APPENDIX 6

Delmarva Power & Light

Air Quality and Health Impacts Assessment of Alternative Energy Generation for Delmarva Power & Light's 2010 Integrated Resource Plan

Final Technical Report

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Executive Summary

The Delmarva Power & Light (Delmarva) Integrated Resource Plan (IRP) requires a comprehensive assessment of the environmental impacts and benefits associated with the use of alternative energy production sources, including the estimation of monetized costs and/or benefits for use by decision makers. This report summarizes the application of air quality modeling tools to examine the air quality impacts and related health costs and benefits associated with shifting traditional energy production sources to more environmentally-friendly alternative sources.

The Community Multiscale Air Quality (CMAQ) model was used to quantify the changes in air quality and mercury deposition associated with selected power generation scenarios. The Benefits Mapping and Analysis Program (BenMAP) was used to assess the health impacts and monetized health-related impacts of the simulated changes in ozone and fine particulate matter ($PM_{2.5}$) air quality. Pollutants that contribute to the formation of secondary aerosols include oxides of nitrogen ($NO_{x,}$), sulfur dioxide (SO_2), and other species. Thus this assessment of the health effects and benefits for ozone and $PM_{2.5}$ addresses the effects of changes in NO_x and SO_2 emissions. More qualitative methods were used to estimate the health and economic effects related to mercury deposition and also greenhouse gases. The analysis focused on the Mid-Atlantic states and the State of Delaware. The modeling analysis region is defined by a 4-km resolution grid encompassing Delaware and portions of other Mid-Atlantic and neighboring states.

The CMAQ simulations included a 2020 Reference Case simulation, and two alternative power-generation scenarios: one in which the emissions were adjusted to reflect the addition of offshore wind energy (Scenario S1) and a second scenario to reflect the addition of a combined-cycle gas facility (Scenario S3). Note that due to time constraints of the IRP submittal, an onshore wind energy scenario (Scenario S2) was examined based on the offshore wind scenario (S1), but not modeled with CMAQ. Two additional CMAQ simulations were run to examine the contributions from all electric generating unit (EGU) emissions to overall air quality as well as changes in air quality with time (from 2010 to 2020).

EGU emissions for use in the air quality modeling were estimated using ICF's Integrated Planning Model (IPM) and emissions for all other source sectors were obtained from future-year estimates prepared by the U.S. Environmental Protection Agency (EPA). The EGU emissions for the 2020 Reference Case reflect estimates of future economic and population growth and corresponding electric generation demand, any planned shutdowns of existing facilities, inclusion of new facilities to meet future generation demands, and application of emission controls on existing facilities associated with applicable state and national rules.

The CMAQ Particle and Precursor Tagging Methodology (CMAQ/PPTM) was used to examine the contributions of emissions from the major source categories, comprising point (EGU and non-EGU), on-road motor vehicle, non-road, and area sources, to simulated $PM_{2.5}$ concentrations and specifically to quantify the contributions from EGU sources. The CMAQ/PPTM results indicate that in 2020 EGU sources located with the region of interest account for about 12 percent of the simulated annual average $PM_{2.5}$ concentration for the Mid-Atlantic states, including Delaware. Overall, the contribution from EGU sources located in Delaware is very small to negligible.

The EGU emission estimates for 2020 for the offshore wind (S1), onshore wind (S2), and combined cycle (S3) scenarios show a mix of increases and decreases at various facilities in Delaware and surrounding states. In most cases, the changes in emissions at any one facility in 2020 are very small, and the overall change in EGU emissions from the 2020 Reference Case in each of the scenarios is also very small.

The CMAQ modeling results for both of the modeled alternative power generation scenarios show small increases and decreases in ozone concentration associated with the changes in emissions. The differences in ozone concentrations are projected to be very small (less than 0.1 part per billion (ppb)). Reference Case values for ozone range from approximately 20 to 100 ppb.

The absolute and relative differences in $PM_{2.5}$ concentration for 2020 are also projected to be small for both the S1 and S3 scenarios, compared to the Reference Case simulation. For the offshore wind scenario (S1), annual average $PM_{2.5}$ concentrations are slightly higher throughout much of the region of interest (including in Delaware) compared to the Reference Case and the differences range from approximately -0.01 to 0.01 microgram per cubic meter (μgm^{-3}). The increases appear to be due primarily to increases in emissions outside of the 4-km grid region (as projected by the IPM). For the combined cycle (S3) scenario, the simulated annual average $PM_{2.5}$ concentrations are lower throughout the majority of the region of interest compared to the 2020 Reference Case and the differences range from approximately -0.02 to 0.01 μgm^{-3}. Reference Case values for $PM_{2.5}$ range from approximately 4 to 40 μgm^{-3}.

For both scenarios, the CMAQ results indicate a mix of very small decreases and increases in mercury deposition throughout the region. For S1 (offshore wind), the maximum simulated decrease in annual mercury deposition for any grid cell in the domain is approximately 0.04 grams per square kilometer ($g\ km^{-2}$), while the maximum increase is 0.09 $g\ km^{-2}$. For S3 (combined cycle), the maximum simulated decrease in annual mercury deposition for any grid cell in the domain is approximately 0.09 $g\ km^{-2}$, while the maximum increase is 0.1 $g\ km^{-2}$. These are compared to absolute deposition amounts ranging from about 7 to greater than 100 $g\ km^{-2}$ within the 4-km grid region.

The increases and decreases in the modeling results reflect increases and decreases in the emissions at the various EGU facilities, including those outside of the principal region of interest, and the complex interactions between primary and secondary pollutants that, under certain conditions, can be counterintuitive. For example, simulated reductions in precursor emissions such as nitric oxide (NO) can lead to simulated increases in secondary pollutants such as ozone.

