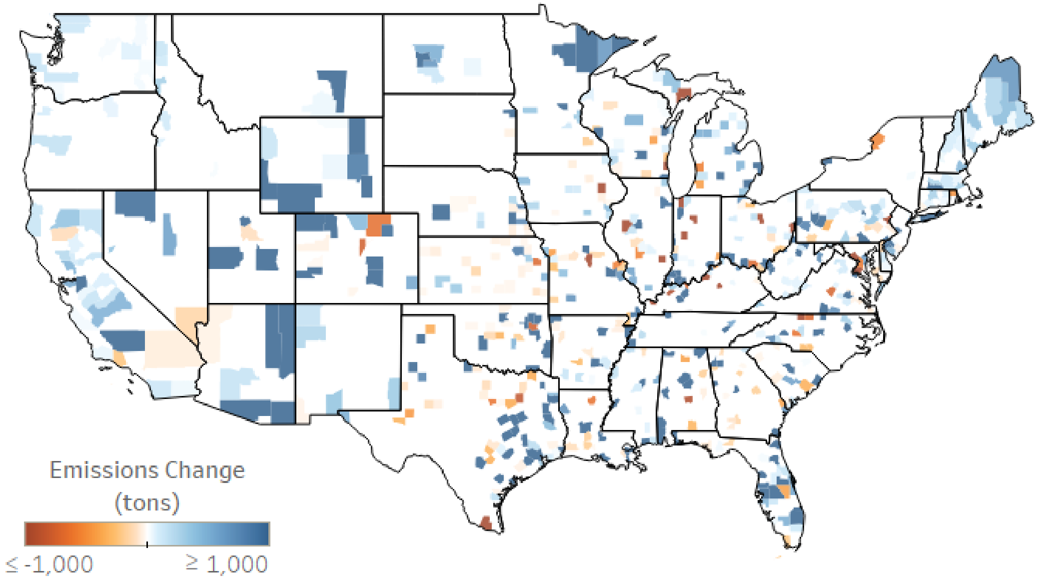
[3] Federal Register, Vol. 79, No. 117, Wednesday, June 18, 2014. https://www.govinfo.gov/content/pkg/FR-2014-06-18/pdf/2014-13726.pdf

[4] Federal Register, Vol. 80, No. 205, Friday, October 23, 2015. https://www.gpo.gov/fdsys/pkg/FR-2015-10-23/pdf/2015-22837.pdf.

[5] Federal Register, Vol. 84, No. 130, Monday, July 8, 2019. https://www.govinfo.gov/content/pkg/FR-2019-07-08/pdf/2019-13507.pdf.

[6] US EPA (2014a). Regulatory Impact Analysis for the Proposed Carbon Pollution Guidelines for Existing Power Plants and Emission Standards for Modified and Reconstructed Power Plants. https://www.epa.gov/sites/production/files/2014-06/documents/20140602ria-clean-power-plan.pdf.

EXHIBIT 2-3. CPP PROPOSAL COUNTY-LEVEL TOTAL EMISSIONS CHANGES



The CPP Proposal scenario targeted non-ground stationary point sources distributed across the US. Relative to other policy scenarios included in this analysis, the CPP Proposal scenario had the largest total emissions change and includes emissions increases as well as reductions. It is also the only scenario to include ammonia (NH_3) emissions changes and one of two scenarios to include changes in emissions of volatile organic compounds (VOCs). Emissions changes occur at locations of large power plants which may either be situated in rural or near highly populated areas. Emissions increases and reductions are distributed across the country.

2.1.2 TIER 3

The Tier 3 Emission and Fuel Standards established more stringent vehicle emission standards and reduced the sulfur content of gasoline. It was published in the Federal Register in April 2014 and took effect beginning in 2017.[7] The action took a holistic approach to addressing the impacts of both motor vehicle technologies and their fuels on air quality and public health. This approach enabled emissions reductions that are both technologically feasible and cost effective beyond what would be possible through addressing vehicle and fuel standards in isolation. The Tier 3 vehicle standards reduced tailpipe and evaporative emissions from passenger and some heavy-duty vehicles, and the lower gasoline sulfur standard reduced sulfur dioxide emissions and made vehicular emissions control systems more effective.

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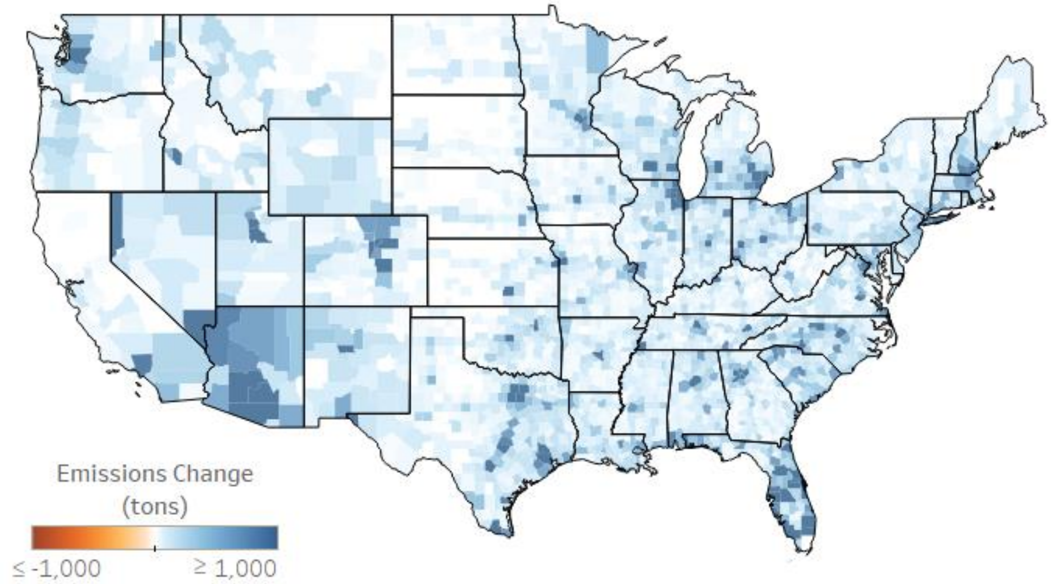
[7] Federal Register, Vol. 79 No. 81, Monday, April 28, 2014 https://www.gpo.gov/fdsys/pkg/FR-2014-04-28/pdf/2014-06954.pdf

EXHIBIT 2-4. TIER 3 COUNTY-LEVEL TOTAL EMISSIONS CHANGES



The Tier 3 scenario targeted on-road mobile sources that are widely distributed across the US (Exhibit 2-4; blue shading represents an emissions decrease and orange an emissions increase).[8] Emissions changes from this scenario were modeled using an internal regulatory version of MOVES (MOtor Vehicle Emissions Simulator).[9] Relative to other policy scenarios included in this analysis, the Tier 3 scenario was dominated by NO_X emissions reductions, and had VOC emissions reductions that account for a third of total emissions reductions. All emissions reductions in California are solely attributed to VOC changes. Most reductions occur in highly populated areas with a lot of vehicle traffic.

2.1.3 CEMENT KILNS

Cement is the binding agent that holds together the ingredients in concrete, a widely used construction material in buildings and roads. Cement is manufactured in kilns, which produce large amounts of carbon dioxide as well as particulate matter, NOx and SO_2. This policy scenario was based on a hypothetical policy that substantially reduces emissions from cement kilns. This does not reflect an actual EPA policy, but rather is meant to reflect how a hypothetical reduction in emissions based on available control technology would affect air quality across the US (Exhibit 2-5). This hypothetical scenario assumed uniform emissions reductions from the 2025 emissions baseline that was developed as part of the analysis for the CPP proposal: 40% reduction in baseline

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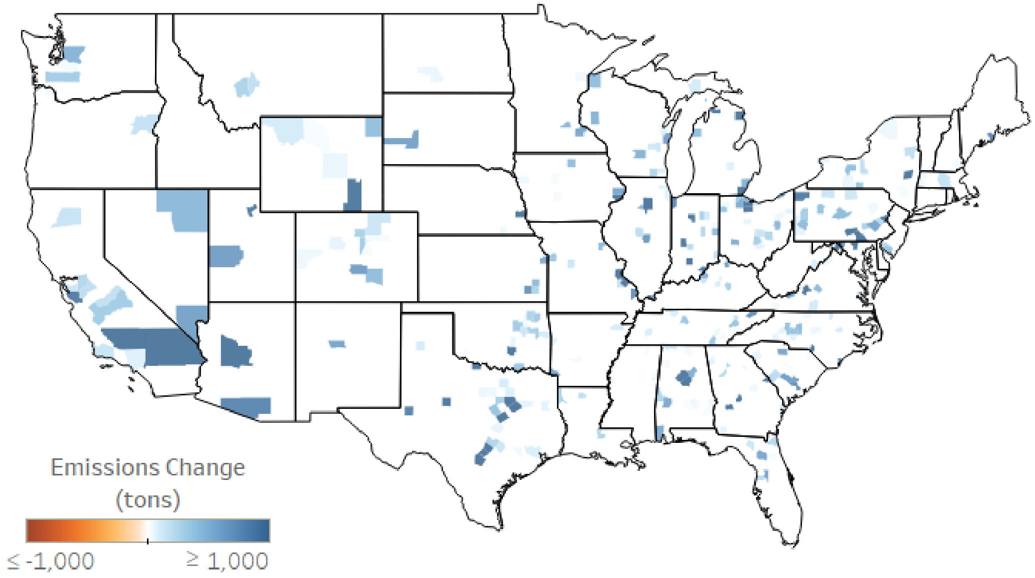
[8] US EPA, (2014b) Emissions Modeling Technical Support Document: Tier 3 Motor Vehicle Emission and Fuel Standards, EPA-454/R-14-003.

[9] US EPA, 2014. MOVES and Nonroad Code and Databases Used to Generate Inventories for Air Quality Modeling and National Inventories for the Tier 3 FRM. (EPA-HQ-OAR-2011-0135).

NO_X emissions, 50% reduction in baseline SO_2 emissions, and 40% reduction in baseline $prPM_{2.5}$ emissions.

Relative to the CPP Proposal and Tier 3 scenarios, the Cement Kilns scenario focused on smaller emissions reductions, primarily of NO_X and SO_2, in diffuse locations across the country. Two thirds of the emissions reductions are attributed to NO_X and one third of the emissions reductions are attributed to SO_2. Emissions reductions are focused in industrialized areas of the continental US, particularly the rust belt region, Texas, and the desert Southwest.

EXHIBIT 2-5. CEMENT KILNS COUNTY-LEVEL EMISSIONS CHANGES

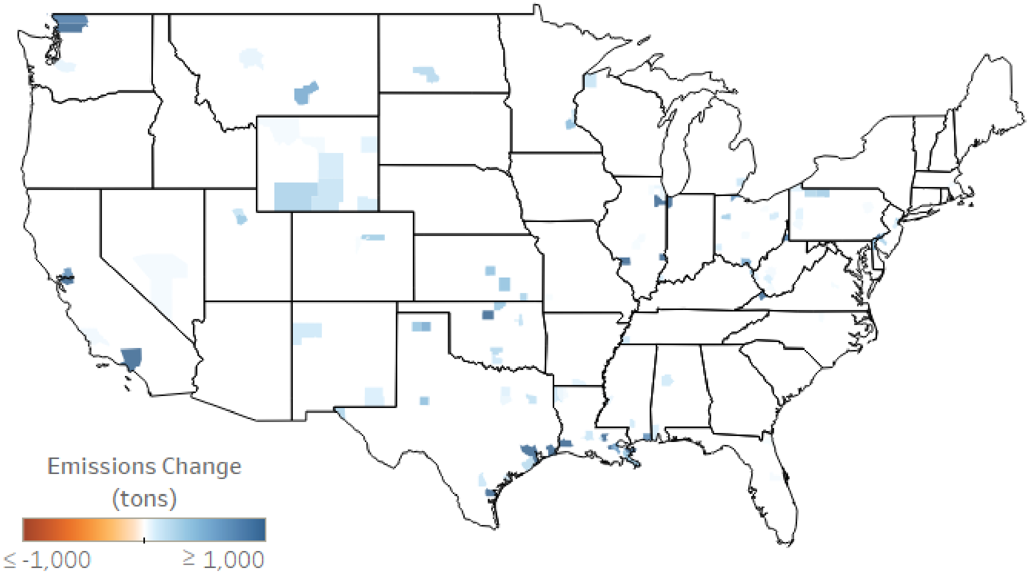


2.1.4 REFINERIES

The petroleum refining industry performs the process of separating crude oil into a range of petroleum products using physical and chemical separation techniques. Petroleum refineries are a major source of air pollutants, including $prPM_{2.5}$, NO_X, carbon monoxide, hydrogen sulfide, and SO_2. This policy scenario was based on a hypothetical policy that substantially reduced emissions from refineries. This does not reflect an actual EPA policy, but rather is meant to reflect how a hypothetical reduction in emissions based on available control technology would affect air quality across the US (Exhibit 2-6). This hypothetical scenario assumed uniform emissions reductions from the 2025 emissions baseline that was developed as part of the analysis for the CPP proposal: 40% reduction in baseline NO_X emissions, 15% reduction in baseline SO_2 emissions, and 15% reduction in baseline $prPM_{2.5}$ emissions.

The Refineries scenario was quite similar to the Cement Kilns scenario, and focused on smaller emissions reductions, primarily of NO_X and SO_2, in diffuse locations across the country. Two thirds of the emissions reductions were attributed NO_X and one third of the emissions reductions were attributed to SO_2. Emissions reductions occur primarily along the Gulf Coast and in low-populated areas of the Midwest.

EXHIBIT 2-6. REFINERIES COUNTY-LEVEL EMISSIONS CHANGES

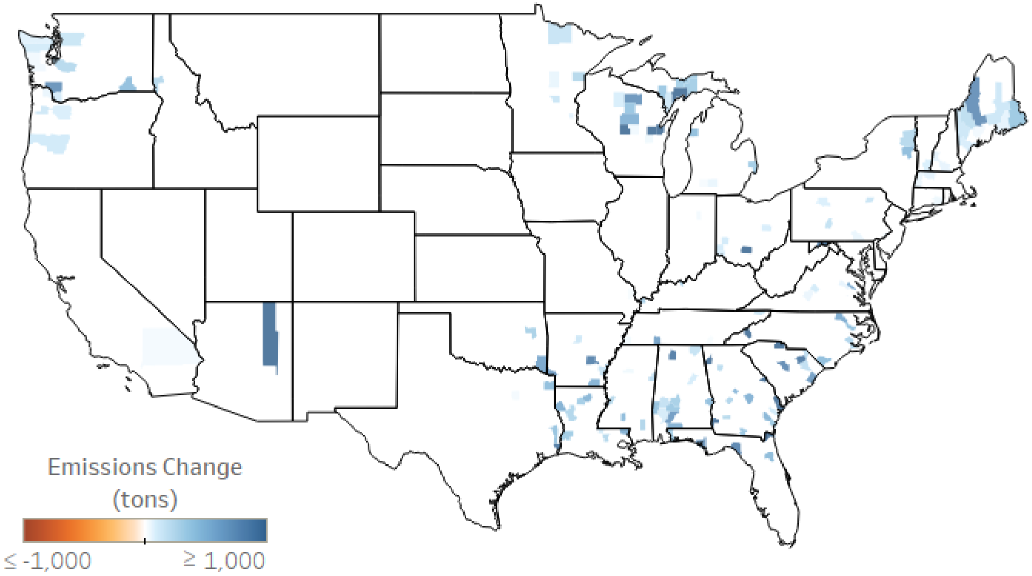


2.1.5 PULP AND PAPER

The Pulp and Paper industry includes companies that process wood into paper and other cellulose-based products. Facilities involved in this process produce emissions of nitrogen dioxide, sulfur dioxide, and carbon dioxide. This analysis examined a hypothetical policy scenario based on available control technology in which $PM_{2.5}$ precursor emissions from Pulp and Paper production facilities were reduced. This does not reflect an actual EPA policy, but rather is meant to reflect how a hypothetical reduction in emissions based on available control technology would affect air quality across the US (Exhibit 2-7). This hypothetical scenario assumed uniform emissions reductions from the 2025 emissions baseline that was developed as part of the analysis for the CPP proposal: 20% reduction in baseline NO_X emissions, 35% reduction in baseline SO_2 emissions, and 25% reduction in baseline $prPM_{2.5}$ emissions.

The Pulp and Paper scenario was also similar to the other industrial point source scenarios, and focused on smaller emissions reductions, primarily of NO_X and SO_2, in diffuse locations across the country. However, for this scenario, the reductions of NO_X and SO_2 each account for about half of the total emissions reductions. Emissions reductions are concentrated in forested areas of the continental US, including the Southeast, northern Midwest, Pacific Northwest, and rural Maine.

EXHIBIT 2-7. PULP AND PAPER COUNTY-LEVEL EMISSIONS CHANGES



2.2 FULL-FORM MODELS

For each of the policy scenarios outlined above, we compared reduced-form tool results to full-form BenMAP results calculated by running the future-year baseline and policy emissions scenarios through a full-form chemical transport model and then running the full-form model-generated $PM_{2.5}$ air quality surfaces through BenMAP-CE. We evaluated both CMAQ- and CAMx-based results for each scenario, except for Tier 3, for which only the CMAQ output was available. CAMx modeling was not available for Tier 3 because the chemical speciation used for that scenario do not conform to input requirements for the currently available version of CAMx.

We used the CMAQ BenMAP results as the primary point of comparison for each of the reduced-form tools. However, while full-form models represent the current state-of-the-science, they are themselves representations of actual processes and the results of different full-form models can vary to some degree. For example, they can differ with respect to how they treat secondary $PM_{2.5}$ formation. Therefore, we also compared the CMAQ BenMAP results to CAMx BenMAP results in order to assess the congruence between these two models and better understand the potential limitations of our analysis. Both full-form models produced air quality estimates at a 12 km resolution.

2.3 REDUCED-FORM TOOLS

We conducted an extensive literature review to identify reduced-form approaches for predicting policy-related air quality changes and associated benefits.[10] Based on this review, we selected four reduced-form tools for this analysis. All four tools are both publicly available and published in the peer-reviewed scientific literature (Exhibit 2-8).[11] They also comprise a range of complexity, geographic scope, and usability.

EXHIBIT 2-8. REDUCED-FORM TOOLS

REDUCED-FORM TOOL	SAMPLE REFERNCE(S)
Source Apportionment (SA) BPT	Fann, Baker, & Fulcher, 2012; Fann, Fulcher, & Baker, 2013; United States Environmental Protection Agency, 2013
Air Pollution Emission Experiment and Policy Analysis Model (APX)	Muller & Mendelsohn, 2006
Intervention Model for Air Pollution (InMAP)	Tessum, Hill, et al., 2017
Estimating Air Pollution Social Impacts Using Regression (EASIUR)	Heo et al., 2016

We followed two guiding principles when applying these tools in this analysis:

1. Key model inputs should be standardized across reduced-form tools to the extent allowable to ensure that results are as comparable as possible.
2. The underlying model architecture should not be substantially altered so that the results still reflect the unique properties of each reduced-form tool.

Adjustments made to accommodate the first principle typically involved relatively straightforward input changes to each model. For example, because not all models can produce morbidity benefits, we estimated benefits for mortality impacts only. In addition, we standardized the concentration response function and value of statistical life (VSL) applied in each tool or model. The second principle dictated that some differences be preserved in order to avoid substantively changing the model design. For example, the reduced-form tools differed in the $PM_{2.5}$ precursors they modeled (Exhibit 2-9). We did not attempt to standardize that component across models. Additional detail on the models are provided below, as well as specific adjustments made to each model and/or its inputs.

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[10] Bankert J, Amend M, Penn S, Roman H, personal communication memorandum, November 17, 2017.

[11] The AP3 model is not yet publicly available but can be obtained by contacting the developer - Nicholas Muller at Carnegie Mellon University. When available, it will be posted at: https://public.tepper.cmu.edu/nmuller/APModel.aspx.

EXHIBIT 2-9. INPUT AND OUTPUT SPECIES AND GEOGRAPHIC RESOLUTION FOR EACH REDUCED-FORM TOOL

TOOL		INPUTS	GEOGRAPHIC RESOLUTION OF INPUTS AND OUTPUTS	OUTPUTS
SA Direct		prPM$_{2.5}$, SO$_2$, and NO$_x$ emissions	National	prPM$_{2.5}$, NO$_3$, SO$_4$, and Total PM$_{2.5}$ benefits (ultimately applied to emissions deltas)
AP3	Direct	prPM$_{2.5}$, SO$_2$, NO$_x$, NH$_3$, and VOC emissions	US counties	prPM$_{2.5}$, SO$_2$, NO$_x$, NH$_3$, and VOC BPT estimates (ultimately applied to emissions deltas)
	BenMAP	prPM$_{2.5}$, NO$_3$, NH$_4$, SO$_4$, SOA, and Total PM$_{2.5}$ concentrations	US counties	prPM$_{2.5}$, NO$_3$, NH$_4$, SO$_4$, SOA, and Total PM$_{2.5}$ benefits
AP2	Direct	prPM$_{2.5}$, SO$_2$, NO$_x$, NH$_3$, and VOC emissions	US counties	prPM$_{2.5}$, SO$_2$, NO$_x$, NH$_3$, and VOC BPT estimates (ultimately applied to emissions deltas)
	BenMAP	prPM$_{2.5}$, NO$_3$, NH$_4$, SO$_4$, SOA, and Total PM$_{2.5}$ concentrations	US counties	prPM$_{2.5}$, NO$_3$, NH$_4$, SO$_4$, SOA, and Total PM$_{2.5}$ benefits
InMAP BenMAP		prPM$_{2.5}$, SO$_2$, NO$_x$, NH$_3$, and VOC emissions	12 km x 12 km grid	prPM$_{2.5}$, NO$_3$, NH$_4$, SO$_4$, SOA, and Total PM$_{2.5}$ benefits
EASIUR Direct		prPM$_{2.5}$, SO$_2$, NO$_x$, and NH$_3$ emissions	36 km x 36 km grid	prPM$_{2.5}$, NO$_3$, NH$_4$, SO$_4$, and Total PM$_{2.5}$ benefits
Note: all models were adjusted to use an underlying all-cause mortality concentration-response function for ages 30-99 derived from Krewski et al., 2009. In addition, all benefits were quantified using a VSL of $8.7M in ($2015) derived from a distribution based on 26 value-of-life studies.				

2.3.1 SA DIRECT

The SA Direct BPTs report the economic value of reducing a ton of directly emitted PM$_{2.5}$ or PM$_{2.5}$ precursor from a given class of area, industrial and mobile sectors. The BPT estimates were originally derived from full-form BenMAP results for sector-specific air quality scenarios that were divided by the total emissions changes underlying the air quality surfaces. EPA has historically calculated BPT estimates across various source sectors to understand different proposed air quality policies.

When using a BPT, one assumes that the key attributes of the policy scenario match the “source” modeling and assumptions (e.g., the policy scenario and source modeling share the same emissions profile, affected population, etc.) (Fann et al., 2012). The SA BPT values used in this analysis are publicly available.[12] There is one set of BPT values for each sector that are applicable to emissions changes within the contiguous US. Specifically, the SA BPT estimates were calculated using CAMx version 5.30 with Particulate Matter Source Apportionment Technology (PSAT) to trace $PM_{2.5}$ precursor emissions, including directly-emitted $prPM_{2.5}$, SO_2, NO_X, and volatile organic compounds (VOCs), from individual source sectors in the continental US.

The Fann et al. (2012) BPT reflect emissions levels and facility operation from the 2005 National Emission Inventory. Air quality impacts were estimated using 2005 meteorology input to the CAMx model. The BPT values reflect any deficiencies in the characterization of sources in different sectors as part of the 2005 NEI and may not reflect the more contemporary state of these sectors. It is important that the SA BPT be updated periodically so that estimated results reflect a current realization of facility emissions and locations.

For this analysis, the original Fann et al. (2012) SA BPT values were updated in December 2017. The Fann et al. (2012) BPT values were used with a newer version of BenMAP-CE v. 1.3.7.1, which included updated population, baseline incidence rates, and income growth, in currency year 2015.[13]

SA BPT values described above reflect per-ton benefits related to changes in mortality and morbidity incidence for $prPM_{2.5}$, NO_X, and SO_2. We applied adjustment factors to the SA BPT values so that they accounted for mortality benefits only. We multiplied these mortality-only SA BPT values by the NO_X, SO_2, and $PM_{2.5}$ emissions changes associated with each policy scenario to produce national-level results for each scenario. BPT estimates were available for the following source sectors to match our five policy scenarios:

- Electricity generating units (used to estimate the benefits of the CPP Proposal),
- On-road vehicles (used to estimate the benefits of Tier 3),
- Cement kilns (used to estimate the benefits of the Cement Kilns sector-specific policy),
- Refineries (used to estimate the benefits of the Refineries sector-specific policy), and
- Pulp and paper facilities (used to estimate the benefits of the Pulp and Paper sector-specific policy).

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[12] US EPA. Technical Support Document: Estimating the benefit per ton of reducing $PM_{2.5}$ precursors from 17 sectors. Retrieved from: https://www.epa.gov/sites/production/files/2018-02/documents/sourceapportionmentbpttsd_2018.pdf

[13] After the December 2017 update of the SA BPT values, IEc discovered an error in baseline mortality rates in the BenMAP-CE version used for the update of these values. This error may result in the overestimation of benefits by less than three percent for aggregate benefits values. This difference is unlikely to alter the relative comparison of SA BPT values to full-form modeling or to other reduced-form tools.

Additional information on the calculation of SA Direct results, including the mortality-only adjustment factors, is included in Appendix A. Relative to other BPT reduced-form tools included in this analysis, the SA BPT values we applied were available for a smaller number of $PM_{2.5}$ precursors and do not contain different values for different emission heights.

2.3.2 APX

AP2 and AP3 (elsewhere referred to jointly as APX) are more recent updates of the Air Pollution Emission Experiments and Policy Analysis (APEEP) model.[14] These models are comprised of several scripts that run in the MathWorks program MATLAB and calculate marginal damage-per-ton values, or the social cost of increasing emissions above baseline by one ton. These values can alternatively be viewed as the benefits of avoiding or reducing one ton of emissions and are therefore similar to other BPT estimates. AP2 and AP3 estimate the marginal cost of emissions by quantifying the total health burden and monetized costs associated with a baseline emissions scenario, systematically increasing the baseline emissions by one ton, recalculating the total health burden and monetized costs, and taking the difference between the two estimates. BPT values are generated for five $PM_{2.5}$ precursors ($prPM_{2.5}$, SO_2, NO_X, NH_3, and VOCs), each county in the contiguous US, and four different stack heights (ground sources, low stacks, medium stacks, and tall stacks).

The APX models can estimate damages from both health-related and non-health-related (e.g., materials damage) impacts associated with changes in emissions and associated changes in air quality. They can also be tailored to estimate costs associated with different combinations of specific impacts under each of those broad categories. For this analysis, we configured the models to quantify only the damages associated with all-cause mortality for ages 30-99 as estimated by the Krewski et al., 2009 concentration-response function. The model VSL estimates were also updated to use a value consistent with the other reduced-form tools we evaluated. Using an approach detailed in the BenMAP-CE user manual (US EPA, 2018), we adjusted the base VSL to account both for inflation and future growth in personal income.

We compared two types of APX results to full-form model results: one generated by applying the APX BPT values to changes in emissions (AP3 Direct and AP2 Direct), and one generated by running the APX-generated air quality surfaces through BenMAP-CE (AP3 BenMAP and AP2 BenMAP). We calculated APX Direct values by multiplying the precursor- and county-specific BPT values for each stack height by the corresponding change in emissions in each county for each policy. For example, if the SO_2 low stack height emissions for county 1001 decreased by five tons, the associated benefits were calculated as five times the SO_2 low stack height APX BPT value for that county. This

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[14] Muller, Nicholas. AP3 (AP2, APEEP) Model. Retrieved from: https://public.tepper.cmu.edu/nmuller/APModel.aspx. Note, currently only the AP2 model is available on this site.

resulted in policy-specific benefits attributed at the county-level based on the change in emissions in that county.

It's also possible to export the underlying county-level air quality surfaces from APX by slightly modifying the model source code. Although this is not a feature of the standard model, this change enabled us to test the reduced-form air quality model element of the APX tools separately from the benefits assessment module. We extracted baseline and control policy scenario air quality surfaces from AP3 and AP2 runs and fed into BenMAP-CE to assess the avoided mortality benefits associated with the change in air quality between the baseline and control scenarios. We refer to these results as "AP3 BenMAP" and "AP2 BenMAP" results, because they represent a hybrid of APX air quality modeling with BenMAP health benefits modeling.

We analyzed both AP2 and AP3 because these two versions of the model use different approaches to quantify the marginal costs of NO_X emissions relative to the baseline. APX is distributed so that users can obtain estimates of benefits to the counties where the *emissions* changes occur whereas the full-form and other BenMAP results link benefits to the counties where *air quality* changes occur. APX was modified to also output where air quality changes occur, and those air quality surfaces were input to BenMAP for more direct comparison to the modeling systems that estimate health impacts where they occur (e.g., InMAP) rather than the county in which the emissions change occurs (e.g., EASIUR). The APX Direct results were included in this analysis because some users may not have the technical expertise to modify the standard APX models to extract the air quality surfaces as well as to understand the magnitude of these potential effects.

Additional detail on the calculation of APX results as well as how the AP2 and AP3 models were modified for this analysis is provided in Appendix A. Relative to other BPT reduced-form tools included in this analysis, the APX Direct model utilizes policy-specific BPT estimates for a larger number of $PM_{2.5}$ precursors as well as different emissions stack heights.

2.3.3 INMAP

The InMAP model estimates the annual average primary and secondary $PM_{2.5}$ related to changes in emissions. The modeling system can provide marginal health damages based on source-receptor relationships calculated by the WRF-Chem full-form chemical transport model using 2005 emissions and meteorology.[15] For consistency in comparison with CMAQ and CAMx we applied InMAP version 1.4.1 with emissions and meteorology consistent with each emissions scenario. The Tier 3 simulation used 2007 emissions and meteorology/chemistry/deposition and the other scenarios used 2011 emissions and meteorology/chemistry/deposition.

Inputs to the model include precursor emissions (i.e., NH_3, SO_2, $prPM_{2.5}$ [not speciated], NO_X, and VOCs) as well as 3D annual average meteorology, air quality, and deposition

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[15] InMAP Intervention Model for Air Pollution. Retrieved from: http://spatialmodel.com/inmap/

information. Emission inputs include annual gridded surface emissions and point sources that include stack parameter information (e.g., stack height). Inputs are fed into the model as shapefiles and therefore InMAP can be applied with a range of geographic resolutions. For this analysis, we applied the same 12 km grid used by the full-form models to ensure maximum compatibility. Gridded model predictions were later aggregated for comparison to the other tools.

The InMAP model generates air quality surfaces related to the emissions input to the modeling system. The tool passes through population and health incidence data that can be used to estimate health impacts post-model simulation. For this analysis, the air quality surfaces from the model were used as input to BenMAP-CE to ensure consistency across tools for the health impact analysis.

Relative to other air quality reduced-form tools, InMAP required the most computational time to complete each simulation. Additionally, generating new source-receptor relationships to reflect the 2007 and 2011 meteorology and air quality required the application of a prognostic meteorological and photochemical model.

2.3.4 EASIUR DIRECT

EASIUR is a web-based model that calculates the monetized health impacts of emissions changes in the contiguous US.[16] The model consists of multiple sets of BPT estimates that can be applied to annual or seasonal emissions changes for EC, SO_2, NO_X, and NH_3 (20 sets = 4 species x 5 seasons). The elemental carbon BPT was the only $prPM_{2.5}$ BPT provided as part of the tool and was used to estimate benefits associated with any $prPM_{2.5}$ emission species for this analysis. BPT estimates are available at both the 36 km resolution and the county-level resolution. Benefits were estimated with EASIUR version 0.2 at the 36 km resolution and then interpolated to county-level. As with the APX BPT values, the EASIUR BPT values are attributed to the counties with emissions changes rather than the counties in which the mortality effects accrue.

EASIUR's BPT estimates were based on a statistical regression analysis of tagged simulations of 2005 National Emissions Inventory (NEI) emissions run through CAMx with PSAT. Because EASIUR consists of BPT values this reduced-form tool is most comparable to the SA Direct and APX Direct results.[17]

While the EASIUR BPT values were developed using a slightly different VSL and concentration-response function, the authors provide equations that can be used to adjust the standard BPT values to reflect concentration-response and VSL inputs consistent with the other models. For this analysis, we adjusted the standard EASIUR BPT values to

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[16] EASIUR: Marginal social costs of emissions in the United States. Retrieved from: https://barney.ce.cmu.edu/~jinhyok/easiur/. We used version 0.2 for this analysis.

[17] A separate reduced-form tool – Air Pollution Social Cost Accounting (APSCA; https://barney.ce.cmu.edu/~jinhyok/apsca/), was released after this study began that estimates air quality related to changes in emissions, but was not used as part of this analysis.

reflect the Krewski et al., 2009 all-cause mortality function for ages 30-99 and the $8.7M VSL estimate.

EPA developed a simple tool to match the BPT for each precursor and grid cell in the 36 km domain with the emissions change in each grid cell of that domain. This was done to efficiently estimate benefits for these complex emissions scenarios that impacted many different grid cells.

Additional detail on the calculation of EASIUR Direct results as well as how to apply the BPT values can be found in Appendix A of this document as well as EASIUR's online User's Guide, respectively.[18]

2.4 APPROACH TO BENMAP-CE DERIVED RESULTS

The SA Direct, APX Direct, and EASIUR Direct results all directly quantify the benefits of each air quality policy scenario and can be normalized per ton of emissions. Results for the full-form models as well as the APX BenMAP and InMAP BenMAP reduced-form tools were generated by using the tools/models to create air quality surfaces that were then run through BenMAP-CE. This section provides additional detail on the BenMAP analyses.

BenMAP-CE version 1.5.0.4 was used for all analyses. We ran the baseline and control $PM_{2.5}$ air quality surfaces from each model and scenario through the program to generate the total avoided-mortality-related benefits estimated by each model. To run an analysis in BenMAP-CE the user must select a population dataset, baseline incidence dataset, concentration-response function, and valuation function. For each model run, we relied on datasets from the United States Setup that is pre-loaded in BenMAP-CE (Exhibit 2-10). We ran each BenMAP-CE analysis at the resolution matching each model's air quality surface resolution (i.e., 12 km for the full-form models and InMAP and county-level for APX).

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[18] https://barney.ce.cmu.edu/~jinhyok/easiur/EASIUR-Users-Guide-200505-Jinhyok.pdf

EXHIBIT 2-10. BENMAP-CE PARAMETERS BY POLICY

BENMAP-CE INPUT	2025 POLICIES: CPP PROPOSAL, CEMENT KILNS, REFINERIES, PULP AND PAPER	2030 POLICY: TIER 3
Population[A]	County-level US Census population estimate for 2025	County-level US Census population estimate for 2030
Health Incidence[A]	County-level death rates projected to 2025	County-level death rates projected to 2030
Concentration-Response Relationship[B]	All-cause mortality, ages 30-99 (Krewski et al., 2009)	All-cause mortality, ages 30-99 (Krewski et al., 2009)
Valuation[B]	VSL based on 26 value-of-life studies with an inflation adjustment to $2015 and an income growth adjustment to 2025. A 3% discount rate and a 20-year cessation lag was applied to all estimated benefits.	VSL based on 26 value-of-life studies with an inflation adjustment to $2015 and an income growth adjustment to 2026 (the latest value provided in BenMAP-CE). A 3% discount rate and a 20-year cessation lag was applied to all estimated benefits.

[A] These population and incidence datasets are also reflected in the SA Direct and APX Direct BPT values. The only model that does not reflect these inputs is the EASIUR Direct reduced-form tool.

[B] This is the same concentration-response function and VSL estimate used for all reduced-form tools.

We derived precursor-specific benefits by apportioning the total benefits for each scenario to each $PM_{2.5}$ component based on its fractional contribution to the change in overall $PM_{2.5}$ concentrations. For example, if the change in sulfate concentrations accounted for 70% of the change in total $PM_{2.5}$ concentrations, then 70% of the total benefits would be attributed to sulfate. We summarized total benefits and all component-specific benefits output at the county-level initially and aggregated as necessary for comparison to other tools.

2.5 MODEL COMPARISONS

We generated county-level results for each full-form model and reduced-form tool and expressed these in terms of monetized benefits of avoided premature mortality ($2015). Results were compared at the national- and regional-level for $prPM_{2.5}$ (defined as the results attributed to changes in EC emissions only), NO_3 (results attributed to changes in NO_X emissions), SO_4 (results attributed to changes in SO_2 emissions), and $PM_{2.5}$ (results attributed to EC, NO_X, and SO_2 emissions as well as NH_3 and VOC emissions, where applicable).