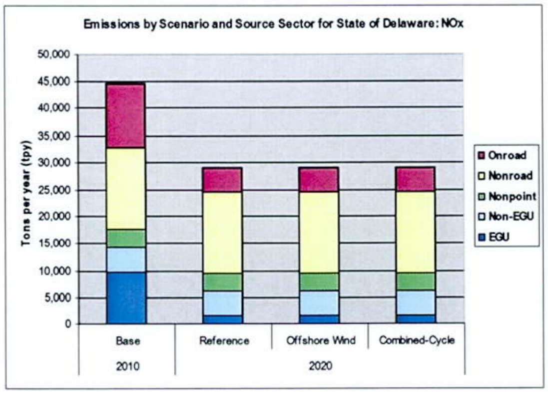
It is useful to compare the changes in concentration and deposition for Scenarios S1 and S3 (2020) with those associated with the larger emissions changes projected to occur between 2010 and 2020, which reflect implementation of emission control technologies following state and federal rule requirements, the shutting down of older facilities, fleet turnover of on-road motor vehicles and off-road equipment, the introduction of cleaner engine technologies, and the use of cleaner fuels. As a result, the CMAQ-simulated differences in pollutant concentrations between 2010 and 2020 are primarily reductions. Within the region of interest, daily maximum 8-

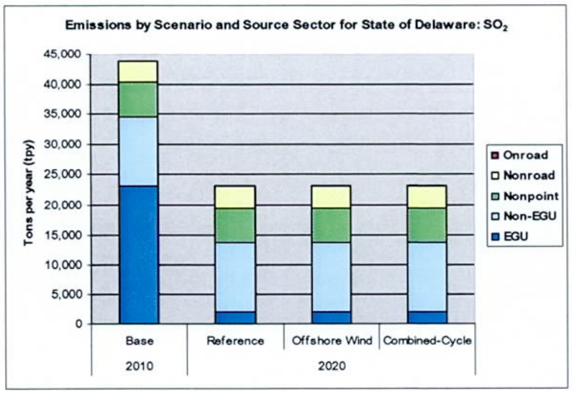
hour ozone is lower by as much as 20 ppb and annual average $PM_{2.5}$ is lower by more than 3 μgm^{-3}. Mercury deposition differences are characterized by small areas of increase and decrease with an average decrease of approximately 1 g km^{-2}.

These changes are consistent with the changes in emissions between the 2010, 2020, S1, and S3 scenarios as illustrated for Delaware (for NO_x, SO_2 and Hg) in Figures ES-1 (a) through (c).

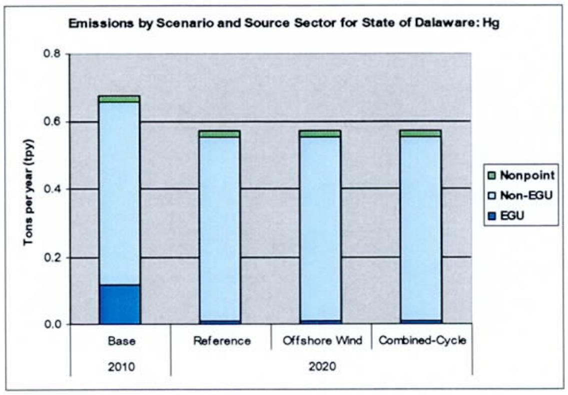
Figure ES-1. Emission Totals by Source Category for the State of Delaware for the IRP Modeling Analysis Scenarios 2010 Base, 2020 Reference Case, Scenario S1 (Offshore Wind), and Scenario S3 (Combined-Cycle): NO_x, SO_2 and Hg

(a) NO_x (b) SO_2





(c) Hg



Total monetized benefits (or costs) for scenarios S1 and S3 (ozone, $PM_{2.5}$ and mercury deposition) are as follows. The ranges encompass the different health-incidence studies used in this analysis and different assumptions regarding cessation lag (discount rate) for $PM_{2.5}$ mortality. The monetized health-related benefits are given in 2008-equivalent U.S. dollars.

The estimated total *cost* associated with Scenario S1 ranges from 16 to 47 million dollars for the full analysis region and from 1.4 to 4.2 million dollars for Delaware. As noted above, the costs appear to be associated with increases in emissions that are outside of the 4-km grid region. The estimated total *benefit* associated with Scenario S3 ranges from 22 to 60 million dollars for the full analysis region and from 0.4 to 1.4 million dollars for Delaware. The corresponding values for Scenario S2 are expected to be similar to those for S3. Most of the costs/benefits are associated with $PM_{2.5}$; the overall costs/benefits associated with mercury deposition are a small fraction of the overall totals.

Based on data from a recent National Academy of Sciences (NAS) report, the *benefits* associated with changes in carbon dioxide (CO_2) for the offshore wind scenario (S1) range from 0.17 to 16 million dollars and the *benefits* for the onshore wind scenario (S2) range from 0.03 to 3 million dollars. Due to the estimated increase in CO_2 emissions, estimated *costs* associated with the combined cycle case (S3) range from 0.02 to 2 million dollars. These estimates are for the Mid-Atlantic states.

For perspective, it is useful to compare these values with estimated costs and benefits associated with larger emissions changes. Two additional simulations were run to examine the contributions from all EGU emissions to overall air quality and changes in air quality with time (from 2010 to 2020). The estimated total *cost* associated with EGU emissions alone (based on their contribution to simulated ozone and $PM_{2.5}$ concentrations for the 2020 Reference Case simulation) ranges from 30 to 81 billion dollars for the full analysis region and from 2.1 to 5.6 billion dollars for Delaware. Note the change from million to billion. The estimated total *benefit* associated with the expected emissions changes between 2010 and 2020 range from 26 to 63 billion dollars for the full analysis region and from 1.8 to 4.3 billion dollars for Delaware.

In conclusion, the air quality and health effects modeling results indicate improvements in air quality between 2010 and 2020 due to expected changes in emissions from all sources, including EGUs. The simulated improvements in air quality result in a lower incidence of adverse health effects and substantial monetized health-effects benefits for Delaware and the surrounding region. The modeling results also indicate that the environmental impacts and health-related costs/benefits associated with the alternative energy production scenarios considered in this study are small compared to the changes from 2010 to 2020.

1. Introduction

This report summarizes the application of air quality modeling tools to examine the air quality impacts and related health benefits associated with future power generation alternatives for the State of Delaware.

1.1. Background and Objectives

Delmarva Power & Light (Delmarva)'s Integrated Resource Plan (IRP) requires that a comprehensive environmental externalities assessment be conducted on the utilization of specific methods of energy production. This assessment is intended to examine the environmental impacts and benefits associated with the use of alternative energy production sources and to appropriately monetize these benefits or costs for policy decision makers. Included in this IRP is an evaluation of the costs and benefits of alternative generation options. Such options include wind and other alternative sources for generating electricity. As part of the IRP, an analysis of the environmental costs and benefits, specifically related to air quality, provides a means for comparing the various options available to Delmarva. The analysis summarized herein was conducted using an air quality modeling system from which information was derived and used as input to a health benefits model to calculate and evaluate costs and benefits.

The primary objective of the air quality modeling analysis was to simulate the environmental health impacts and estimate the benefits that may be achieved from shifting traditional energy production sources to more environmentally-friendly alternative sources (including renewable sources). The modeling analysis includes a base-case simulation for 2010, a future-year Reference Case simulation for 2020, and three alternate power generation scenarios for the future year. The emissions for the electric generating units (EGUs) were estimated using ICF International, Inc. (ICF)'s Integrated Planning Model (IPM). Pollutants of interest in this analysis are oxides of nitrogen (NO_x), sulfur dioxide (SO_2), ozone, fine particulate matter ($PM_{2.5}$), and mercury. The Community Multiscale Air Quality (CMAQ) model, which was developed by the U.S. EPA, was used to simulate ozone and $PM_{2.5}$ concentrations and airborne mercury deposition over the ten-year planning horizon. The Particle and Precursor Tagging Methodology (PPTM), a feature of the CMAQ model, was used to quantify the contribution of emissions from power generation facilities to the simulated concentrations and deposition amounts. For ozone and $PM_{2.5}$, the Benefits Mapping and Analysis Program (BenMAP) (Abt and Associates, 2008), which was also developed by the U.S. EPA, was used to estimate the health-related impacts and monetized health related costs associated with power generation in Delaware as well as the health and monetized health-related benefits associated with the alternative power generation scenarios. For mercury, qualitative methods were used to estimate the health and economic benefits. For greenhouse gases (CO_2), estimates of costs/benefits were estimated following methodologies outlined in the 2009 National Academy of Sciences (NAS) report related to the costs of energy production and use.

1.2. Overview of the Methodology

This regional-scale photochemical air quality modeling and health risk assessment was conducted to examine and quantify the air quality and health-related benefits associated with alternative energy generation. Key components of this assessment included:

- Emission inventory preparation
- Air quality model application
- Health impact/benefit assessment

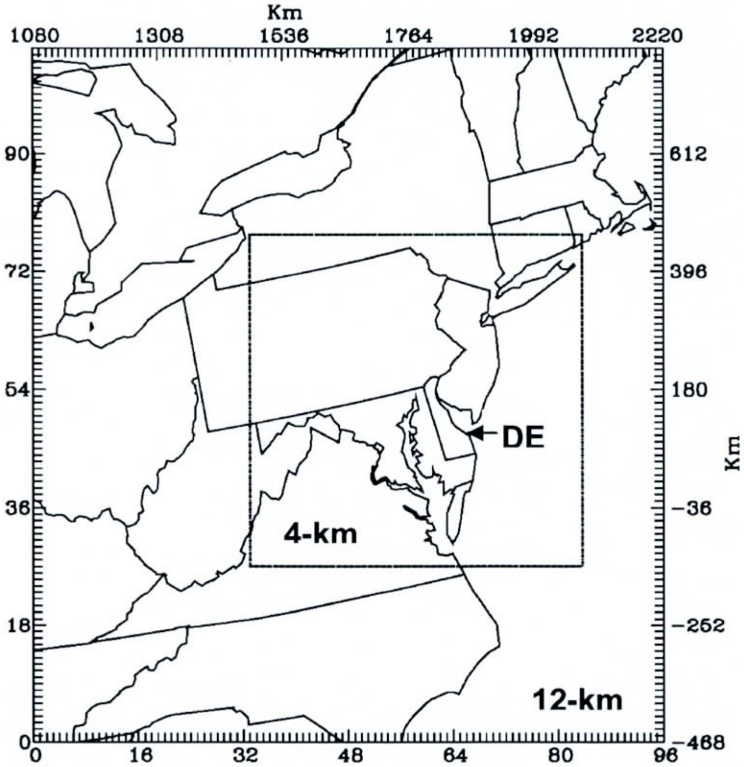
The primary tools that were used for this assessment include:

- Sparse-Matrix Operator Kernel Emissions (SMOKE) processing tool (version 2.5) for the preparation of model-ready emissions;
- Community Multiscale Air Quality (CMAQ) model (version 4.6) for quantifying the air quality changes for the different power generation alternatives; and
- Environmental Benefits Mapping and Analysis Program (BenMAP) tool (version 3.0.14) to assess the health-related impacts of the simulated changes in air quality.

These tools are widely used for conducting air quality and health effects analysis.

The CMAQ modeling domain is depicted in Figure 1-1. It consists of an outer, regional-scale grid that covers the mid-Atlantic region and portions of some surrounding states and an inner, high-resolution grid that is focused on Delaware. The horizontal resolution is 12 kilometers (km) for the outer grid and 4 km for the inner grid. Air quality impacts and health effects were evaluated for the 4-km grid and specifically for Delaware.

Figure 1-1. CMAQ Modeling Domain for the Alternative Power Generation Analysis; Horizontal Grid Spacing is 12 km for the Outer Grid and 4 km for the Inner Grid.



Boundary conditions for the 12-km domain were derived from corresponding national-scale simulations run for a 36-km resolution continental U.S. (CONUS) modeling domain.

The CMAQ model was applied for an annual simulation period, using meteorological inputs for a base year of 2001. The meteorological inputs were originally prepared by EPA and have been used for a number of past and recent air quality modeling studies. This simulation period is characterized by typical meteorological conditions for the area of interest, with normal temperatures and precipitation amounts during the summer months (compared to 40 years of climatological data), but less than normal precipitation during the fall period. For these reasons, it was also selected for use in the Virginia Mercury Study (Douglas et al. 2008a).

The modeling was conducted for 2020 and used to examine selected alternative power generation scenarios. This year was chosen for the analysis to meet the regulatory requirements of the IRP ten-year planning horizon and to realize the environmental impacts and benefits associated with the potential avoided emissions from the addition of offshore and onshore wind power and/or combined cycle gas facility. Emissions for 2020, for all but the EGU sources, were obtained from the latest projected 2020 national-scale emission inventory released by EPA. EGU emissions were estimated using the IPM (ICF, 2010). The resulting model-ready inventories contain emissions for all criteria pollutants (as required for photochemical modeling) for ten source category sectors, including on-road mobile sources, non-road mobile sources (construction equipment, locomotives, ships, aircraft, etc.), electric generating unit (EGU) point sources, non-EGU point sources, area sources, biogenic sources, etc.

For the 2020 Reference Case simulation, the CMAQ/PPTM tool was used to quantify the contribution of emissions from power generation facilities to the simulated concentrations and deposition amounts. Tags were applied to the EGU facilities in Delaware and also to EGU facilities in the remainder of the modeling domain.

An additional base-case simulation was also conducted for 2010, for the purposes of examining the changes in air quality with time and quantifying the benefits associated with the expected air quality changes between 2010 and 2020. Quantifying the air quality changes from 2010 to 2020 provides some perspective for assessing the changes due to variations in the EGU emissions for 2020.