For comparisons of $PM_{2.5}$ at the national level, we use $prPM_{2.5}$ benefits that have been scaled up to better represent the fraction of $PM_{2.5}$ benefits that would be attributed to total

$prPM_{2.5}$ emissions (EC, crustal and prOC). We scaled the results by multiplying the $prPM_{2.5}$ benefit-per-ton based on EC only by the total amount of primary $PM_{2.5}$ emissions to generate an estimate of impacts for total primary $PM_{2.5}$ emissions. Model comparison at the national-level is limited to an overall comparison of total estimated benefits and ratios of total reduced-form tool benefits to CMAQ-derived benefits.

At the regional-level, we compared full- and reduced-form tool results using a subset of the statistical metrics defined in Exhibit 2-11, which have been published previously in the peer-reviewed literature (Boylan and Russel, 2006 and Simon et al., 2012). Most studies that have employed these metrics have used them to compare observed pollutant concentrations (O_i) to modeled results from full-form air quality models (M_i), such as CMAQ or CAMx. However, for this analysis, CMAQ BenMAP results took the place of observed pollutant concentrations and are compared to the results of the reduced-form tools. In this context, the relative performance of reduced-form tools compares more closely to the full-form model when bias and error metrics approached zero and when the coefficient of determination approached one.

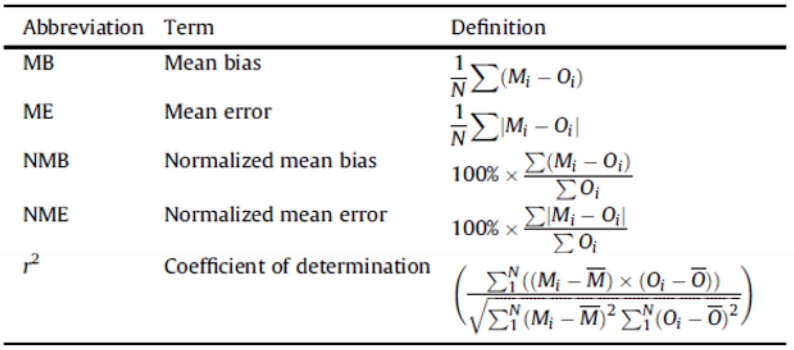
We focused on the following statistics for this analysis:

- Total estimated benefits
- Mean bias (MB)
- Mean error (ME)
- Normalized mean bias (NMB)
- Normalized mean error (NME)
- Coefficient of determination (r^2)

This set of statistics is both widely reported in the literature and is consistent with the recommendations provided in Simon et al. (2012). It was necessary to examine several metrics to comprehensively characterize performance of reduced-form tools because the results of different statistics are not always correlated. For example, not all models with low bias estimates have high coefficient of determination (r^2) estimates. Including multiple metrics provided a fuller picture of model differences.

Where this document uses certain bounds to differentiate metrics closer to the predictions made by photochemical grid models (e.g., factor of two), this document does not intend that differentiation to be a threshold indicating “good” or “bad” performance or an indicator of model acceptability for particular assessments.

EXHIBIT 2-11. DEFINITIONS OF PERFORMANCE METRICS (TABLE 2 OF SIMON ET AL., 2012)



Abbreviation	Term	Definition
MB	Mean bias	$\frac{1}{N}\sum(M_i - O_i)$
ME	Mean error	$\frac{1}{N}\sum\lvert M_i - O_i\rvert$
NMB	Normalized mean bias	$100\% \times \frac{\sum(M_i - O_i)}{\sum O_i}$
NME	Normalized mean error	$100\% \times \frac{\sum\lvert M_i - O_i\rvert}{\sum O_i}$
r^2	Coefficient of determination	$\left(\frac{\sum_1^N((M_i - \overline{M}) \times (O_i - \overline{O}))}{\sqrt{\sum_1^N(M_i - \overline{M})^2 \sum_1^N(O_i - \overline{O})^2}}\right)$

We compared model results at the region-level, where regional results are simply the sum of county results within each of seven NCA areas.[19] As noted above, BPT estimates allocate benefits to the counties where emissions changes occur rather than the counties where air quality changes occur. By aggregating the results to the regional scale, we minimized the distinction between emissions locations and receptor locations caused by emissions transport.

In addition to these quantitative metrics, we also qualitatively compared the strengths and weaknesses of each reduced-form tool as well as the amount of time and level of expertise required to run it.

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[19] https://www.epa.gov/cira. A table identifying which states are included in each NCA region is provided in Appendix B.

Chapter 3 | RESULTS

This chapter presents the results of the comparison between reduced-form tool mortality and valuation estimates and full-form model mortality and valuation estimates. First, for each policy scenario, we compare the total national-level $PM_{2.5}$ benefits calculated by each reduced-form tool against the full-form benefits calculated using the combination of CMAQ and BenMAP-CE. We also examine these results by $PM_{2.5}$ component. We then present region-level results for a subset of the statistics considered in this analysis, focusing on r^2 values, normalized mean bias (NMB) and normalized mean error (NME) results for total $PM_{2.5}$ benefits. Finally, we present a qualitative comparison of the level of effort needed to operate each reduced-form tool based on our experience conducting this analysis.

In discussing these results, we focus on distinctions that can be identified across four primary axes:

1. Ability to predict benefits from $PM_{2.5}$ concentrations from all constituent species/precursors versus individual component species/precursors.;
2. How model type affects model performance – highlighting similarities and differences between BPT reduced-form tools (i.e., SA Direct, EASIUR Direct, and APX Direct) and air quality model based reduced-form tool projected concentration changes coupled with BenMAP (i.e., APX BenMAP and InMAP BenMAP);
3. How geographic scale affects model comparisons – national versus region; and
4. How scenario type affects model comparisons.

A table of national-level results for each reduced-form tool as well as all regional statistics are provided in Appendix C.

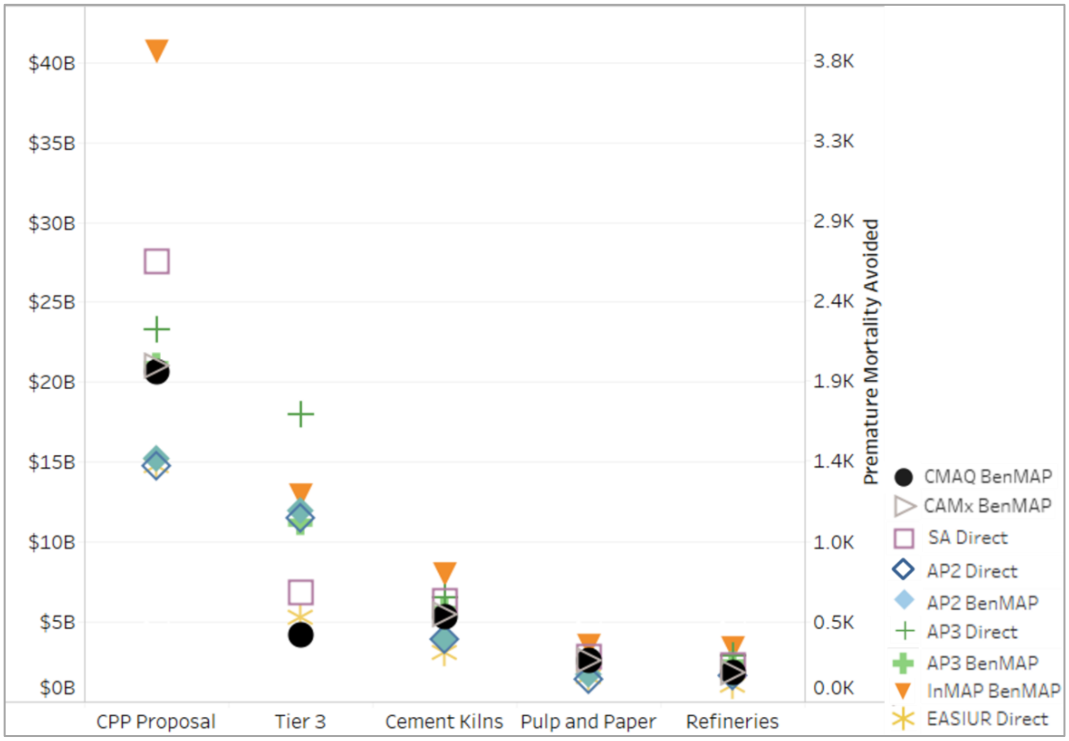
3.1 COMPARISON OF REDUCED-FORM TOOLS AT THE NATIONAL-LEVEL

3.1.1 TOTAL BENEFITS

The policies considered in this analysis produce a wide range of benefits estimates, reflecting both the range in emissions control scenarios underlying each policy and the number and location of affected facilities. The benefits estimated for the CPP Proposal were by far the largest among the policies we considered, followed by Tier 3 and the industrial point source scenarios. Nationally aggregated monetized benefits were compared between full-form and reduced-form tools. Predictions of total $PM_{2.5}$ benefits vary substantially across the policies considered (Exhibit 3-1). For example, there is not a consistent pattern in the reduced-form tool results across policy scenarios (i.e., the relative size of the benefits estimated among the tools was not consistent across the scenarios).

However, some overall patterns are clear. Some reduced-form tools tend to consistently underestimate CMAQ benefits, while others tend to overestimate. In addition, almost all reduced-form tools fail to reproduce the CMAQ $PM_{2.5}$-related benefits estimated for Tier 3.

EXHIBIT 3-1. NATIONAL AVOIDED PREMATURE MORTALITY BENEFITS FROM $PM_{2.5}$ REDUCTIONS, AS ESTIMATED BY REDUCED- AND FULL-FORM TOOLS FOR EACH POLICY SCENARIO (BILLIONS OF 2015$)



Presenting the same results as ratios of CMAQ benefits allows for a clearer depiction of similarities and differences in performance across reduced-form tools (Exhibit 3-2). First, there is significant agreement between the two full-form model-derived benefits. All CAMx-based estimates are within 5% of the CMAQ estimates.[20] In addition, the overall predictions made by these reduced-form tools were often fairly similar, with a few exceptions.

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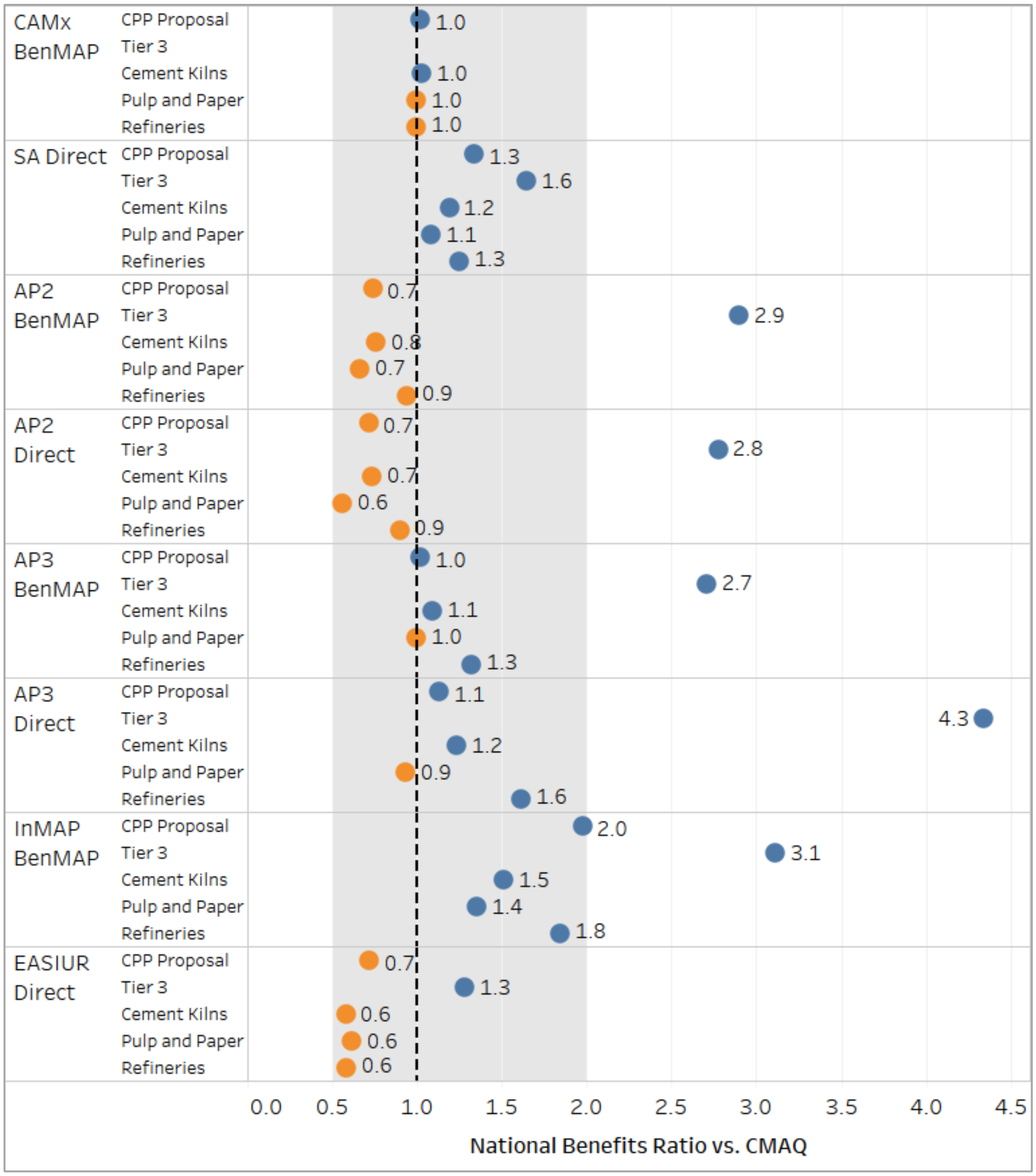
[20] Note that there are no CAMx full-form model results for the Tier 3 policy scenario.

EXHIBIT 3-2. RATIO OF NATIONAL AVOIDED PREMATURE MORTALITY BENEFITS ESTIMATES COMPARED AGAINST CMAQ ESTIMATES, BY TOOL AND POLICY SCENARIO. ORANGE DOTS REPRESENT RATIOS LESS THAN 1 AND BLUE DOTS RATIOS GREATER THAN 1.



First, InMAP BenMAP benefits tend to be further from CMAQ benefits, relative to other reduced-form tools. InMAP BenMAP results were between 40-310% higher than the CMAQ BenMAP benefits. In addition, AP3 Direct's performance varied across policies the most with relative bias of the full-form benefits ranging from -10% (Pulp and Paper) to 430% (Tier 3). EASIUR Direct was the most consistent in its performance across policies, underestimating by 30-40% for all scenarios except Tier 3. All other reduced-form tools produced benefits that were typically within 10-40% of CMAQ benefits (excluding estimates for Tier 3).

Exhibit 3-2 also demonstrates that most of the reduced-form tools tended to consistently over- or underestimate the CMAQ-derived benefits. AP2 BenMAP, AP2 Direct, and EASIUR Direct all underestimate CMAQ benefits except for Tier 3, while SA Direct, AP3 BenMAP, AP3 Direct, and InMAP BenMAP all overestimate CMAQ results to varying degrees. There is no apparent consistent difference between the performance of BPT reduced-form tools and the reduced-form air quality tools coupled with BenMAP, i.e., one type of model does not tend to over- or underestimate CMAQ benefits.

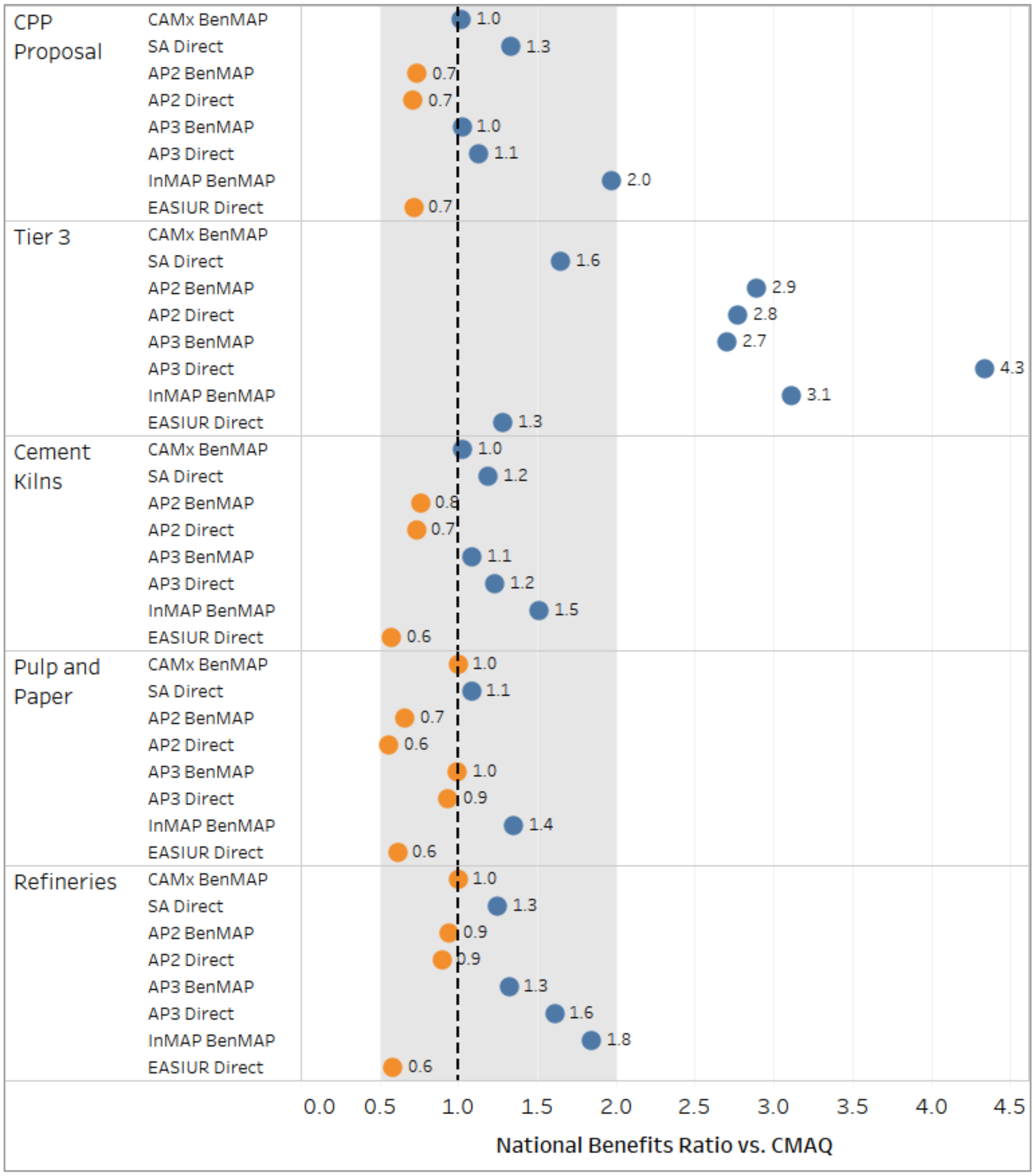
The APX models perform more similarly based on the version of the model (AP2 versus AP3) rather than the approach used to generate the benefits estimates (Direct versus BenMAP). The AP2 results across all policy scenarios are remarkably similar. Likewise, the AP3 results across policy scenarios show a consistent pattern, although the AP3 Direct results tend to overestimate CMAQ benefits by a larger amount.