Following the application of CMAQ, the CMAQ outputs were processed for input to the BenMAP health effects analysis tool. For the 2020 Reference Case simulation, BenMAP was used to estimate the health-related impacts and monetized health-related costs associated with power generation in the 4-km grid and Delaware. For each of the modeled alternative power-generation scenarios, BenMAP was used to estimate the benefits associated with the changes in air pollution simulated by CMAQ. Finally, BenMAP was used to quantify the heath-related impacts associated with expected improvements in air quality between 2010 and 2020. The BenMAP tool includes health impact functions, which relate a change in the concentration of a pollutant with a change in the incidence of a health endpoint. BenMAP also calculates the economic value of health impacts. For this study, the health effects analysis considered the effects of ozone and fine particulate matter ($PM_{2.5}$).

For mercury, qualitative methods were used to estimate the health and economic benefits. The benefits assessment for mercury deposition was based on information from a comprehensive study of the benefits of controlling mercury emissions from coal fired power plants (NESCAUM, 2005). Specifically, estimates of monetized benefits per change in mercury deposition for the Mid-Atlantic states from the NESCAUM report were used along with the CMAQ modeling results from this present study to estimate mercury benefits for 2020.

1.3. Scenarios

Five annual CMAQ simulations comprise this study. These include the 2020 Reference Case simulation, and two alternative power-generation scenarios: one in which the emissions were adjusted to reflect the addition of offshore wind energy (Scenario S1) and a second scenario to reflect the addition of a combined-cycle gas facility (Scenario S3). Note that due to time constraints of the IRP submittal, an onshore wind energy scenario (S2) was examined based on the offshore wind scenario (S1), but not modeled. Two additional simulations were run to examine the contributions from all EGU emissions to overall air quality and changes in air quality with time (from 2010 to 2020).

2. Emission Inventory Preparation

This section summarizes the data, methods, and procedures followed in preparing modeling emission inventories for use in the air quality modeling exercise supporting the environmental benefits and health impacts analysis for the IRP. The analysis examined the expected changes in criteria pollutant emissions from electric generation units (EGUs) in 2020 resulting from the addition of offshore and onshore wind generation and a combined-cycle facility in Delaware and/or the surrounding region. Specification of emissions for all EGUs was accomplished using the IPM (ICF, 2010). The EGU emissions changes were incorporated into a national emission inventory originally developed by EPA for 2020. The IPM model provided a revised set of EGU emission estimates for a 2020 Reference Case and the three alternative scenarios, and impacts for S1 and S3 were assessed using EPA's Community Multiscale Air Quality (CMAQ) model (Version 4.6), containing the Carbon Bond 2005 (CB-05) chemical mechanism.

2.1. Emissions Data and Methods

The CMAQ model requires as input hourly, gridded criteria pollutant emissions of both anthropogenic and biogenic sources that have been spatially allocated to the appropriate grid cells and chemically speciated for the applicable chemical mechanism used in the model. The modeling inventories were processed and prepared for CMAQ using EPA's Sparse-Matrix Operator Kernel Emissions (SMOKE) software (Version 2.5). The emissions inventories prepared for the IRP modeling analysis were derived, in part, from information developed by EPA for 2020 based on the 2002 modeling platform database (EPA, 2009). The SMOKE input files include the following categories:

- Area fugitive dust
- Agricultural
- Aircraft, locomotive and commercial marine vessels
- Average fires
- Nonpoint (Area)
- Non-road
- On-road
- IPM Point
- Non-IPM Point.

The SMOKE input files for 2020 were obtained from the following EPA ftp site: ftp://ftp.epa.gov/EmisInventory/2002v3CAP. Input information was provided in these files for the 50 states and D.C. for a national-scale modeling domain. New biogenic emissions for the 12- and 4-km grids used in this analysis were generated using the BEIS3.14 model with BELD3 land use and 2001 meteorological data. The gridded surrogate data for the 12-km grid required for SMOKE processing were obtained from EPA, while the surrogates for the 4-km grid required for SMOKE processing were prepared using the Spatial Allocator in the Surrogate Tool and various shape file catalog files provided by EPA.

In addition to these files, emissions for the portions of Canada, Mexico, and offshore areas were obtained for the year 2020 from EPA. The modeling inventories include the following pollutants: volatile organic compounds (VOC), oxides of nitrogen (NO_x), carbon monoxide (CO), sulfur dioxide (SO_2), fine particulates ($PM_{2.5}$), coarse particulates (PM_{10}), mercury (Hg), and ammonia (NH_3). The 2020 anthropogenic mercury emissions are based on the EPA Clear Skies database which included files for IPM point source, non-IPM point source, and nonpoint (area source) sectors (EPA, 2003).

2.2. Emissions Processing Procedures

As noted above, SMOKE, version 2.5 was utilized to process the emissions and prepare CMAQ-ready inputs for the 2020 Reference Case (2020 baseline scenario) and the two scenarios (S1 and S3) using source sector files provided by EPA and revised EGU emissions provided by IPM. Emission files were prepared for the 12- and 4-km resolution grids used in the modeling analysis, and included a) processing of all source sectors using various SMOKE programs and inputs, b) substitution of the new IPM EGU emissions into the point source file, and c) review and quality assurance checks.

Once the IPM results were obtained, the modified files were processed by SMOKE with the other source category input files to prepare model-ready inputs for CMAQ. The general procedures followed in preparing the modeling inventories, using various programs included with SMOKE, were the following:

- Modify EPA point source file to substitute emissions for all EGUs using new estimates from IPM.
- Perform chemical speciation to transform input criteria pollutants into the Carbon Bond 2005 (CB-05) chemical mechanism species, as required by CMAQ.
- Perform temporal distribution to distribute the input annual/monthly emissions into hourly emissions.
- Perform spatial distribution of input emissions to the 12- and 4-km resolution modeling grids.
- Merge emissions from all source categories into the CMAQ model-ready files.
- Conduct a review and quality assurance of the inventory processing.

The emissions inventory processing quality assurance (QA) procedures included the preparation and examination of tabular emissions summaries and graphical display products.

Tabular summaries were used to examine emissions totals for various steps of the emissions processing. Summaries for input emissions are based on the input inventory data: monthly emissions for the on-road and non-road sectors, and annual emissions for other sectors for criteria pollutants. Summaries for the emissions are based on the SMOKE output reports which include daily emissions for each CB-05 species for each sector. The output daily emissions are summed over all days in the year and the CB-05 species are summed for the criteria pollutants. The emissions summaries were made for each scenario by state and sector, and comparisons were made between the input emissions and output emissions for each sector to assure consistency.

In addition to the tabular summaries, various graphical displays were prepared for one day of each month to examine the spatial distribution and temporal variation for each sector and the final merged emissions using a graphical plotting package.