Of all the models, AP3 BenMAP and AP3 Direct estimates of health benefits are within 10% of CMAQ benefits estimates for more scenarios (3: CPP Proposal, Cement Kilns, and Pulp and Paper) than any of the other reduced form tools. SA Direct, AP2 BenMAP and AP2 Direct each perform within 10% of CMAQ estimates for a single scenario.

Showing the same comparison by policy scenario makes it easier to compare how reduced-form tools performed for specific types of policies. Exhibit 3-3 highlights how each reduced-form tool poorly replicated CMAQ-based estimates for the Tier 3 policy. The SA Direct and EASIUR Direct reduced-form tools perform best with this scenario, but even those models overestimate CMAQ benefits by 60% and 30%, respectively.

In general, the point source scenarios with non-ground-level emissions showed much better agreement with CMAQ-based estimates across reduced-form tools. The two policies that resulted in the best alignment between CMAQ results and reduced-form tool results were the CPP Proposal and Pulp and Paper scenarios. For the CPP Proposal scenario, the reduced-form tools produced benefits within 10-30% of CMAQ (except for InMAP BenMAP, which overestimates by 200%). This is particularly interesting given that the CPP Proposal has the largest emissions change of any policy scenario considered, and it is the only policy scenario that includes both emissions *increases* as well as emissions *reductions*. For Pulp and Paper, all reduced-form tools, including InMAP BenMAP, produced benefits within 10-40% of CMAQ benefits. This scenario has the second lowest amount of emissions reductions relative to the other scenarios and, along with the CPP Proposal, is one of the two scenarios where NO_X and SO_2 emissions reductions are relatively equal.

EXHIBIT 3-3. RATIO OF NATIONAL AVOIDED PREMATURE MORTALITY BENEFITS ESTIMATES COMPARED AGAINST CMAQ ESTIMATES, BY POLICY SCENARIO. ORANGE DOTS REPRESENT RATIOS LESS THAN 1 AND BLUE DOTS RATIOS GREATER THAN 1.

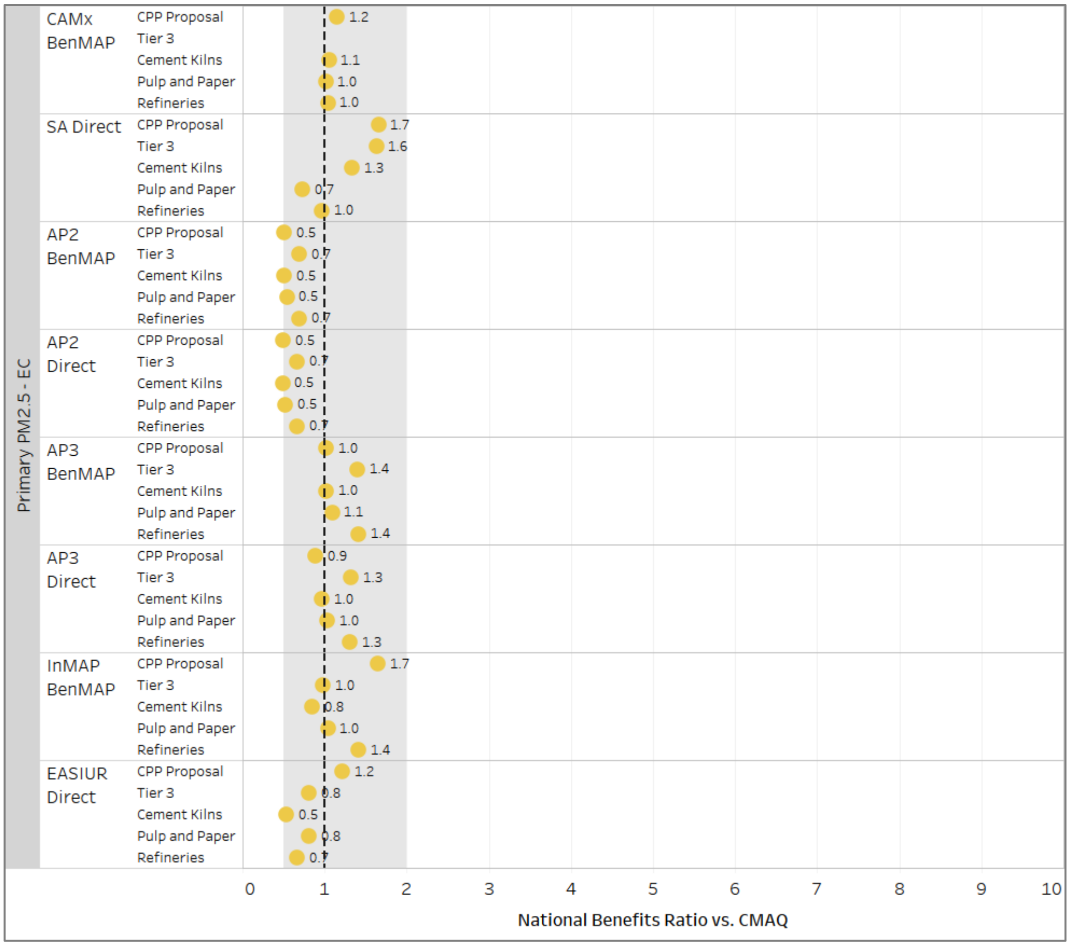


3.1.2 BENEFITS BY PRECURSOR

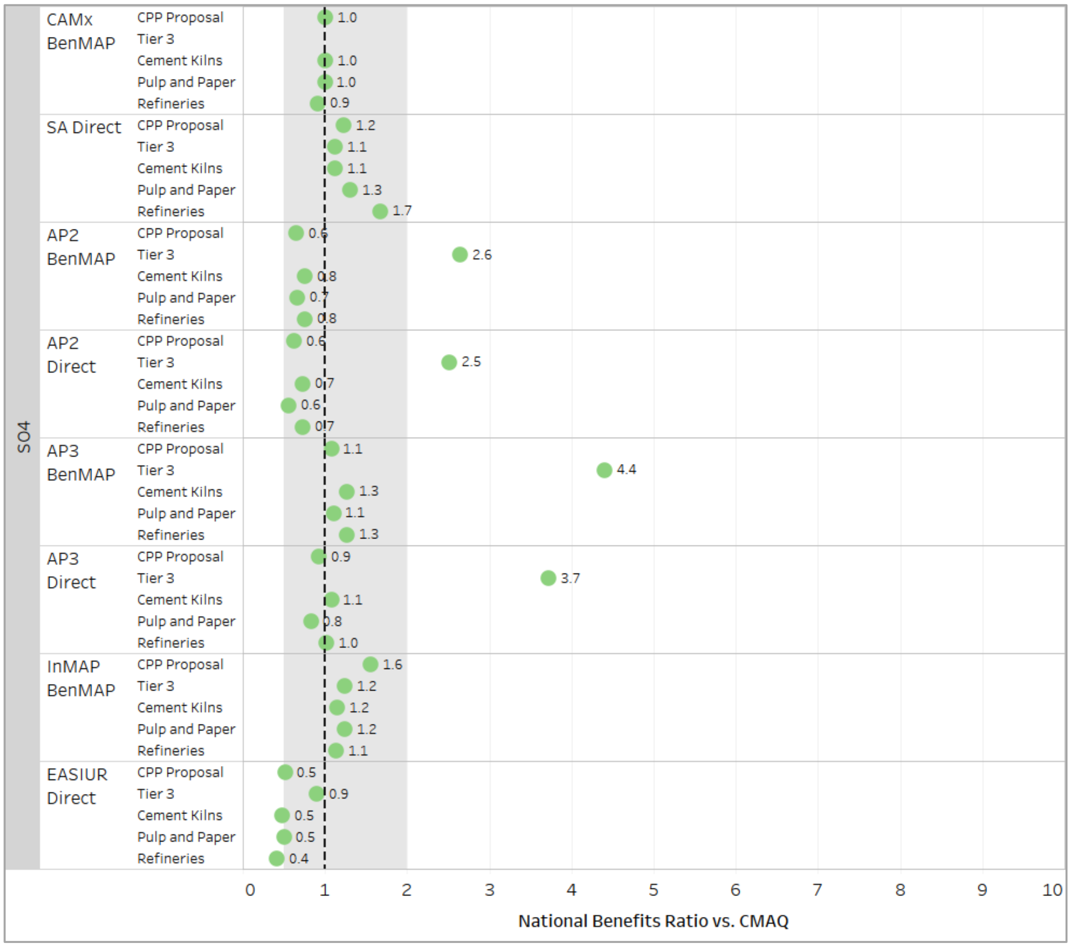
Separating total $PM_{2.5}$ benefits into the fraction contributed by $prPM_{2.5}$, sulfate, and nitrate allows us to examine how well each reduced-form tool predicts these individual components (Exhibit 3-4). It also reveals how much of the results for total $PM_{2.5}$ are due to potentially offsetting errors. Tools that perform similarly for individual precursors as well as total $PM_{2.5}$ are more likely to have predictable performance for additional policy scenarios.

EXHIBIT 3-4. RATIO OF REDUCED-FORM TO FULL-FORM NATIONAL AVOIDED PREMATURE MORTALITY BENEFITS BY $PM_{2.5}$ SPECIES FOR EACH MODEL AND POLICY SCENARIO

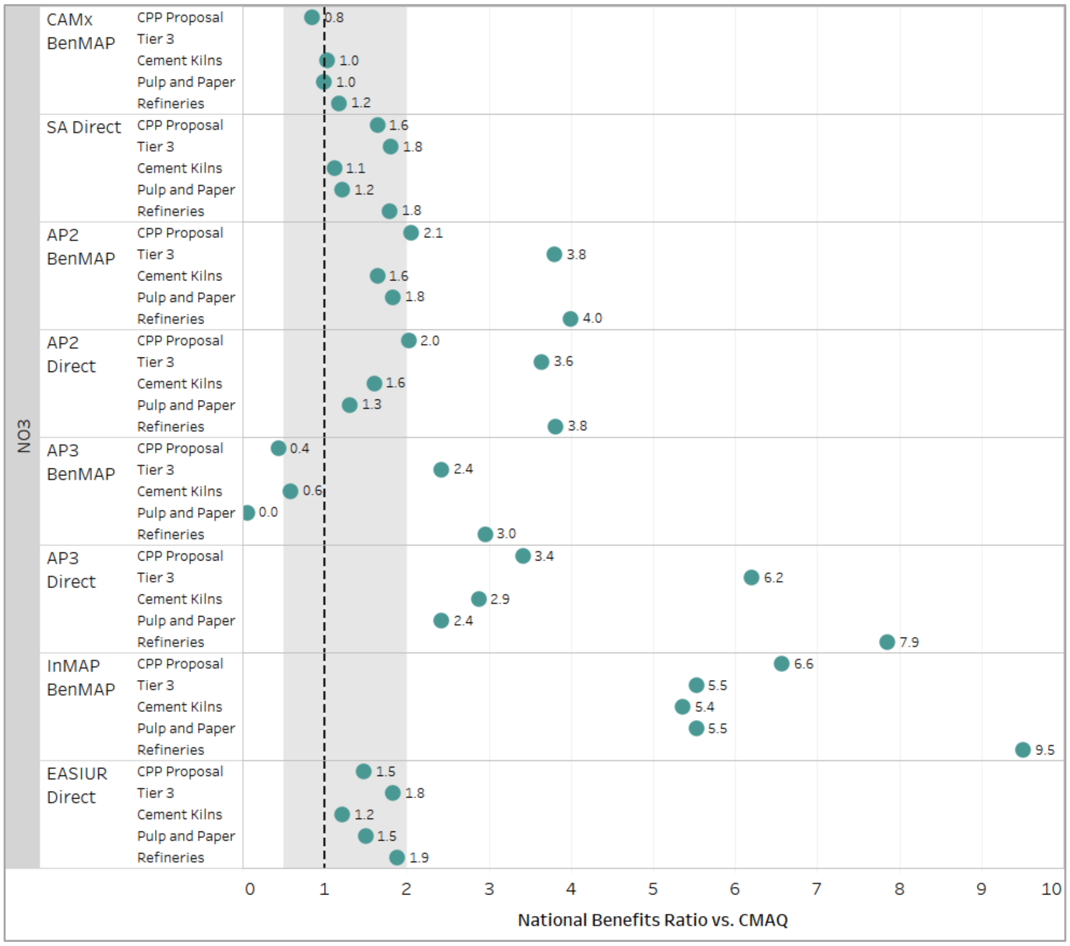
PRIMARY $PM_{2.5}$ (EC ONLY):



SULFATE:


SO4
CAMx BenMAP
CPP Proposal 1.0
Tier 3
Cement Kilns 1.0
Pulp and Paper 1.0
Refineries 0.9
SA Direct
CPP Proposal 1.2
Tier 3 1.1
Cement Kilns 1.1
Pulp and Paper 1.3
Refineries 1.7
AP2 BenMAP
CPP Proposal 0.6
Tier 3 2.6
Cement Kilns 0.8
Pulp and Paper 0.7
Refineries 0.8
AP2 Direct
CPP Proposal 0.6
Tier 3 2.5
Cement Kilns 0.7
Pulp and Paper 0.6
Refineries 0.7
AP3 BenMAP
CPP Proposal 1.1
Tier 3 4.4
Cement Kilns 1.3
Pulp and Paper 1.1
Refineries 1.3
AP3 Direct
CPP Proposal 0.9
Tier 3 3.7
Cement Kilns 1.1
Pulp and Paper 0.8
Refineries 1.0
InMAP BenMAP
CPP Proposal 1.6
Tier 3 1.2
Cement Kilns 1.2
Pulp and Paper 1.2
Refineries 1.1
EASIUR Direct
CPP Proposal 0.5
Tier 3 0.9
Cement Kilns 0.5
Pulp and Paper 0.5
Refineries 0.4
0
1
2
3
4
5
6
7
8
9
10
National Benefits Ratio vs. CMAQ

NITRATE[21]:



Again, we see that CAMx-derived benefits are in close agreement with CMAQ-derived benefits. The differences at the component level are slightly larger than for total $PM_{2.5}$. However, CAMx benefits for each component across all policy scenarios are less than 20% different than those predicted by CMAQ.

Across components, we see that reduced-form tools generally perform better for $prPM_{2.5}$ and sulfate than for nitrate. The tools produced estimates of $prPM_{2.5}$ that fell within a factor of two of CMAQ in all cases. Results for sulfate were also within a factor of two of the CMAQ-based estimates, with the exceptions of APX for Tier 3 (ratios ranging from 2.5 to 4.4) and EASIUR Direct for refineries (ratio of 0.4).

Comparisons to CMAQ results showed poor agreement for nitrate for most models with only SA Direct and EASIUR Direct having estimates within a factor of two of the CMAQ estimates for all scenarios. The other models all overestimated CMAQ estimates by at

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[21] Note the 0.0 nitrate value for the Pulp and Paper scenario for AP3 BenMAP is actually a ratio of 0.049, representing an ~95% underestimation.

least a factor of three for at least one scenario. InMAP BenMAP overestimated CMAQ nitrate by a factor of 9.5 for the refineries scenario. AP3 BenMAP had both large underestimates and large overestimates of nitrate benefits compared to CMAQ.

Many of the largest exceedances for both sulfate and nitrate are associated with the Tier 3 scenario (although for sulfate this effect is limited to the APX models). However, for nitrate, we see that the Refineries scenario also generates large differences between CMAQ and reduced-form tools.

All reduced-form tools consistently overestimate nitrate, except AP3 BenMAP, which has both large overestimates and underestimates depending on the policy scenario. Consistent with total $PM_{2.5}$, we see that some of the largest differences from CMAQ-based benefits are exhibited by InMAP BenMAP and AP3 Direct, which means the nitrate component of those models is driving the total $PM_{2.5}$ results. However, AP3 Direct also produces estimates that agree most closely to CMAQ results for $prPM_{2.5}$ and sulfate for several scenarios.

Comparing species-specific results can illuminate whether total $PM_{2.5}$ performance is masking compensating errors. The SA Direct model consistently produces overestimates of CMAQ benefits for all PM components as well as for total $PM_{2.5}$. Similarly, InMAP BenMAP consistently overestimates CMAQ benefits for both total $PM_{2.5}$ as well as for each component of $PM_{2.5}$. In contrast, EASIUR Direct underestimates total $PM_{2.5}$, $prPM_{2.5}$ and sulfate, but overestimates nitrate.

The APX models perform consistently by model version at the component level. AP2 underestimates total $PM_{2.5}$, $prPM_{2.5}$ and sulfate, but overestimates nitrate whether applied directly or in combination with BenMAP. AP3 produces consistently better matches to CMAQ than AP2 for both total $PM_{2.5}$ and sulfate, with slight overestimates in some cases, but it consistently produces greater bias than AP2 when estimating nitrate. This effect is somewhat mitigated by coupling AP3 with BenMAP but can also lead to underestimates of nitrate.

Finally, comparing across policies, we see that Tier 3 continues to result in the greatest variance against CMAQ at the component level, and Refineries also produced relatively wide variances for nitrate. The CPP Proposal and Pulp and Paper scenarios continue to result in some of the closest reduced-form tool/CMAQ comparisons.