2.3. Emissions Summaries

Although the processed emission inventories were prepared for the full set of species listed above, most of the presentation and discussion that follows focuses on the NO_x, SO_2, and mercury emissions, since these are the species specified by IPM for EGUs that differed between the 2020 Reference Case and the scenarios. NOx is a precursor for ozone and both NO_x and SO_2 are precursor species for PM2.5. Tables 2-1 and 2-2 present emission totals for the 12-km and 4-km resolution grids, respectively, for the 2010 base case, the 2020 Reference Case, the offshore wind scenario (S1), and the combined-cycle scenario (S3). Tables 2-3 and 2-4 present this same information for the Mid-Atlantic states and the State of Delaware, respectively. The expected reductions in emissions between 2010 and 2020 in the various source sectors reflect implementation of emission control technologies reflecting state and federal rule requirements, the shutting down of older facilities, fleet turnover of on-road motor vehicles and off-road equipment, the introduction of cleaner engine technologies, and the use of cleaner fuels.

From the 2020 Reference Case, only emissions for the EGU sector changed in each of the scenarios. EGU NO_x emissions within the 12-km grid are slightly lower for both scenarios, compared to the 2020 Reference Case. For the 4-km grid, NO_x emissions are slightly lower for the offshore wind case (S1) and slightly higher for the combined-cycle case (S3), compared to the Reference Case. For the combined Mid-Atlantic states, NO_x emissions are slightly lower for both scenarios. For Delaware, the NO_x emissions are unchanged for the offshore wind case (S1) and slightly higher for the combined-cycle case (S3).

EGU SO_2 emissions within the 12-km grid are slightly higher for both scenarios, compared to the 2020 Reference Case. For the 4-km grid, SO_2 emissions are lower for both scenarios, compared to the Reference Case. For the combined Mid-Atlantic states, SO_2 emissions are slightly lower for the offshore wind case and higher for the combined-cycle case. For Delaware, the SO_2 emissions are nearly the same as the Reference Case for both scenarios.

EGU mercury emissions within the 12-km grid are slightly higher for both scenarios, compared to the 2020 Reference Case. For the 4-km grid and the Mid-Atlantic states, mercury emissions are slightly higher for the offshore wind case (S1) and slightly lower for the combined-cycle case (S3), compared to the Reference Case. For Delaware, total mercury emissions are the same as the Reference Case for both scenarios.

Table 2-1. Emission Inventory Totals (tons/yr) by Sector for 2020 for the IRP Modeling Scenarios for the 12-km Grid.

Pollutant	Sector	2010 Base	2020 Reference	Offshore Wind (S1)	Combined-Cycle (S3)
NO_x	EGU	539,135	401,103	400,902	400,921
	Non-EGU Point	411,826	408,745	408,745	408,745
	Nonpoint	441,012	440,212	440,212	440,212
	Nonroad	798,882	662,304	662,304	662,304
	On-road Vehicle	1,279,712	491,344	491,344	491,344
SO_2	EGU	1,740,789	678,173	678,625	675,868
	Non-EGU Point	582,052	567,749	567,749	567,749
	Nonpoint	453,637	453,554	453,554	453,554
	Nonroad	70,559	72,978	72,978	72,978
	On-road Vehicle	10,997	10,733	10,733	10,733
Hg	EGU	7.7918	3.2801	3.2815	3.2811
	Non-EGU Point	9.7821	10.7567	10.7567	10.7567
	Nonpoint	3.6571	3.8610	3.8610	3.8610

Table 2-2. Emission Inventory Totals (tons/yr) by Sector for 2020 for the IRP Modeling Scenarios for the 4-km Grid.

Pollutant	Sector	2010 Base	2020 Reference	Offshore Wind (S1)	Combined-Cycle (S3)
NO_x	EGU	168,830	114,487	114,455	114,492
	Non-EGU Point	145,021	142,595	142,595	142,595
	Nonpoint	205,407	205,095	205,095	205,095
	Nonroad	324,163	268,106	268,106	268,106
	On-road Vehicle	491,757	182,117	182,117	182,117
SO_2	EGU	408,104	98,223	97,788	96,074
	Non-EGU Point	158,247	152,253	152,253	152,253
	Nonpoint	218,050	218,010	218,010	218,010
	Nonroad	38,838	39,998	39,998	39,998
	On-road Vehicle	4,636	4,721	4,721	4,721
Hg	EGU	2.0342	0.8472	0.8477	0.8463
	Non-EGU Point	3.9888	4.3576	4.3576	4.3576
	Nonpoint	1.6078	1.6975	1.6975	1.6975

Table 2-3. Emission Inventory Totals (tons/yr) by Sector for 2020 for the IRP Modeling Scenarios for the Mid-Atlantic States (New Jersey, Pennsylvania, Maryland, DC, Delaware, and Virginia).

Pollutant	Sector	2010 Base	2020 Reference	Offshore Wind (S1)	Combined-Cycle (S3)
NO_x	EGU	197,306	156,482	156,445	156,478
	Non-EGU Point	161,304	159,026	159,026	159,026
	Nonpoint	162,173	161,700	161,700	161,700
	Nonroad	302,452	253,926	253,926	253,926
	On-road Vehicle	448,253	167,917	167,917	167,917
SO_2	EGU	491,035	158,782	158,323	161,181
	Non-EGU Point	201,114	195,277	195,277	195,277
	Nonpoint	160,541	160,472	160,472	160,472
	Nonroad	35,113	37,725	37,725	37,725
	On-road Vehicle	3,998	4,004	4,004	4,004
Hg	EGU	2.5235	0.9936	0.9940	0.9920
	Non-EGU Point	4.7052	5.2918	5.2918	5.2918
	Nonpoint	0.9741	1.0194	1.0194	1.0194

Table 2-4. Emission Inventory Totals (tons/yr) by Sector for 2020 for the IRP Modeling Scenarios for the State of Delaware.

Pollutant	Sector	2010 Base	2020 Reference	Offshore Wind (S1)	Combined-Cycle (S3)
NO_x	EGU	9,678	1,509	1,509	1,525
	Non-EGU Point	4,678	4,678	4,678	4,678
	Nonpoint	3,265	3,253	3,253	3,253
	Nonroad	15,144	15,173	15,173	15,173
	On-road Vehicle	11,893	4,334	4,334	4,334
SO_2	EGU	23,056	2,095	2,096	2,097
	Non-EGU Point	11,530	11,530	11,530	11,530
	Nonpoint	5,797	5,796	5,796	5,796
	Nonroad	3,315	3,672	3,672	3,672
	On-road Vehicle	112	110	110	110
Hg	EGU	0.1168	0.0083	0.0083	0.0083
	Non-EGU Point	0.5395	0.5423	0.5423	0.5423
	Nonpoint	0.0166	0.0182	0.0182	0.0182

To illustrate and check the reasonableness of the spatial distribution of emissions throughout the modeling domain, daily emission density plots for a selected day were prepared and examined. Figures 2-1a through c present daily emissions for the 2020 Reference Case for July 15, 2020 for NO_x, SO_2, and mercury, respectively, for the 4-km grid. As noted above, the meteorological inputs for the modeling exercise are for 2001, while the emissions correspond to 2020. The plots show the highest emissions corresponding to the locations of the major cities (Richmond, Washington, D.C., Baltimore, Philadelphia, and New York) and transportation corridors (freeways) as well as locations of large industrial facilities.

Figure 2-1a. Daily NO_x Emissions (July 15, 2001) for the 2020 Reference Case for the 4-km grid.

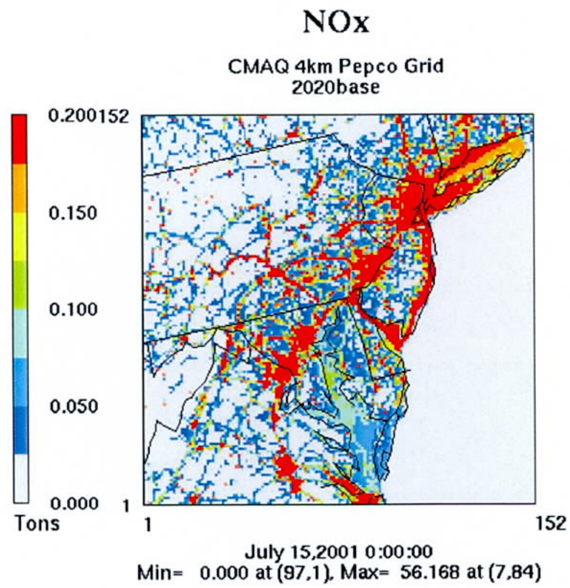


Figure 2-1b. Daily SO_2 Emissions (July 15, 2001) for the 2020 Reference Case.

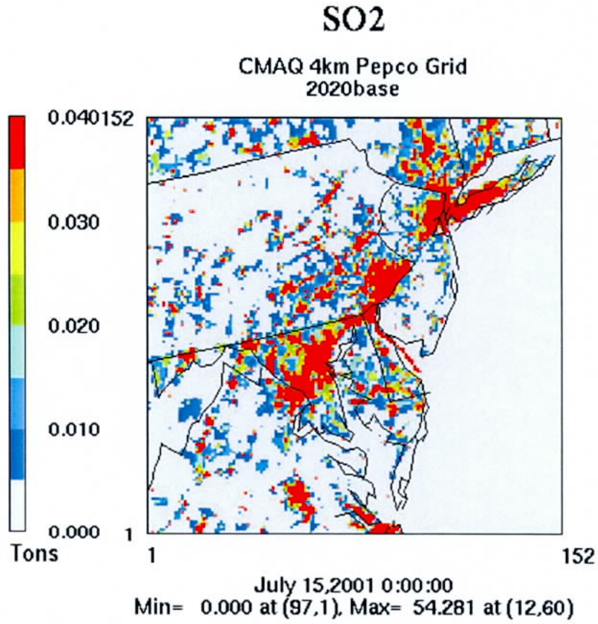


Figure 2-1c. Daily Total Mercury Emissions (July 15, 2001) for the 2020 Reference Case.

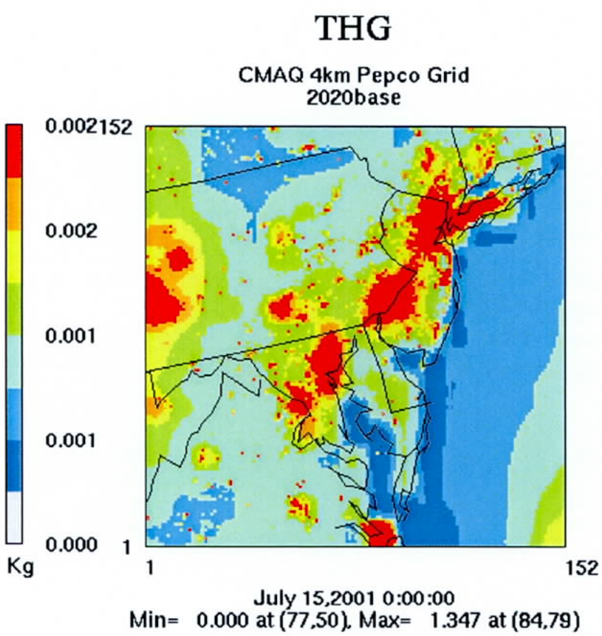


Table 2-5 presents a listing of EGUs located within the State of Delaware and the neighboring Mid-Atlantic states and the associated changes in mercury, NO_x, and SO_2 emissions from the 2020 Reference Case and for each of the scenarios, including the onshore wind scenario (S2).

The table lists only those EGUs for which changes were specified by IPM, and the information illustrates the mix of forecasted increases and decreases in emissions. In most cases, the changes in emissions at any one facility are very small, but changes are estimated in a number of facilities throughout the Mid-Atlantic states. For the State of Delaware, IPM estimates changes to two facilities in the offshore and onshore wind cases and four facilities in the combined-cycle case. Within the State of Maryland, emissions change for 8 facilities in the offshore wind scenario and 10 facilities in onshore wind and combined-cycle scenarios. Within the State of New Jersey, emissions change for 17 facilities in the offshore and onshore wind scenarios and 19 facilities in the combined-cycle scenario. Within the State of Pennsylvania, emissions change for 9 facilities in the offshore wind scenario, 12 facilities for the onshore wind scenario, and 18 facilities in the combined-cycle scenario. Finally, for the Commonwealth of Virginia, emissions change for 17 facilities in the offshore wind scenario, 15 facilities in the onshore wind scenario, and 6 facilities in the combined-cycle scenario.

Table 2-5. EGU facility Mercury, NO_x, and SO_2 Emissions Totals for the 2020 Reference Case, the Offshore Wind Case, the Onshore Wind Case, and the Combined Cycle Case for EGUs Located within the Mid-Atlantic States.