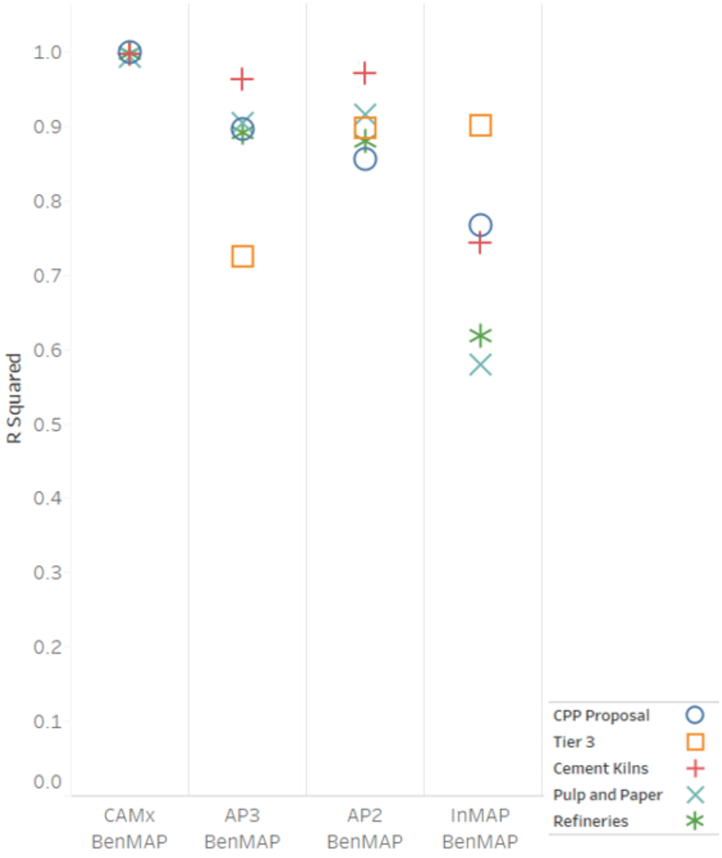
3.2 REGIONAL RESULTS

Using results at the region-level we can generate comparison statistics for each reduced-form tool to quantitatively compare their performance relative to CMAQ. For this comparison, we focus on the r^2, NMB, and NME statistics calculated with total $PM_{2.5}$-related avoided mortality benefits at the region-level. We provide additional statistics results in Appendix C.

3.2.1 R² VALUES

The r^2 values describe the proportion of the variance in CMAQ benefits across regions that can be predicted by the variance of reduced-form tool benefits (Exhibit 3-5). Reduced-form tool performance improves as r^2 values approach one.

EXHIBIT 3-5. COMPARISON BETWEEN REDUCED-FORM AND FULL-FORM MODEL BENEFITS ESTIMATES AT REGIONAL SCALE, R²



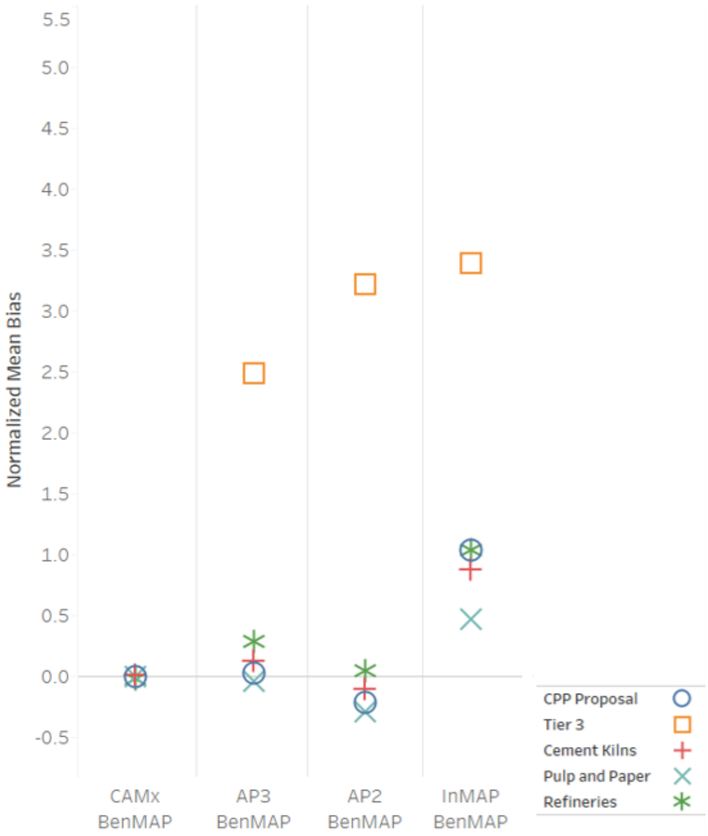
Comparing AP2 BenMAP and AP3 BenMAP, AP2 BenMAP performs slightly better on this metric on average and performs significantly better for the Tier 3 scenario. In contrast, InMAP has the lowest r^2 values of any of the reduced-form models coupled with BenMAP. CAMx and CMAQ were highly correlated for the point source-based emissions scenarios. AP3 BenMAP performed better for the point source-based scenarios compared to the mobile scenario while InMAP BenMAP performed best for the mobile scenario.

3.2.2 NORMALIZED MEAN BIAS (NMB)

NMB estimates summarize total regional differences in reduced-form tool benefits and CMAQ benefits as a percentage of total CMAQ benefits (Exhibit 3-6). These values vary between -100% and positive infinity, and performance improves as values approach zero.

The AP2 BenMAP estimates tended to be slightly lower than CMAQ for the point source scenarios while AP3 BenMAP estimates tended to be slightly higher than CMAQ. The InMAP BenMAP predictions were generally higher than CMAQ estimated benefits. Both APX and InMAP BenMAP had the highest error related to the Tier 3 scenario. The CAMx model predicted benefits were very similar to CMAQ for the point source-based scenarios.

EXHIBIT 3-6. NORMALIZED MEAN BIAS OF REGIONAL ESTIMATES BY MODEL, COMPARED AGAINST CMAQ ESTIMATES



3.2.3 NORMALIZED MEAN ERROR (NME)

Like NMB, NME estimates also summarize total regional differences in reduced-form tool benefits and CMAQ benefits as a percentage of total CMAQ benefits (Exhibit 3-7). However, for NME, it is the absolute value of regional differences that is used; thus, NME emphasizes accuracy independent of direction. NME values vary between zero and positive infinity, and performance improves as values approach zero.

EXHIBIT 3-7. NORMALIZED MEAN ERROR OF REGIONAL ESTIMATES BY MODEL, COMPARED AGAINST CMAQ ESTIMATES

The metrics for NME were similar to the NMB results for each of these modeling systems and emissions scenarios. CAMx BenMAP, AP2 BenMAP, and AP2 BenMAP performed very consistently against CMAQ BenMAP for the point source-based scenarios while the Tier 3 mobile scenario had notably worse performance for the reduced form tools.

3.3 REDUCED-FORM TOOL COMPLEXITY AND LEVEL OF EFFORT

Each of the reduced-form tools considered in this analysis required a different level of analytical and technical skill to produce benefits estimates. While running these tools, we maintained a log of the amount of time each tool took to use, whether specific pre- or post-processing steps were required, what software programs were needed to execute the analyses, and other descriptive factors (Exhibit 3-8).

SA Direct has the lowest time requirements and does not require any special skills or software programs. EASIUR Direct also has low time requirements and only involves the use of Excel, or similar software. If BenMAP-CE is used in conjunction with air quality estimated by a reduce form tool (rather than allowing the reduced form tool to calculate benefits directly), this increases the time requirement and degree of knowledge required for BenMAP-CE application. All APX models require both MATLAB expertise and a MATLAB license but, for AP2 and AP3 Direct results, have a more moderate time requirement. Finally, InMAP requires knowledge of the GO programming language and has a relatively high level of effort.

EXHIBIT 3-8. LEVEL OF EFFORT REQUIRED TO USE EACH REDUCED-FORM TOOL

TOOL	TOOL FORMAT	PRE-PROCESSING REQUIREMENTS	POST-PROCESSING REQUIREMENTS	TIME REQUIREMENTS[1]	SPECIAL SKILLS / SOFTWARE REQURED
SA Direct	Table of nationally-applicable BPT values that can be applied to policy-specific emissions changes.	Acquire and format emissions data. Depending on the endpoints of interest, the raw BPT values may need to be adjusted to consider mortality or morbidity impacts alone.	N/A	Low	N/A
AP2 Direct and AP3 Direct	AP2 and AP3 are MATLAB-based programs and require a license for that software program.	Acquire and format emissions, population, and mortality rate data. Adjust APX code to include desired impacts in BPT values.	Multiply the model-generated county- and precursor-specific BPT values by corresponding emissions deltas for each source type.	Medium	MATLAB
AP2 BenMAP and AP3 BenMAP	AP2 and AP3 are MATLAB-based programs and require a license for that software program. BenMAP is an open-source software program available for download on EPA's website.	Acquire and format emissions data. Modify APX code to output air quality concentrations. Run APX to obtain air quality surfaces and format surfaces into BenMAP-ready inputs.	Run APX-generated air quality surfaces through BenMAP.	High	MATLAB and BenMAP-CE; Must modify MATLAB code.
InMAP BenMAP	InMAP is an open-source program written in the GO programming language available for download from the InMAP GitHub repository. BenMAP is an open-source software program available for download on EPA's website.	Acquire and format emissions data. Develop annual average meteorology, chemistry, and deposition information. Run InMAP to obtain air quality surfaces and format surfaces into BenMAP ready inputs.	Run InMAP-generated air quality surfaces through BenMAP.	High	GO programming language and BenMAP-CE
EASIUR Direct	16 pollutant- and season-specific BPT arrays that can be applied to policy-specific emissions changes.	Acquire and format emissions data. EASIUR provides a web tool that can be used to help format emissions data.	Multiply the pollutant- and season-specific 36 km BPT values by corresponding emissions deltas for each season.	Low	N/A; some familiarity with GIS or spatial analysis for formatting emissions data would be helpful.

[1] "Low" indicates 1-5 hours, "Medium" indicates 5-10 hours, "High" indicates 10+ hours required to perform a model run for one policy scenario. Full-form models are known to be time- and resource-intensive. None of the reduced-form tools are as time- and resource-intensive as running a full-form model.

Chapter 4 | DISCUSSION

The objective of this analysis was to demonstrate a systematic comparison of the monetized health benefits estimated using reduced-form tools for air quality health benefits assessment against those generated using full-form air quality and health modeling approaches. The goal was to identify the primary drivers for observed differences in model results and the conditions under which different reduced-form tools might be expected to provide similar estimates as the full-form approach.

The results presented in Chapter 3 allow us to make several important observations about this set of reduced-form tools and their potential utility in Regulatory Impact Analyses (RIAs). We also briefly discuss the similarities and differences between the two full-form models (CAMx and CMAQ). It is important to note that this document sometimes nominally uses a factor of two to differentiate performance metrics more similar to the photochemical grid model prediction but the factor of two delineation is not a measure of acceptability for any particular type of assessment.

4.1 COMPARISON OF FULL-FORM AIR QUALITY MODELS

Across all comparators examined in this analysis, CMAQ and CAMx produce very similar estimates of both total $PM_{2.5}$ benefits and benefits related to specific components of $PM_{2.5}$. They are also in agreement on the spatial distribution of those benefits at the region-level. This finding, which was consistent across all policies for which both results were available, is important to validate our approach for evaluating the reduced-form tools.

EPA uses both CMAQ and CAMx to perform full-form health benefits analyses for RIAs. Based on the similarity between benefits estimates from these two models, we can have confidence that the performance of reduced-form tools relative to CMAQ estimates would also hold if CAMx were the full-form model being used. In addition, it gives us confidence that there are no issues unique to CMAQ that could skew the performance of the reduced-form tools. Knowing that the full-form air quality models agree gives us more confidence that we are not introducing significant uncertainty into our analysis of reduced-form tools by relying on a single model as our sole comparator.

4.2 OVERALL REDUCED-FORM TOOL PERFORMANCE FOR $PM_{2.5}$ AND ITS COMPONENTS

The results presented in Chapter 3 allow us to draw important conclusions about each reduced-form tool's ability to replicate CMAQ benefits for the policies considered. Using those results, we can begin to identify which reduced-form tools may be more or less suitable for particular policy analyses.

Overall, we find that the InMAP BenMAP model matched least well with CMAQ's predictions. For the specific scenarios we evaluated, it consistently overestimated CMAQ benefits and was also one of the more complicated reduced-form tools to use.

In contrast, the SA Direct and EASIUR Direct models require the lowest level of effort across reduced-form tools and produce some of the most similar estimates to CMAQ at the national level. These models were the only ones that produced comparable results for the Tier 3 policy. Furthermore, they demonstrated consistent performance for total $PM_{2.5}$ and its components, which indicates that they would perform in a similarly reliable way for air quality policies beyond those considered in this analysis. EASIUR Direct also did a reasonable job capturing variation in benefits across large regions of the US (0.88 r^2 value on average). They key differences between these two models were in direction of bias, with SA Direct tending to overestimate and EASIUR tending to underestimate CMAQ results, and in performance for sector-specific policies, where SA Direct tended to be slightly closer to the CMAQ estimates.

A drawback of these reduced-form tools (SA Direct, EASIUR Direct, and APX Direct) is their inability to provide geographically-specific estimates of where benefits occur, primarily because they are BPT tools that assign benefits to locations with emissions changes rather than air quality changes. Thus, they cannot provide fine-scale insight into the locations or populations that might be most affected by a policy, nor can they be used to break impacts out by locations with differing $PM_{2.5}$ levels. In addition, EASIUR Direct results displayed a consistent downward bias of 30 to 40% compared to CMAQ, with the exception of the Tier 3 analysis.

The other BPT tools considered in this analysis, AP2 Direct and AP3 Direct, did not produce a similar level of consistent performance as SA Direct and EASIUR Direct. While AP2 Direct and AP3 Direct generate BPT estimates specific to a set of baseline emissions, this different emissions baseline implemented in AP2 and AP3 does not appear to result in better performance for the set of policies considered in this analysis, owing primarily to differences related to estimation and processing of nitrate results. We found that AP3 Direct improves on AP2's performance with respect to modeling EC and sulfate $PM_{2.5}$ components, producing values quite similar to CMAQ. In addition, APX requires proprietary software (i.e., MATLAB) and a significant level of technical expertise.

The remaining reduced-form tools are the AP2 BenMAP and AP3 BenMAP models that we adapted for this analysis. Both models replicate CMAQ benefits relatively well, with the newer version of the model, AP3, comparing slightly better across the statistics considered in this analysis. In addition, of all the reduced-form tools, AP3 BenMAP produced several estimates of total $PM_{2.5}$ that were within <10% of CMAQ estimates. Furthermore, because AP3 BenMAP provides an air quality surface, it can provide insight into the locations and populations that might be most affected by a policy. Given the relatively high r^2 estimates for this model at the region-level, this combination of tools provides promising evidence that a reduced-form tool could perform well matching the distribution of full-form benefits at smaller spatial scales, though additional analysis would be required to confirm this.

The primary drawback of the AP3 BenMAP model is its complexity. It is complex to run and requires proprietary software (i.e., MATLAB). In addition, it produces somewhat inconsistent nitrate results, which may make it harder to predict how this model would perform for policies that include large changes in NO_x emissions.

As a final note, while we saw a high degree of consistency between AP2 Direct and AP2 BenMAP, we saw slightly less consistency between AP3 Direct and AP3 BenMAP. Based on our examinations of the AP3 model, we believe this is attributable to how the AP3 model addresses the nitrate component of $PM_{2.5}$. As noted in the methods section, AP2 and AP3 estimate the marginal cost of emissions by quantifying the total health burden and monetized costs associated with a baseline emissions scenario, systematically increasing the baseline emissions by one ton, recalculating the total health burden and monetized costs, and taking the difference between the two estimates. In the AP2 model, the chemical transformation of NO_X emissions into nitrate is calculated the same way in both the baseline and marginal estimates. However, the AP3 model uses slightly different approaches for the baseline and marginal cases. This results in a portion of the difference between the baseline and marginal benefits estimates being attributable to nitrate calculation rather than an actual difference in effect. We believe this is a contributor to the larger degree of overestimation observed for the AP3 Direct model, particularly for the Tier 3 scenario, which is dominated by changes in NO_X emissions.

4.3 PERFORMANCE ACROSS DIFFERENT AIR QUALITY POLICIES

It is important to understand how particular aspects of the air quality policies examined in this analysis may have contributed to reduced-form tool performance in order to understand how well the reduced-form tools might perform for other policies. We saw that relative performance across reduced-form tools in general was best for the CPP Proposal and Pulp and Paper scenarios and worst for the Tier 3, and to a lesser extent, the Refineries scenarios.

Based on the emission changes associated with these scenarios, we think the primary driver of this difference in performance is attributable to the reduced-form tools' ability to predict the nitrate component of $PM_{2.5}$ and its effects. The Tier 3 and Refineries scenarios have the highest fraction of emissions changes that are attributable to nitrate (64% and 67%, respectively). In contrast, the CPP Proposal and Pulp and Paper scenarios have the lowest fraction of emissions changes that are attributable to nitrate (49% for both).

However, it is possible that the exceptionally poor performance for Tier 3 may be attributable to more than just nitrate predictions. The Refineries scenario has a larger fraction of NO_X emissions, but is associated with better performance than the Tier 3 scenario. Thus, the fact that the Tier 3 scenario is exclusively comprised of ground-level emissions may be a secondary contributing factor, as may the use of a different base year emissions inventory (2005) than the other policies. Additional investigation or model runs would be required to determine this definitively. Regardless, the reduced-form tools considered in this analysis should be applied with caution to policies with large changes in NO_X emissions.

Finally, some of the policies affected ammonia and VOC emissions, yet only some reduced-form tools had the ability to account for those precursors. The photochemical grid models account for these changes and so do some of the reduced-form tools (see Exhibit 2-9). Overall, the impact of these precursors was small compared to SO_2, NO_X, and primary $PM_{2.5}$ changes for the emission scenarios examined here. Given the complexities in SOA formation from anthropogenic VOC and challenges in the underlying science related to SOA formation it is not expected that these tools would be comparable for VOC impacts on $PM_{2.5}$ concentrations; however, the limited data from this study does not enable us to test this hypothesis.

4.4 LIMITATIONS OF THE ANALYSIS

While this analysis provides a representative snapshot of reduced-form tool performance across a range of potential policy scenarios, there are several limitations and important caveats worth describing. While the policies that were analyzed to demonstrate the abilities of each reduced-form tool compared with full-form model results are a thorough subset of policy types, ranging from mobile sources to industrial point sources to EGUs, it is not an exhaustive or fully representative set of policies. Furthermore, when subdivided by policy type, it only includes one mobile source policy (Tier 3), one EGU policy (CPP Proposal), and three sector-specific policies which each apply uniform emissions reductions. This limited sample size makes it difficult to draw conclusive opinions about reduced-form tool performance for any particular type of policy scenario. In addition, this set of policies is not representative of all potential policy scenarios that may be analyzed by these tools in the future. Other policies could vary from those we evaluated in the size, timing, and distribution of emissions changes across both time and PM precursors. Therefore, future users should carefully consider the specific characteristics of a policy before deciding whether a specific reduced-form tool is or is not a good fit for estimating benefits.