Plant Name	County	State	2020 Reference			2020 Offshore Wind (S1)			2020 Onshore Wind (S2)			2020 Combined Cycle (S3)		
			Hg (tpy)	NO_x (tpy)	SO_2 (tpy)	Hg (tpy)	NO_x (tpy)	SO_2 (tpy)	Hg (tpy)	NO_x (tpy)	SO_2 (tpy)	Hg (tpy)	NO_x (tpy)	SO_2 (tpy)
Hay Road	New Castle	DE	0.0000	398.5	0.0	0.0000	398.4	0.0	0.0000	398.0	0.0	0.0000	396.8	0.0
Indian River Generating Station (DE)	Sussex	DE	0.0083	1,050.6	2,095.0	0.0083	1,050.6	2,096.0	0.0083	1,050.4	2,095.8	0.0083	1,050.6	2,097.0
Warren F Sam Beasley Generation	Kent	DE	0.0000	2.8	0.0	0.0000	2.8	0.0	0.0000	2.8	0.0	0.0000	2.1	0.0
Delmarva CC unit	Kent	DE	0.0000	0.0	0.0	0.0000	0.0	0.0	0.0000	0.0	0.0	0.0000	18.1	0.0
AES Warrior Run Cogeneration F	Allegany	MD	0.0064	405.5	2,466.1	0.0066	405.5	2,244.1	0.0065	405.5	2,346.1	0.0066	405.5	2,291.7
Berlin	Worcester	MD	0.0000	0.9	0.0	0.0000	0.9	0.0	0.0000	0.9	0.0	0.0000	0.7	0.0
Brandon Shores	Anne Arundel	MD	0.0423	4,071.3	7,948.2	0.0423	4,071.3	7,948.2	0.0418	4,071.3	8,701.7	0.0423	4,071.3	7,948.2
C P Crane	Baltimore	MD	0.0107	3,819.7	2,430.4	0.0107	3,819.7	2,430.4	0.0110	3,819.7	2,177.6	0.0110	3,819.7	2,177.6
Chalk Point	Prince Georges	MD	0.0229	4,419.9	3,064.9	0.0229	4,420.9	3,064.9	0.0229	4,420.1	3,064.9	0.0229	4,417.4	3,064.9
Dickerson	Montgomery	MD	0.0179	2,559.6	2,379.9	0.0178	2,550.2	2,379.9	0.0178	2,552.3	2,379.9	0.0178	2,556.2	2,379.8
Easton	Talbot	MD	0.0000	17.2	0.0	0.0000	17.2	0.0	0.0000	17.2	0.0	0.0000	17.1	0.0
Easton 2	Talbot	MD	0.0000	18.5	0.0	0.0000	18.5	0.0	0.0000	18.5	0.0	0.0000	18.3	0.0
Herbert A Wagner	Anne Arundel	MD	0.0100	685.7	2,354.1	0.0099	685.7	2,524.1	0.0102	685.7	2,152.8	0.0100	685.7	2,354.1
Morgantown Generating Station	Charles	MD	0.0384	2,051.4	5,131.3	0.0384	2,058.0	5,131.3	0.0384	2,052.0	5,131.3	0.0384	2,051.4	5,131.3
PJM - BGE	Baltimore	MD	0.0000	1,724.3	0.0	0.0000	1,694.6	0.0	0.0000	1,718.4	0.0	0.0000	1,718.1	0.0
PJM - PEPCO	Prince Georges	MD	0.0000	1,115.9	0.0	0.0000	1,116.1	0.0	0.0000	1,116.9	0.0	0.0000	1,117.3	0.0
Rock Springs Generating Facility	Cecil	MD	0.0000	19.6	0.0	0.0000	19.3	0.0	0.0000	20.6	0.0	0.0000	22.9	0.0
Bergen	Bergen	NJ	0.0000	173.1	0.0	0.0000	173.4	0.0	0.0000	172.8	0.0	0.0000	173.7	0.0
Calpine Parlin Inc	Middlesex	NJ	0.0000	59.6	0.0	0.0000	59.7	0.0	0.0000	59.6	0.0	0.0000	59.8	0.0
Carlls Corner	Cumberland	NJ	0.0000	3.2	0.0	0.0000	3.0	0.0	0.0000	3.1	0.0	0.0000	4.4	0.0
Carneys Point Generating Plant	Salem	NJ	0.0049	1,215.3	532.2	0.0049	1,212.2	530.8	0.0049	1,215.3	532.2	0.0049	1,215.3	532.2
Cumberland (NJ)	Cumberland	NJ	0.0000	34.6	0.0	0.0000	34.3	0.0	0.0000	34.4	0.0	0.0000	35.9	0.0
Essex (NJ PSEG)	Essex	NJ	0.0000	39.6	0.0	0.0000	40.3	0.0	0.0000	38.1	0.0	0.0000	39.2	0.0
Forked River	Ocean	NJ	0.0000	4.0	0.0	0.0000	4.0	0.0	0.0000	4.0	0.0	0.0000	4.1	0.0
Gilbert	Hunterdon	NJ	0.0000	90.2	0.0	0.0000	94.6	0.0	0.0000	93.0	0.0	0.0000	78.5	0.0
Hudson Generating Station	Hudson	NJ	0.0045	322.2	1,124.3	0.0045	322.2	1,124.3	0.0045	322.2	1,124.2	0.0045	322.2	1,124.2
Kearny Generating Station	Hudson	NJ	0.0000	73.7	0.0	0.0000	73.7	0.0	0.0000	73.7	0.0	0.0000	73.7	0.0
Lakewood Cogeneration LP	Ocean	NJ	0.0000	121.5	0.0	0.0000	121.7	0.0	0.0000	121.5	0.0	0.0000	121.9	0.0
Mickleton Station	Gloucester	NJ	0.0000	2.6	0.0	0.0000	2.4	0.0	0.0000	2.5	0.0	0.0000	3.5	0.0
Middle Station	Cape May	NJ	0.0000	3.0	0.0	0.0000	2.9	0.0	0.0000	3.0	0.0	0.0000	3.6	0.0