A second limitation relates to the lack of CAMx-based full-form estimates for the Tier 3 scenario. We are confident in the congruence of the CMAQ and CAMx results for the four scenarios for which we have data from both models. The results of those comparisons suggest that treatment of key precursors for $PM_{2.5}$ would also be consistent across other scenarios, and that using CMAQ as our single full-form comparator does not introduce significant uncertainty into our analysis. However, this conclusion would be stronger if we were able to review Tier 3 data from both models; especially since Tier 3 is the only scenario comprised of exclusively ground-level emissions sources. As a result, our ability to draw conclusions about the large variances observed between the reduced-form tool and full-form benefits estimates associated with the Tier 3 scenario is limited.

As noted in the methods section, we calculate statistics related to each reduced-form tool as compared to CMAQ, but do not establish strict model performance thresholds. We have instead sought to provide a picture of performance across a range of metrics that measure different aspects of performance relevant to the use of these models in a policy assessment context.

In addition, the present analysis does not attempt to identify and quantify potential sources of uncertainty within each of the model types. Previous studies have identified some of these sources, which include uncertainty in the VSL estimate and the slope of the mortality concentration-response relationship (Holland et al., 2016a; Holland et al., 2016b). While these sources of uncertainty are common across the reduced- and full-form models (since they use the same values for these parameters), there may be additional sources of uncertainty that are unique to each reduced-form tool, including the source-receptor relationship between precursor emissions and ambient pollutant concentrations, policy impacts on emissions, the emissions inventory, and others. Without characterizing uncertainty, we can only compare point estimates and therefore cannot evaluate whether differences in reduced-form tool estimates are statistically different from full-form model results for any of the policy scenarios analyzed.

Finally, some of the reduced-form tools, such as EASIUR Direct, InMAP, and AP3 are relatively new (or in the case of AP3 a recent iteration on an existing model). In addition, the models are periodically updated; our observations are only accurate with respect to the versions of the reduced-form tools we tested.

The use of EC to represent the impacts of all primarily emitted $PM_{2.5}$ may not always reflect the impacts of a particular scenario in situations where the speciation of primary $PM_{2.5}$ emissions varies geographically or in relative amount of the total primary $PM_{2.5}$ such that the components of $PM_{2.5}$ differentially impact particular downwind populated areas.

Despite these limitations, this analysis provides useful initial insights into the agreement of multiple reduced-form tool estimates with full-form results for a broad array of policy scenarios. Furthermore, our analysis of individual $PM_{2.5}$ component benefit estimates allows us to provide insights into what specific aspects of the reduced-form tools may be driving overall performance differences across the scenarios. As a result, this analysis provides valuable information on how these models can best be utilized in the policy assessment context.

Chapter 5 | CONCLUSION

5.1 RECOMMENDATIONS FOR CONTINUED EVALUATION OF REDUCED-FORM TOOLS

Based on the results of this analysis, we believe there continues to be value in evaluating how reduced-form tools compare to full-form air quality model estimates in emission reduction scenarios. Some of the reduced-form tools considered in this analysis produced results that were reasonably comparable at the national level to national level results derived from less refined full-form models and offer a quicker approach to generating ballpark estimates of the health-related benefits or costs associated with an air quality policy. In particular, the SA Direct and EASIUR Direct models are easy to use and produce estimates of national $PM_{2.5}$ benefits that match those generated by full-form models relatively well. Some reduced-form tools produced estimates that were extremely close to CMAQ estimates at the national level, but they were not able to do so uniformly across policy scenarios, nor at finer spatial scales.

5.2 FUTURE RESEARCH

This analysis comparing reduced-form tools has identified several areas for future research. We examined a small number of policy scenarios in our analysis; performing similar analyses for a broader range of scenarios would help to clarify the nature of the differences between reduced-form tools. Additional analyses could incorporate comparison of these reduced-form tools for an expanded set of policy types, including non-road mobile sources like aircraft and marine vessels, area sources, iron and steel facilities, residential wood combustion, and others. Expanding the set of policy scenarios included in the analysis may help to provide further detail on the relative differences between reduced- and full-form approaches, as well as advance understanding about which reduced-form tool(s) may be more or less appropriate for specific policy types or emissions source sectors.

The Tier 3 scenario was notable for the high bias of the reduced-form tools when compared against CMAQ results. Not only did models that performed relatively well for other scenarios perform much more poorly for Tier 3, some models that appeared to systematically underestimate results across all other scenarios overestimated results for Tier 3. As noted above, while it appears that this difficulty matching CMAQ relates at least in part to the higher proportion of nitrate-related impacts in Tier 3, other factors may be at play as well. It may be worth investigating how these tools compare for a more recent mobile source scenario that has input files compatible with contemporary photochemical model formulations (e.g., gas phase chemical mechanism).

In our analysis we saw differences in how the tools performed at different geographical scales and locations. Future research to examine if there are consistent biases in particular locations would be useful. For AP2 and AP3, additional detail in the model documentation would help users to determine when and how the models should be calibrated for a particular policy scenario, or if there are particular scenarios for which the models may not be suitable.

The accuracy of a reduced form tool depends very heavily on the air quality modeling that underlies it. The extent that the air quality modeling can be updated and improved over time may enable improved benefits estimates that better compare with full form model results. Further, the source-receptor relationships in these tools may need periodic updates to reflect contemporary emission inventories and representation of chemistry. Additional work to understand how these models improve when underlying assumptions are adjusted to better reflect current conditions or expected future conditions would be useful when prioritizing model development and understanding circumstances where certain tools may be more or less informative.

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APPENDIX A | DETAILED REDUCED-FORM TOOL METHODS

This Appendix describes in detail the approach used to run the different reduced form tools we used in this analysis. Detailed input, configuration, and output files from these approaches were provided separately to EPA (https://github.com/epa-kpc/RFMEVAL) and are available upon request.

A1. AP3 METHODS

The AP3 reduced-form tool was designed for and runs in the MathWorks program MATLAB, which is required to run the AP3 model. The model is composed of 20 individual script files and two data files that operate together to estimate pollutant- and county-specific BPT estimates for each of four emissions source types. To facilitate the use of the 2014 AP3 model as part of this project, several of the original scripts were modified to enable the import and export of data. Exhibit A-1 below provides a brief description of the calculations that occur in each script, and identifies where scripts were modified by IEc. The scripts run in the following order; several scripts are called more than once throughout the program:

PM_CRDM_Marginal.m
    Emissions_Import.m
    PM_Setup.m
    Population.m
    PM_Base_Conc.m
        Nitrate_Sulfate_Ammonium.m
        PM_25_Base_Raw.m
        PM_25_Health_Base.m
    Mortality.m
        Area_Sources.m
            Area_Reset.m
            Nitrate_Sulfate_Ammonium_Marginal_New.m (for NO_X only)
            Nitrate_Sulfate_Ammonium.m (for all other pollutants)
            PM_25_Health.m

- Low_Stacks.m
    - Area_Reset.m
    - Low_Reset.m
    - Nitrate_Sulfate_Ammonium_Marginal_New.m (for NO_X only)
    - Nitrate_Sulfate_Ammonium.m (for all other pollutants)
    - PM_25_Health.m
- Medium_Stacks.m
    - Med_Reset.m
    - Nitrate_Sulfate_Ammonium_Marginal_New.m (for NO_X only)
    - Nitrate_Sulfate_Ammonium.m (for all other pollutants)
    - PM_25_Health.m
- Tall_Stacks.m
    - Med_Reset.m
    - Tall_Reset.m
    - Nitrate_Sulfate_Ammonium_Marginal_New.m (for NO_X only)
    - Nitrate_Sulfate_Ammonium.m (for all other pollutants)
    - PM_25_Health.m

Damages.m

EXHIBIT A-1. AP3 MODEL SCRIPTS

AP3 MODEL SCRIPTS	
PM_CRDM_Marginal	This is the master script that runs all other components of the AP3 model.
Emissions_Import	This script was created by IEc and allows the user to update the area, low stack, medium stack, tall stack and new tall stack emissions stored in the two .mat files that the AP3 model calls.
PM_Setup	This script initializes a series of output matrices and is where the value per statistical life is set. It also includes a set of hard coded calibration factors for each precursor that are used in converting emissions into concentrations. These calibration factors are different between AP2 and AP3.
Population	This script creates a set of matrices that store different population data (e.g., total population or population over 30).

AP3 MODEL SCRIPTS	
PM_Base_Conc	This script translates the raw precursor pollutant emissions into their $PM_{2.5}$ components and then calculates total $PM_{2.5}$ concentrations.
Nitrate_Sulfate_Ammonium	This script is run is several places throughout the model and is used to capture the secondary transformation of precursor pollutants into $PM_{2.5}$.
PM_25_Base_Raw	This script calculates and stores the baseline $PM_{2.5}$ concentration.
PM_25_Health_Base	This script calculates the estimated number of health impacts, and their cost, associated with the baseline quantity of precursor emissions.
Mortality	This script runs the "Area_Sources", "Low_Stacks", "Medium_Stacks", and "Tall_Stacks" scripts that incrementally adjust the baseline emissions and calculate the marginal change in health impacts.
Area_Sources, Low_Stacks, Medium_Stacks, and Tall_Stacks	These scripts loop over each precursor pollutant and each county, incrementally adjusting the baseline emissions by 1 ton and calculating the marginal change in health impacts. This marginal change becomes the county- and pollutant- specific BPT value for each source type.
Area_Reset, Low_Reset, Med_Reset, and Tall_Reset	These scripts re-calculate the precursor pollutant concentrations from the baseline emissions for each source type.
Nitrate_Sulfate_Ammonium_Marginal_New	This script is run is several places throughout the model and is used to capture the secondary transformation of precursor pollutants into $PM_{2.5}$. This script is only run for marginal changes in NOx emissions.
PM_25_Health	This script calculates the estimated number of health impacts, and their cost, associated with the incrementally adjusted precursor emissions.
Damages	This script combines the BPT values into a set of output matrices. This code was modified by IEc to export these results to an Excel file.

In addition to the model scripts described above, the AP3 model also includes two .mat data files: one including data associated with the area and low stack sources ("2014_PM_Worksheet_Area_Low_Western_Adj.mat") and the other including data for the medium and tall stack sources ("2014_PM_Worksheet_Med_Tall_Western_Adj.mat"). Both of these files also contain the population and incidence rate data utilized by the model[22]. Prior to running the model, the data stored in these files need to be updated with values that are specific to the policy scenario being analyzed. The next few

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[22] As distributed, these data represent 2014.

sections provide instructions for updating the .mat files, describe the outputs generated by the AP3 model, and outline how the AP3 BPT values are used to estimate benefits.

A.1.1 AP3 MODEL INPUTS

For this project, two types of AP3 results were compared to full-form model results: one generated from applying the AP3 BPT values to changes in emissions, and one generated by running the AP3 air quality surfaces through BenMAP. Note that the AP3 BPT values are generated by running the baseline scenario emissions through the model. The control emissions are only run to obtain the air quality surfaces needed to generate the second set of results. Therefore, when doing model runs using control emissions, the code can be stopped after running "PM_Base_Conc.m." To run AP3 for a new policy scenario, the following steps should be followed. These steps are necessary to ensure that all of the model inputs are consistent with the policy scenario being analyzed.

1. Emissions file preparation[23]:
    a. Save each source type's emissions as individual .csv files.
    b. The first column should contain county FIPS codes and columns 2-8 should contain pollutant-specific emissions in tons [NH_3, NO_X, PM_{10}, $PM_{2.5}$, SO_2, VOC (anthropogenic origin), and VOC (biologic origin)].
    c. The FIPS order and included FIPS must match each source type's AP3 source/receptor matrix.
    d. No headers should be included.
2. Population data preparation
    a. The population data occupies a 3,109x19 matrix in AP3. The data should contain population totals for the following age groups for each of the 3,109 counties included in A3: 0TO0, 1TO4, 5TO9, 10TO14, 15TO19, 20TO24, 25TO34, 30TO34, 35TO39, 40TO44, 45TO49, 50TO54, 55TO59, 60TO64, 65TO69, 70TO74, 75TO79, 80TO84, 85TOUP.
    b. The FIPS order and included FIPS must match AP3's FIPs order.
3. Mortality data preparation
    a. The mortality data occupies a 3,109x19 matrix in AP3. The data should contain all-cause mortality rates for the following age groups for each of the 3,109 counties included in A3: 0TO0, 1TO4, 5TO9, 10TO14, 15TO19,

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[23] Three of the five source receptor matrices include transport coefficients for the total quantity of emissions generated in a particular county in the contiguous United States. However, the tall stack and new tall stack source types have source-specific values. As such, factors are only available for a subset of counties. For this project, any tall stack emissions generated in a county not included in either the tall stack or new tall stack matrices were combined with the medium stack county-level emissions. Furthermore, the tall stack and new tall stack matrices contain coefficients for multiple point sources in some counties. Because the scenario emissions could not be linked to these specific sources, they were divided evenly among the different point sources.

20TO24, 25TO34, 30TO34, 35TO39, 40TO44, 45TO49, 50TO54, 55TO59, 60TO64, 65TO69, 70TO74, 75TO79, 80TO84, 85TOUP.

   b. The FIPS order and included FIPS must match AP3's FIPs order.

4. Updates to script code and data files:
   a. Load the scenario-specific population data into cell reference "Mortality{6,1}" in both AP3 .mat files and save.
   b. Load the scenario-specific all-cause mortality rates into cell reference "Mortality{3,1}" in both AP3 .mat files and save.
   c. Update the load file references in "Emissions_Import.m", "PM_Setup.m", "PM_Base_Conc.m", "Area_Sources.m", and "Medium_Stacks.m".
   d. Update "Emissions_Import.m" with the .csv file names for the scenario-specific emissions files for each source type.
   e. Update "PM_Setup.m" with the scenario-specific value of statistical life.

A.1.2 AP3 MODEL OUTPUTS

Four files are directly output of the AP3 scripts as modified by IEc:

1. A .mat file called "AP3 BPT Estimates" containing the source-specific BPT values for each county and precursor pollutant. The columns correspond to: NH_3, NO_X, PM_{10}, $PM_{2.5}$, SO_2, VOC (anthropogenic origin), and VOC (biologic origin). By default this file will be saved in the same directory as the AP3 scripts.
2. An Excel spreadsheet called "AP3 BPT Estimates" containing the source-specific BPT values for each county and precursor pollutant. The columns correspond to: NH_3, NO_X, PM_{10}, $PM_{2.5}$, SO_2, VOC (anthropogenic origin), and VOC (biologic origin). By default this file will be saved in the same directory as the AP3 scripts.
3. An Excel spreadsheet called "Total $PM_{2.5}$ Concentrations" containing the estimated $PM_{2.5}$ values for each county. By default this file will be saved in the same directory as the AP3 .mat files.
4. An Excel spreadsheet called "Speciated $PM_{2.5}$" containing the speciated $PM_{2.5}$ concentrations for each precursor pollutant and county. The columns correspond to: NO_3, SO_4, $PM_{2.5}$ primary, VOC (anthropogenic origin, VOC (biologic origin), and NH_4. By default this file will be saved in the same directory as the AP3 .mat files.

To facilitate future use of these output files, FIPS codes and column headers are added to each of the spreadsheets outside of MATLAB.

A.1.3 CALCULATING AP3-DIRECT BENEFITS

AP3-Direct benefits for each scenario are calculated by multiplying the precursor- and county-specific BPT values for each source type by the corresponding change in emissions.[24] For example, if the NH_3 low stack height emissions for county 1001 decreased by five tons, the associated benefits would be five times the NH_3 low stack height BPT value. The total benefits associated with each scenario are then simply the sum of all of these individual calculations. This makes it possible to analyze how the benefits are distributed across the different precursor pollutants, counties, and source types. For the purposes of this analysis, a three percent discount rate was applied to all benefits estimates. All tools use the same discount rate and cessation lag structure.

Because the reduced-form tools were developed at different times, the counties included in each model are slightly different, reflecting changes to counties in the US over time. To ensure consistency when comparing results from different models the following adjustments were made to AP3 direct model results:

1. Results from FIPS code 12025 were re-assigned to FIPS code 12086.
2. Results from FIPS code 51560 were combined with those from FIPS code 51005.

A.1.4 CALCULATING AP3-BENMAP BENEFITS

As noted above, the air quality surfaces generated in AP3 were also run through BenMAP for a separate point of comparison. Please refer to the appendix section A3 covering BenMAP methods for a detailed description of how those analyses were performed.

A.2 AP2 METHODS

The AP2 reduced-form tool was designed for and runs in the MathWorks program MATLAB, and that program is required to run the AP2 model. The model is composed of 19 individual script files and two data files that operate together to estimate pollutant- and county-specific BPT estimates for each of four emissions source types. To facilitate the use of the 2011 AP2 model as part of this project, several of the original scripts were modified to enable the import and export of data. Exhibit A-2 below provides a brief description of the calculations that occur in each script, and identifies where scripts were modified by IEc. The scripts run in the following order; several scripts are called more than once throughout the program:

PM_CRDM_Marginal.m

    Emissions_Import.m

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[24] For the tall stack counties where multiple BPT values were available, a single BPT value was used to calculate the tall stack benefits. The different BPT estimates were often less than 1% different from each other so the use of a single value did not significantly impact results.

- PM_Setup.m
- Population.m
- PM_Base_Conc.m
  - Ammonium_Excess.m
  - PM_25_Base_Raw.m
  - PM_25_Health_Base.m
- Mortality.m
  - Area_Sources.m
    - Area_Reset.m
    - Ammonium_Excess.m
    - PM_25_Health.m
  - Low_Stacks.m
    - Area_Reset.m
    - Low_Reset.m
    - Ammonium_Excess.m
    - PM_25_Health.m
  - Medium_Stacks.m
    - Med_Reset.m
    - Ammonium_Excess.m
    - PM_25_Health.m
  - Tall_Stacks.m
    - Med_Reset.m
    - Tall_Reset.m
    - Ammonium_Excess.m
    - PM_25_Health.m
- Damages.m

EXHIBIT A-2. AP2 MODEL SCRIPTS

AP2 MODEL SCRIPTS	
PM_CRDM_Marginal	This is the master script that runs all other components of the AP2 model.

AP2 MODEL SCRIPTS	
Emissions_Import	This script was created by IEc and allows the user to update the area, low stack, medium stack, tall stack and new tall stack emissions stored in the two .mat files that the AP2 model calls.
PM_Setup	This script initializes a series of output matrices and is where the value per statistical life is set.
Population	This script creates a set of matrices that store different population data (e.g., total population or population over 30).
PM_Base_Conc	This script translates the raw precursor pollutant emissions into their $PM_{2.5}$ components and then calculates total $PM_{2.5}$ concentrations. It also includes a set of hard coded calibration factors for each precursor that are used in converting emissions into concentrations. These calibration factors are different between AP2 and AP3.
Ammonium_Excess	This script is run is several places throughout the model and is used to capture the secondary transformation of precursor pollutants into $PM_{2.5}$.
PM_25_Base_Raw	This script calculates and stores the baseline $PM_{2.5}$ concentration.
PM_25_Health_Base and	This script calculates the estimated number of health impacts, and their cost, associated with the baseline quantity of precursor emissions.
Mortality	This script runs the “Area_Sources”, “Low_Stacks”, “Medium_Stacks”, and “Tall_Stacks” scripts that incrementally adjust the baseline emissions and calculate the marginal change in health impacts.
Area_Sources, Low_Stacks, Medium_Stacks, and Tall_Stacks	These scripts loop over each precursor pollutant and each county, incrementally adjusting the baseline emissions by 1 ton and calculating the marginal change in health impacts. This marginal change becomes the county- and pollutant- specific BPT value for each source type.
Area_Reset, Low_Reset, Med_Reset, and Tall_Reset	These scripts re-calculate the precursor pollutant concentrations from the baseline emissions for each source type.
PM_25_Health	This script calculates the estimated number of health impacts, and their cost, associated with the incrementally adjusted precursor emissions.
Damages	This script combines the BPT values into a set of output matrices. This code was modified by IEc to export these results to an Excel file.

In addition to the model scripts described above, the AP2 model also includes two .mat data files: one including data associated with the area and low stack sources (“2011_PM_Worksheet_Area_Low_Western_Adj.mat”) and the other including data for the medium and tall stack sources (“2011_PM_Worksheet_Med_Tall_Western_

Adj.mat"). Both of these files also contain the population and incidence rate data utilized by the model.[25] Prior to running the model, the data stored in these files need to be updated with values that are specific to the policy scenario being analyzed. The next few sections provide instructions for updating the .mat files, describe the outputs generated by the AP2 model, and outline how the AP2 BPT values are used to estimate benefits.

A.2.1 AP2 MODEL INPUTS

For this project, two types of AP2 results were compared to full-form model results: one generated from applying the AP2 BPT values to changes in emissions, and one generated by running the AP2 air quality surfaces through BenMAP. Note that the AP2 BPT values are generated by running the baseline scenario emissions through the model. The control emissions are only run to obtain the air quality surfaces needed to generate the second set of results. Therefore, when doing model runs using control emissions, the code can be stopped after running "PM_Base_Conc.m." To run AP2 for a new policy scenario, the following steps should be followed. These steps are necessary to ensure that all of the model inputs are consistent with the policy scenario being analyzed.

1. Emissions file preparation[26]:
    a. Save each source type's emissions as individual .csv files.
    b. The first column should contain county FIPS codes and columns 2-8 should contain pollutant-specific emissions in tons [NH_3, NO_X, PM_{10}, $PM_{2.5}$, SO_2, VOC (anthropogenic origin), and VOC (biologic origin)].
    c. The FIPS order and included FIPS must match each source type's AP2 source/receptor matrix.
    d. No headers should be included.
2. Population data preparation
    a. The population data occupies a 3,109x19 matrix in AP2. The data should contain population totals for the following age groups for each of the 3,109 counties included in A2: 0TO0, 1TO4, 5TO9, 10TO14, 15TO19, 20TO24, 25TO34, 30TO34, 35TO39, 40TO44, 45TO49, 50TO54, 55TO59, 60TO64, 65TO69, 70TO74, 75TO79, 80TO84, 85TOUP.

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[25] In the un-modified version of the model, these data will be from 2011.

[26] Three of the five source receptor matrices include transport coefficients for the total quantity of emissions generated in a particular county in the contiguous United States. However, the tall stack and new tall stack source types have source-specific values. As such, factors are only available for a subset of counties. For this project, any tall stack emissions generated in a county not included in either the tall stack or new tall stack matrices were combined with the medium stack county-level emissions. Furthermore, the tall stack and new tall stack matrices contain coefficients for multiple point sources in some counties. Because the scenario emissions could not be linked to these specific sources, they were divided evenly among the different point sources.

   b. The FIPS order and included FIPS must match AP2's FIPs order.

3. Mortality data preparation
   a. The mortality data occupies a 3,109x19 matrix in AP2. The data should contain all-cause mortality rates for the following age groups for each of the 3,109 counties included in A3: 0TO0, 1TO4, 5TO9, 10TO14, 15TO19, 20TO24, 25TO34, 30TO34, 35TO39, 40TO44, 45TO49, 50TO54, 55TO59, 60TO64, 65TO69, 70TO74, 75TO79, 80TO84, 85TOUP.
   b. The FIPS order and included FIPS must match AP2's FIPs order.
4. Updates to script code and data files:
   a. Load the scenario-specific population data into cell reference "Mortality{6,1}" in both AP2 .mat files and save.
   b. Load the scenario-specific all-cause mortality rates into cell reference "Mortality{3,1}" in both AP2 .mat files and save.
   c. Update the load file references in "Emissions_Import.m", "PM_Setup.m", "PM_Base_Conc.m", "Area_Sources.m", and "Medium_Stacks.m".
   d. Update "Emissions_Import.m" with the .csv file names for the scenario-specific emissions files for each source type.
   e. Update "PM_Setup.m" with the scenario-specific value of statistical life.

A.2.2 AP2 MODEL OUTPUTS

Four files are directly output of the AP2 scripts as modified by IEc:

1. A .mat file called "AP2 BPT Estimates" containing the source-specific BPT values for each county and precursor pollutant. The columns correspond to: NH_3, NO_X, PM_{10}, $PM_{2.5}$, SO_2, VOC (anthropogenic origin), and VOC (biologic origin). By default this file will be saved in the same directory as the AP2 scripts.
2. An Excel spreadsheet called "AP2 BPT Estimates" containing the source-specific BPT values for each county and precursor pollutant. The columns correspond to: NH_3, NO_X, PM_{10}, $PM_{2.5}$, SO_2, VOC (anthropogenic origin), and VOC (biologic origin). By default this file will be saved in the same directory as the AP2 scripts.
3. An Excel spreadsheet called "Total $PM_{2.5}$ Concentrations" containing the estimated $PM_{2.5}$ values for each county. By default this file will be saved in the same directory as the AP2 .mat files.
4. An Excel spreadsheet called "Speciated $PM_{2.5}$" containing the speciated $PM_{2.5}$ concentrations for each precursor pollutant and county. The columns correspond to: NO_3, SO_4, $PM_{2.5}$ primary, VOC (anthropogenic origin, and VOC (biologic origin). By default this file will be saved in the same directory as the AP2 .mat files.

To facilitate future use of these output files, FIPS codes and column headers are added to each of the spreadsheets outside of MATLAB.

A.2.3 CALCULATING AP2-DIRECT BENEFITS

AP2 direct benefits for each scenario are calculated by multiplying the precursor- and county-specific BPT values for each source type by the corresponding change in emissions.[27] For example, if the NH_3 low stack height emissions for county 1001 decreased by five tons, the associated benefits would be five times the NH_3 low stack height BPT value. The total benefits associated with each scenario are then simply the sum of all of these individual calculations. This makes it possible to analyze how the benefits are distributed across the different precursor pollutants, counties, and source types. For the purposes of this analysis, a three percent discount rate was applied to all benefits estimates.

Because the reduced-form tools were developed at different times, the counties included in each model are slightly different, reflecting changes to counties in the US over time. To ensure consistency when comparing results from different models the following adjustments were made to AP2 direct model results:

1. Results from FIPS code 12025 were re-assigned to FIPS code 12086.
2. Results from FIPS code 51560 were combined with those from FIPS code 51005.

A.2.4 CALCULATING AP2-BENMAP BENEFITS

As noted above, the air quality surfaces generated in AP2 were also run through BenMAP for a separate point of comparison. Please refer to the appendix section A3 covering BenMAP methods for a detailed description of how those analyses were performed.

A3. SOURCE APPORTIONMENT BENEFIT PER TON METHODS

The steps below describe the process for applying the source apportionment benefit-per-ton (SA BPT) values to emissions changes in tons for five different policy scenarios – Clean Power Plan Proposal, Tier 3, Cement Kilns, Pulp and Paper, and Refineries – to obtain the SA Direct results discussed in this report.

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[27] For the tall stack counties where multiple BPT values were available, a single BPT value was used to calculate the tall stack benefits. The different BPT estimates were often less than 1% different from each other so the use of a single value did not significantly impact results.

The methodology for the SA BPT development was originally published by EPA in a Technical Support Document (TSD) in 2013[28] and updated in a February 2018 TSD.[29] The values represent estimates of the average avoided human health impacts, and monetized benefits related to emissions of $prPM_{2.5}$, NO_x and SO_2 from 17 sectors using the results of source apportionment photochemical modeling. In our analysis we used BPT values for 5 of these 17 sectors: cement kilns, electricity generating units (CPP Proposal), on-road mobile sources (Tier 3), pulp and paper facilities, and refineries.

In the 2018 TSD, these values are presented as the total dollar value (mortality and morbidity) per ton of $prPM_{2.5}$, NO_x, and SO_2. According to the TSD, "These values represent a national average $/ton of total emissions for each sector; the $/ton for a given location (e.g. state or county) may be higher or lower than the value reported here. Estimates do not capture important differences in marginal $/ton that may exist due to different combinations of reductions (i.e., all other sectors are held constant) or nonlinearities within a particular pollutant."[30] EPA produces BPT estimates for each precursor using two mortality estimates from Krewski et al. (2009) and Lepeule et al. (2012) both paired with a 3% and 7% discount rate. In our analysis we use only the BPT values for Krewski et al. (2009) and the 3% discount rate.

To calculate the SA Direct values in this report, we multiplied the Krewski 3% SA BPT values for 2025 (all scenarios except Tier 3) and 2030 (for the Tier 3 scenario) by emissions reduction amounts in tons for each of the five policy scenarios. Since the SA BPT values represent total dollar value for both mortality and morbidity, we applied adjustment factors to isolate mortality-only benefits (Exhibit A-3).

EXHIBIT A-3. SA DIRECT MORTALITY-ONLY ADJUSTMENT FACTORS

POLICY	ADJUSTMENT FACTOR
EGU	0.973
On-Road	0.972
Cement	0.977
Pulp & Paper	0.973
Refineries	0.971

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[28] Technical Support Document - Estimating the Benefit per Ton of Reducing PM2.5 Precursors from 17 Sectors. January 2013. Accessed at: https://www.epa.gov/sites/production/files/2014-10/documents/sourceapportionmentbpttsd.pdf

[29] Technical Support Document - Estimating the Benefit per Ton of Reducing PM2.5 Precursors from 17 Sectors. February 2018. Accessed at: https://www.epa.gov/sites/production/files/2018-02/documents/sourceapportionmentbpttsd_2018.pdf:

[30] Technical Support Document - Estimating the Benefit per Ton of Reducing PM2.5 Precursors from 17 Sectors. February 2018. Accessed at: https://www.epa.gov/sites/production/files/2018-02/documents/sourceapportionmentbpttsd_2018.pdf

We performed these calculations using county-level emissions change data to obtain SA Direct benefits estimates at the county level, and summed these to produce nation-level estimates. Since SA BPT values exist only for $prPM_{2.5}$[31], NO_x, and SO_2, we summed the benefits for these three precursors to get a SA Direct benefits estimates for Total $PM_{2.5}$.

A4. [MODEL] BENMAP METHODS

BenMAP-CE version 1.5.0.4 was used to generate health benefits estimates for both the full-form models as well as several reduced-form tools. This section describes in greater detail the steps used to convert air quality concentration changes into changes in mortality incidence for those models. For CMAQ, CAMx, and InMAP, benefits were estimated at the 12 km grid level and then aggregated to the county- and national-level. For AP2 and AP3, benefits were estimated at the county-level and aggregated to the national-level. Total $PM_{2.5}$ benefits for each model were generated using the approach outlined in Chapter 2. Total benefits were apportioned to each precursor ($prPM_{2.5}$ represented by EC only, NO_3, and SO_4) based on its contribution to the total $PM_{2.5}$ air quality delta. We performed the analysis using Excel, and we describe the specific steps of this process for each model in greater detail below.

A.4.1. FULL-FORM MODELS AND INMAP

For the CMAQ and CAMx full-form models, and the InMAP reduced-form tool, we used air quality data provided by EPA at the 12 km level and the 12 km total $PM_{2.5}$ benefits produced by BenMAP-CE for each policy scenario. The precursors of interest for this analysis were EC, total sulfate, and total nitrate. We calculated benefits for each precursor at the county- and national-level as follows:

1. Calculating air quality deltas: for total $PM_{2.5}$, $prPM_{2.5}$, SO_4, and NO_3, we subtracted the control air quality concentrations from the baseline.
2. Calculating delta percent: we also calculated the percent that each precursor delta contributes to the total $PM_{2.5}$ delta for each grid cell by dividing the precursor-specific delta by the total $PM_{2.5}$ delta. Due to rounding in the air quality concentrations, we encountered instances where total $PM_{2.5}$ did not have an air quality change, but some precursors in the same grid cell did. In these instances, we assigned all precursors 0 deltas as well.
3. Apportioning total benefits[32]: we multiplied the precursor delta percentages by the total $PM_{2.5}$ benefits for each grid cell. Note, air quality data were available at the 12 km grid level (which extended beyond the contiguous US boundary) while total $PM_{2.5}$ benefits were calculated for the 12 km clipped grid definition in

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[31] The prPM2.5 values represent emissions from elemental carbon (EC) only.

[32] Total $PM_{2.5}$ benefits included contributions from OC and Crustal. Therefore, total benefits were also allocated to those precursors and then later subtracted out of total $PM_{2.5}$ benefits. Such that total $PM_{2.5}$ benefits ultimately only reflected the contribution of EC.

BenMAP-CE (which only contains all 12 km grid cells with population data). Thus, only 47,800 grid cells with air quality data have corresponding benefits estimates.

4. Converting 12 km benefits to county level: we used the 12 km clipped to US county crosswalk from BenMAP-CE to aggregate the 12 km results to the county-level. This crosswalk identifies the fraction of each 12 km grid cell's population which falls within the different counties it intersects. We multiplied this percent by the 12 km benefits to apportion the benefits to the appropriate county/counties. We encountered 3 issues with this step.
    a. During this analysis, we identified four grid cells that contain population data (and therefore should contain total $PM_{2.5}$ benefits) that are missing from BenMAP-CE's 12 km clipped grid definition. Thus, the total $PM_{2.5}$ benefits dataset inadvertently excludes any benefits that would have been calculated for these grid cells. However, the total population in these grid cells was only 68 individuals so this exclusion does not have a significant impact on the final results.
    b. There are also three 12 km clipped grid cells which have total $PM_{2.5}$ benefits, but which are excluded from the 12 km to county crosswalk.[33] These results are also excluded from the analysis, but do not have a significant impact on the final results.
    c. Finally, for 12 km grid cells that intersected multiple counties, the factions in the crosswalk did not always sum to exactly 100%. Therefore, a small percentage (less than .001%) of benefits from these grid cells was not carried through to the county-level.
5. Standardizing county designations: Because the reduced-form tools were developed at different times, the counties included in each model are slightly different, reflecting changes to counties in the US over time. To ensure consistency when comparing results from different models, the following adjustments were made to the county-level results:
    a. Benefits from county 08014 were added to those from 08013.
6. Applying a cessation lag adjustment with a 3% discount rate: all county results were multiplied by an adjustment factor to address how reductions in the incidence of monetized health benefits accrue over time, which is termed the "cessation lag". The adjustment factor we applied, 0.90605998, reflects a 20-year distributed lag structure commonly employed by EPA that assumes 30% of the

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[33] These three grid cells are located in the Florida Keys and their exclusion seems to be related to a misalignment between the national and county borders.

benefits accrue in the first year, 50% accrue evenly over years two through five, and the remaining 20% accrue evenly over the remaining years.[34] The adjustment factor also discounts the value of this stream of benefits to account for the time value of money, using a discount rate of 3%.

7. Calculating national-level benefits: we summed the county-level benefits to calculate the national results.

A.4.2. APX BENMAP

For the AP2 and AP3 BenMAP reduced-form tools, we generated air quality data at the county level and exported it from the model. We combined these data with county-level total $PM_{2.5}$ benefits produced by BenMAP-CE for each policy scenario. The precursors of interest for this analysis were EC, SO_4, and NO_3. We calculated benefits for each precursor at the county- and national-level as follows:

1. Calculating air quality deltas: for total $PM_{2.5}$, $prPM_{2.5}$, SO_4, NO_3 we subtracted the control air quality concentrations from the baseline.
2. Calculating delta percent: we also calculated the percent that each precursor delta contributes to the total $PM_{2.5}$ delta for each grid cell by dividing the precursor-specific delta by the total $PM_{2.5}$ delta. There were two exceptions to this:
    a. The counties with FIPs codes 12025 and 51560 in the APX outputs do not have identical matches in the BenMAP-CE county grid definition. These counties were matched with benefits from counties 12086 and 51005, which are the counties that correspond to the same geographic locations in the more recent county grid definition used by BenMAP-CE.
    b. We summed the total $PM_{2.5}$ delta of the old and new FIPs for each pair and divided the precursor-specific deltas by the sum.
3. Apportioning total benefits[35]: we multiplied the precursor delta percentages by the total $PM_{2.5}$ benefits for each grid cell.
4. Standardizing county designations: Because the county differences between APX and BenMAP were already addressed earlier in the process, no other county adjustments were required at this stage.

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[34] See, for example, Chapter 5 of EPA's 2012 Regulatory Impact Analysis for the most recently promulgated National Ambient Air Quality Standard (NAAQS) for PM2.5. https://www3.epa.gov/ttn/ecas/docs/ria/naaqs-pm_ria_final_2012-12.pdf

[35] Total $PM_{2.5}$ benefits included contributions from OC and Crustal. Therefore, total benefits were also allocated to those precursors and then later subtracted out of total $PM_{2.5}$ benefits. Such that total $PM_{2.5}$ benefits ultimately only reflected the contribution of EC.

5. Applying a cessation lag adjustment with a 3% discount rate: all county results were multiplied by the cessation lag and discounting adjustment factor of 0.90605998, as described above for full-form models and INMAP.
6. Calculating national-level benefits: we summed the county-level benefits to calculate the national results.

A5. EASIUR DIRECT METHODS

For the EASIUR Direct reduced-form tool, EPA provided speciated benefits results at the 36 km grid level for each policy scenario. Benefits were provided for $prPM_{2.5}$ (represented by EC only), SO_4, NO_3, and NH_3. We summed the benefits for $prPM_{2.5}$, SO_4, NO_3, and NH_3 to calculate total $PM_{2.5}$ benefits. The precursors of interest for this analysis were $prPM_{2.5}$, SO_4, and NO_3. We calculated benefits at the county- and national-level as follows:

1. Converting 36 km benefits to county level: We used the 36 km to US county crosswalk from BenMAP-CE to aggregate the 36 km results to the county-level. The crosswalk identifies the fraction of the 36 km grid cell’s population which falls within the different counties it intersects. We multiplied this percent by the 36 km benefits to apportion the benefits to the appropriate county/counties. We encountered one issue with this step.
    a. The 36 km to US county crosswalk excludes grid cells that do not contain population. However, the EASIUR Direct benefits were not calculated using BenMAP-CE. Therefore, EASIUR generated benefits in 173 36 km grid cells that were not included in the BenMAP-CE crosswalk. The grid cells missing varied by policy scenario. Thus, these results are excluded from the county-level EASIUR Direct results. These results average 0.05% of total benefits across the scenarios.
2. Standardizing county designations: Because the reduced-form tools were developed at different times, the counties included in each model are slightly different, reflecting changes to counties in the US over time. To ensure consistency when comparing results from different models, the following adjustments were made to the county-level results:
    a. Benefits from county 08014 were added to those from 08013.
3. Applying a cessation lag adjustment with a 3% discount rate: all county results were multiplied by the cessation lag and discounting adjustment factor of 0.90605998, as described above for full-form models and INMAP.
4. Calculating national-level benefits: since the county-level results excluded some of the 36 km benefits due to a crosswalk issue, we calculated the national-level benefits using the 36 km level benefits. These results are thus slightly larger than they would be if the county-level results were simply summed.

a. Using ArcGIS, we clipped the 36 km grid to the contiguous US boundary.

b. Using this grid, we identified the 36 km level benefits within the contiguous US.

c. We summed those 36 km benefits by precursor to calculate the national-level benefits.

d. These national results were also multiplied by the same cessation lag and discounting adjustment factor of 0.90605998 that we applied to the other model results.

APPENDIX B | STATES IN EACH NCA REGION IN THE CONTINENTAL US

EXHIBIT B-1. STATES IN EACH NCA REGION IN THE CONTINENTAL US

NCA REGION	STATES
Midwest	Arkansas
	Illinois
	Indiana
	Iowa
	Kansas
	Kentucky
	Michigan
	Minnesota
	Missouri
	Nebraska
	North Dakota
	Ohio
	Oklahoma
	Pennsylvania
	South Dakota
	Tennessee
	West Virginia
	Wisconsin
Northeast	Connecticut
	Delaware
	District of Columbia
	Kentucky
	Maine
	Maryland
	Massachusetts
	New Hampshire
	New Jersey
	New York
	Pennsylvania
	Rhode Island
	Vermont
	Virginia
	West Virginia

NCA REGION	STATES
Northern Great Plains	Colorado
	Idaho
	Kansas
	Montana
	Nebraska
	North Dakota
	South Dakota
	Utah
	Wyoming
Northwest	California
	Idaho
	Nevada
	Oregon
	Utah
	Washington
Southeast	Alabama
	Arkansas
	Florida
	Georgia
	Kentucky
	Louisiana
	Mississippi
	North Carolina
	Oklahoma
	South Carolina
	Tennessee
	Texas
	Virginia
Southern Great Plains	Colorado
	Kansas
	New Mexico
	Oklahoma
	Texas
Southwest	Arizona
	California
	Colorado
	Nevada
	New Mexico
	Utah

APPENDIX C | NATIONAL BENEFITS AND MODEL STATISTICS

EXHIBIT C-1. SCALED NATIONAL BENEFITS BY POLICY AND $PM_{2.5}$ COMPONENT (MILLIONS). NOTE THAT TOTAL PM2.5 IS NOT ALWAYS THE SUM OF NITRATE, SULFATE, AND PRIMARY BENEFITS BECAUSE SOME TOOLS AND SCENARIOS HAD NON-ZERO BENEFITS RELATED TO SECONDARY PM2.5 FORMATION FROM AMMONIA AND/OR VOC.

POLICY SCENARIO	$PM_{2.5}$ COMPONENT	CMAQ BENMAP	CAMX BENMAP	AP2 DIRECT	AP2 BENMAP	AP3 DIRECT	AP3 BENMAP	INMAP BENMAP	EASIUR DIRECT	SA DIRECT
Cement Kilns	NO3	$600	$620	$970	$990	$1,700	$350	$3,200	$730	$670
Cement Kilns	Primary $PM_{2.5}$	$1,900	$2,000	$940	$980	$1,900	$2,000	$1,600	$1,000	$2,600
Cement Kilns	SO4	$2,700	$2,700	$2,000	$2,000	$2,900	$3,400	$3,100	$1,300	$3,000
Cement Kilns	Total $PM_{2.5}$	$5,300	$5,400	$3,900	$4,000	$6,500	$5,700	$8,000	$3,100	$6,300
CPP Proposal	NO3	$1,700	$1,400	$3,400	$3,400	$5,700	$720	$11,000	$2,500	$2,700
CPP Proposal	Primary $PM_{2.5}$	$3,500	$4,000	$1,700	$1,700	$3,100	$3,600	$5,800	$4,200	$5,800
CPP Proposal	SO4	$15,000	$16,000	$9,600	$10,000	$14,000	$17,000	$24,000	$7,900	$19,000
CPP Proposal	Total $PM_{2.5}$	$21,000	$21,000	$15,000	$15,000	$23,000	$21,000	$41,000	$15,000	$28,000
Pulp and Paper	NO3	$130	$130	$180	$250	$330	$7	$740	$200	$160
Pulp and Paper	Primary $PM_{2.5}$	$710	$720	$370	$380	$730	$780	$740	$570	$520
Pulp and Paper	SO4	$1,600	$1,600	$890	$1,100	$1,300	$1,800	$2,000	$800	$2,100
Pulp and Paper	Total $PM_{2.5}$	$2,600	$2,600	$1,400	$1,700	$2,400	$2,500	$3,500	$1,600	$2,800
Refineries	NO3	$160	$190	$610	$640	$1,300	$470	$1,500	$300	$290
Refineries	Primary $PM_{2.5}$	$630	$650	$410	$430	$820	$880	$890	$410	$610
Refineries	SO4	$810	$740	$590	$620	$830	$1,000	$920	$340	$1,400
Refineries	Total $PM_{2.5}$	$1,800	$1,800	$1,600	$1,700	$2,900	$2,400	$3,300	$1,100	$2,300
Tier 3	NO3	$1,900	-	$7,000	$7,300	$12,000	$4,600	$11,000	$3,500	$3,500
Tier 3	Primary $PM_{2.5}$	$1,800	-	$1,200	$1,300	$2,400	$2,600	$1,800	$1,500	$3,000
Tier 3	SO4	$320	-	$810	$850	$1,200	$1,400	$400	$290	$360
Tier 3	Total $PM_{2.5}$	$4,100	-	$11,000	$12,000	$18,000	$11,000	$13,000	$5,300	$6,800

EXHIBIT C-2. REGIONAL STATISTICS (DOLLAR VALUES IN THOUSANDS)

SCENARIO	$PM_{2.5}$ COMPONENT	STATISTIC	SCALE	AP2 BENMAP	AP3 BENMAP	INMAP BENMAP
CPP	NO3	Mean Bias	Region	$251,761.35	$(134,098.12)	$1,323,708.16
Cement Kilns	NO3	Mean Bias	Region	$55,287.85	$(35,485.88)	$375,999.35
Pulp and Paper	NO3	Mean Bias	Region	$16,096.54	$(18,267.02)	$87,095.65
Refineries	NO3	Mean Bias	Region	$68,388.10	$44,640.73	$194,445.83
Tier 3	NO3	Mean Bias	Region	$767,714.69	$389,608.87	$1,243,170.87
CPP	SO4	Mean Bias	Region	$(779,540.71)	$171,762.39	$1,220,552.66
Cement Kilns	SO4	Mean Bias	Region	$(91,680.99)	$102,573.66	$58,598.68
Pulp and Paper	SO4	Mean Bias	Region	$(76,986.36)	$23,920.46	$53,939.56
Refineries	SO4	Mean Bias	Region	$(28,014.00)	$30,852.81	$15,287.08
Tier 3	SO4	Mean Bias	Region	$75,724.59	$156,974.71	$11,384.81
CPP	Primary $PM_{2.5}$	Mean Bias	Region	$(9,902.94)	$360.88	$12,979.02
Cement Kilns	Primary $PM_{2.5}$	Mean Bias	Region	$(5,868.34)	$276.71	$(1,817.59)
Pulp and Paper	Primary $PM_{2.5}$	Mean Bias	Region	$(1,808.46)	$358.26	$147.87
Refineries	Primary $PM_{2.5}$	Mean Bias	Region	$(2,957.18)	$3,928.56	$4,005.52
Tier 3	Primary $PM_{2.5}$	Mean Bias	Region	$(12,788.66)	$16,214.44	$(1,033.83)
CPP	Total $PM_{2.5}$	Mean Bias	Region	$(533,542.85)	$56,715.00	$2,557,360.23
Cement Kilns	Total $PM_{2.5}$	Mean Bias	Region	$(48,971.66)	$60,654.30	$426,078.99
Pulp and Paper	Total $PM_{2.5}$	Mean Bias	Region	$(78,886.19)	$(10,176.21)	$125,002.49
Refineries	Total $PM_{2.5}$	Mean Bias	Region	$8,360.64	$50,365.81	$184,689.33
Tier 3	Total $PM_{2.5}$	Mean Bias	Region	$1,189,944.56	$922,114.83	$1,254,971.93
CPP	NO3	Mean Error	Region	$251,761.35	$139,662.67	$1,323,708.16
Cement Kilns	NO3	Mean Error	Region	$55,287.85	$56,009.65	$375,999.35
Pulp and Paper	NO3	Mean Error	Region	$16,096.54	$20,428.15	$87,095.65
Refineries	NO3	Mean Error	Region	$68,388.10	$49,326.09	$194,445.83
Tier 3	NO3	Mean Error	Region	$767,714.69	$390,172.86	$1,243,170.87
CPP	SO4	Mean Error	Region	$789,561.72	$706,130.81	$1,433,445.88

SCENARIO	$PM_{2.5}$ COMPONENT	STATISTIC	SCALE	AP2 BENMAP	AP3 BENMAP	INMAP BENMAP
Cement Kilns	SO4	Mean Error	Region	$91,680.99	$150,561.96	$198,051.11
Pulp and Paper	SO4	Mean Error	Region	$78,164.93	$67,264.91	$180,260.29
Refineries	SO4	Mean Error	Region	$39,279.95	$37,105.64	$79,833.25
Tier 3	SO4	Mean Error	Region	$86,808.91	$158,042.20	$52,976.74
CPP	Primary $PM_{2.5}$	Mean Error	Region	$9,910.04	$3,134.81	$12,989.40
Cement Kilns	Primary $PM_{2.5}$	Mean Error	Region	$5,868.34	$838.90	$2,718.37
Pulp and Paper	Primary $PM_{2.5}$	Mean Error	Region	$1,808.46	$400.00	$828.64
Refineries	Primary $PM_{2.5}$	Mean Error	Region	$2,985.37	$4,023.71	$4,064.39
Tier 3	Primary $PM_{2.5}$	Mean Error	Region	$12,788.66	$22,688.18	$5,141.99
CPP	Total $PM_{2.5}$	Mean Error	Region	$630,986.72	$603,943.70	$2,559,376.43
Cement Kilns	Total $PM_{2.5}$	Mean Error	Region	$59,022.02	$112,279.48	$426,078.99
Pulp and Paper	Total $PM_{2.5}$	Mean Error	Region	$78,886.19	$61,265.82	$173,246.40
Refineries	Total $PM_{2.5}$	Mean Error	Region	$42,997.28	$63,872.26	$184,689.33
Tier 3	Total $PM_{2.5}$	Mean Error	Region	$1,189,944.56	$922,114.83	$1,254,971.93
CPP	NO3	Normalized Mean Bias	Region	106%	-56%	557%
Cement Kilns	NO3	Normalized Mean Bias	Region	64%	-41%	437%
Pulp and Paper	NO3	Normalized Mean Bias	Region	84%	-95%	453%
Refineries	NO3	Normalized Mean Bias	Region	299%	195%	851%
Tier 3	NO3	Normalized Mean Bias	Region	280%	142%	453%
CPP	SO4	Normalized Mean Bias	Region	-35%	8%	55%
Cement Kilns	SO4	Normalized Mean Bias	Region	-24%	27%	15%
Pulp and Paper	SO4	Normalized Mean Bias	Region	-34%	10%	24%
Refineries	SO4	Normalized Mean Bias	Region	-24%	27%	13%
Tier 3	SO4	Normalized Mean Bias	Region	164%	340%	25%

SCENARIO	$PM_{2.5}$ COMPONENT	STATISTIC	SCALE	AP2 BENMAP	AP3 BENMAP	INMAP BENMAP
CPP	Primary $PM_{2.5}$	Normalized Mean Bias	Region	-50%	2%	65%
Cement Kilns	Primary $PM_{2.5}$	Normalized Mean Bias	Region	-50%	2%	-15%
Pulp and Paper	Primary $PM_{2.5}$	Normalized Mean Bias	Region	-46%	9%	4%
Refineries	Primary $PM_{2.5}$	Normalized Mean Bias	Region	-31%	41%	42%
Tier 3	Primary $PM_{2.5}$	Normalized Mean Bias	Region	-31%	40%	-3%
CPP	Total $PM_{2.5}$	Normalized Mean Bias	Region	-22%	2%	104%
Cement Kilns	Total $PM_{2.5}$	Normalized Mean Bias	Region	-10%	12%	87%
Pulp and Paper	Total $PM_{2.5}$	Normalized Mean Bias	Region	-29%	-4%	47%
Refineries	Total $PM_{2.5}$	Normalized Mean Bias	Region	5%	28%	104%
Tier 3	Total $PM_{2.5}$	Normalized Mean Bias	Region	321%	249%	339%
CPP	NO3	Normalized Mean Error	Region	106%	59%	557%
Cement Kilns	NO3	Normalized Mean Error	Region	64%	65%	437%
Pulp and Paper	NO3	Normalized Mean Error	Region	84%	106%	453%
Refineries	NO3	Normalized Mean Error	Region	299%	216%	851%
Tier 3	NO3	Normalized Mean Error	Region	280%	142%	453%
CPP	SO4	Normalized Mean Error	Region	36%	32%	65%
Cement Kilns	SO4	Normalized Mean Error	Region	24%	39%	52%
Pulp and Paper	SO4	Normalized Mean Error	Region	34%	29%	79%
Refineries	SO4	Normalized Mean Error	Region	34%	32%	69%
Tier 3	SO4	Normalized Mean Error	Region	188%	342%	115%

SCENARIO	$PM_{2.5}$ COMPONENT	STATISTIC	SCALE	AP2 BENMAP	AP3 BENMAP	INMAP BENMAP
CPP	Primary $PM_{2.5}$	Normalized Mean Error	Region	50%	16%	65%
Cement Kilns	Primary $PM_{2.5}$	Normalized Mean Error	Region	50%	7%	23%
Pulp and Paper	Primary $PM_{2.5}$	Normalized Mean Error	Region	46%	10%	21%
Refineries	Primary $PM_{2.5}$	Normalized Mean Error	Region	31%	42%	42%
Tier 3	Primary $PM_{2.5}$	Normalized Mean Error	Region	31%	55%	13%
CPP	Total $PM_{2.5}$	Normalized Mean Error	Region	26%	25%	104%
Cement Kilns	Total $PM_{2.5}$	Normalized Mean Error	Region	12%	23%	87%
Pulp and Paper	Total $PM_{2.5}$	Normalized Mean Error	Region	29%	23%	65%
Refineries	Total $PM_{2.5}$	Normalized Mean Error	Region	24%	36%	104%
Tier 3	Total $PM_{2.5}$	Normalized Mean Error	Region	321%	249%	339%
CPP	NO3	R squared	Region	0.82	0.74	0.43
Cement Kilns	NO3	R squared	Region	0.89	0.34	0.85
Pulp and Paper	NO3	R squared	Region	0.58	0.01	0.27
Refineries	NO3	R squared	Region	0.89	0.55	0.73
Tier 3	NO3	R squared	Region	0.81	0.53	0.73
CPP	SO4	R squared	Region	0.85	0.85	0.76
Cement Kilns	SO4	R squared	Region	0.91	0.91	0.54
Pulp and Paper	SO4	R squared	Region	0.85	0.85	0.40
Refineries	SO4	R squared	Region	0.78	0.78	0.18
Tier 3	SO4	R squared	Region	0.14	0.14	0.27
CPP	Primary $PM_{2.5}$	R squared	Region	0.96	0.96	0.99
Cement Kilns	Primary $PM_{2.5}$	R squared	Region	0.98	0.98	0.73
Pulp and Paper	Primary $PM_{2.5}$	R squared	Region	1.00	1.00	0.92
Refineries	Primary $PM_{2.5}$	R squared	Region	0.99	0.99	0.92

SCENARIO	$PM_{2.5}$ COMPONENT	STATISTIC	SCALE	AP2 BENMAP	AP3 BENMAP	INMAP BENMAP
Tier 3	Primary $PM_{2.5}$	R squared	Region	0.90	0.90	0.96
CPP	Total $PM_{2.5}$	R squared	Region	0.86	0.90	0.77
Cement Kilns	Total $PM_{2.5}$	R squared	Region	0.97	0.96	0.74
Pulp and Paper	Total $PM_{2.5}$	R squared	Region	0.91	0.90	0.58
Refineries	Total $PM_{2.5}$	R squared	Region	0.88	0.89	0.62
Tier 3	Total $PM_{2.5}$	R squared	Region	0.90	0.73	0.90