Plant Name	County	State	2020 Reference			2020 Offshore Wind (S1)			2020 Onshore Wind (S2)			2020 Combined Cycle (S3)		
			Hg (tpy)	NO_x (tpy)	SO_2 (tpy)	Hg (tpy)	NO_x (tpy)	SO_2 (tpy)	Hg (tpy)	NO_x (tpy)	SO_2 (tpy)	Hg (tpy)	NO_x (tpy)	SO_2 (tpy)
Ocean Peaking Power LP	Ocean	NJ	0.0000	19.7	0.0	0.0000	19.6	0.0	0.0000	19.8	0.0	0.0000	20.0	0.0
PJM - AE	Atlantic	NJ	0.0000	8.8	0.0	0.0000	8.7	0.0	0.0000	8.7	0.0	0.0000	8.5	0.0
PJM - AE	Cape May	NJ	0.0000	12.4	0.0	0.0000	12.3	0.0	0.0000	12.3	0.0	0.0000	12.1	0.0
PJM - AE	Cumberland	NJ	0.0000	38.6	0.0	0.0000	38.3	0.0	0.0000	38.1	0.0	0.0000	37.5	0.0
PJM - AE	Gloucester	NJ	0.0000	8.6	0.0	0.0000	8.6	0.0	0.0000	8.5	0.0	0.0000	8.4	0.0
PJM - AE	Ocean	NJ	0.0000	9.9	0.0	0.0000	9.9	0.0	0.0000	9.8	0.0	0.0000	9.7	0.0
PSEG Linden Generating Station	Union	NJ	0.0000	171.8	0.0	0.0000	173.1	0.0	0.0000	171.4	0.0	0.0000	170.7	0.0
Red Oak	Middlesex	NJ	0.0000	106.2	0.0	0.0000	107.0	0.0	0.0000	106.7	0.0	0.0000	106.8	0.0
Sayreville	Middlesex	NJ	0.0000	13.8	0.0	0.0000	13.7	0.0	0.0000	13.8	0.0	0.0000	14.0	0.0
Sayreville Cogeneration Facility	Middlesex	NJ	0.0000	161.0	0.0	0.0000	161.2	0.0	0.0000	160.9	0.0	0.0000	161.5	0.0
Sherman Avenue	Cumberland	NJ	0.0000	3.6	0.0	0.0000	3.3	0.0	0.0000	3.4	0.0	0.0000	4.8	0.0
West Station	Cumberland	NJ	0.0000	1.1	0.0	0.0000	1.1	0.0	0.0000	1.1	0.0	0.0000	1.6	0.0
Allegheny Energy Units 3 4 & 5	Allegheny	PA	0.0000	63.2	0.0	0.0000	63.2	0.0	0.0000	63.3	0.0	0.0000	63.2	0.0
Armstrong (PA)	Armstrong	PA	0.0000	52.3	0.0	0.0000	51.3	0.0	0.0000	52.0	0.0	0.0000	49.0	0.0
Bruce Mansfield	Beaver	PA	0.0827	8,042.2	23,339.0	0.0827	8,042.2	23,339.0	0.0827	8,042.2	23,155.9	0.0820	8,042.2	25,361.5
Cheswick Power Plant	Allegheny	PA	0.0144	2,743.9	4,632.8	0.0144	2,743.9	4,842.2	0.0144	2,743.9	4,842.2	0.0144	2,743.9	4,842.2
Conemaugh	Indiana	PA	0.0604	18,381.3	4,041.5	0.0599	18,381.3	4,423.0	0.0595	18,381.3	4,402.2	0.0595	18,381.3	4,402.2
Delta Power Plant	York	PA	0.0000	267.3	0.0	0.0000	267.3	0.0	0.0000	267.3	0.0	0.0000	267.0	0.0
ECAR-First Energy	Lawrence	PA	0.0000	0.7	0.0	0.0000	0.7	0.0	0.0000	0.7	0.0	0.0000	0.7	0.0
Elrama Power Plant	Washington	PA	0.0111	4,915.6	5,568.3	0.0113	4,915.6	5,201.1	0.0114	4,915.6	5,000.9	0.0115	4,915.6	4,792.2
Fairless Energy Center	Bucks	PA	0.0000	254.5	0.0	0.0000	254.3	0.0	0.0000	254.5	0.0	0.0000	254.7	0.0
Fayette Energy Facility	Fayette	PA	0.0000	73.5	0.0	0.0000	73.5	0.0	0.0000	73.5	0.0	0.0000	73.5	0.0
Grays Ferry Cogeneration Partnership	Philadelphia	PA	0.0000	96.5	0.0	0.0000	96.0	0.0	0.0000	96.8	0.0	0.0000	96.8	0.0
Hatfields Ferry Power Station	Greene	PA	0.0478	22,378.6	14,217.0	0.0477	22,378.6	14,349.7	0.0478	22,378.6	14,594.4	0.0478	22,378.6	14,594.4
Homer City Station	Indiana	PA	0.0613	6,531.9	11,165.0	0.0622	6,531.9	10,402.5	0.0626	6,531.9	10,147.9	0.0639	6,531.9	9,087.5
Hunterstown	Adams	PA	0.0000	217.4	0.0	0.0000	217.4	0.0	0.0000	217.4	0.0	0.0000	217.4	0.0
Keystone (PA)	Armstrong	PA	0.0606	4,141.5	8,103.0	0.0606	4,141.5	8,103.0	0.0573	4,141.5	10,814.6	0.0573	4,141.5	10,814.6
Liberty Electric Power LLC	Delaware	PA	0.0000	115.1	0.0	0.0000	115.0	0.0	0.0000	115.1	0.0	0.0000	115.2	0.0
Marcus Hook Refinery Cogeneration	Delaware	PA	0.0000	579.9	0.0	0.0000	577.3	0.0	0.0000	581.5	0.0	0.0000	581.4	0.0
PJM West Central	Adams	PA	0.0000	152.9	0.0	0.0000	152.9	0.0	0.0000	152.9	0.0	0.0000	153.0	0.0
PJM West Central	Berks	PA	0.0000	92.3	0.0	0.0000	92.3	0.0	0.0000	92.3	0.0	0.0000	92.3	0.0
PJM West Central	Lebanon	PA	0.0000	119.6	0.0	0.0000	119.6	0.0	0.0000	119.6	0.0	0.0000	119.7	0.0

Plant Name	County	State	2020 Reference			2020 Offshore Wind (S1)			2020 Onshore Wind (S2)			2020 Combined Cycle (S3)		
			Hg (tpy)	NO_x (tpy)	SO_2 (tpy)	Hg (tpy)	NO_x (tpy)	SO_2 (tpy)	Hg (tpy)	NO_x (tpy)	SO_2 (tpy)	Hg (tpy)	NO_x (tpy)	SO_2 (tpy)
PJM West Central	Northampton	PA	0.0000	301.4	0.0	0.0000	301.4	0.0	0.0000	301.4	0.0	0.0000	301.7	0.0
PJM West Central	York	PA	0.0000	106.9	0.0	0.0000	106.9	0.0	0.0000	106.9	0.0	0.0000	107.0	0.0
York Cogeneration Facility	York	PA	0.0000	54.5	0.0	0.0000	54.5	0.0	0.0000	54.5	0.0	0.0000	53.0	0.0
Bellmeade	Richmond City	VA	0.0000	47.8	0.0	0.0000	47.8	0.0	0.0000	47.7	0.0	0.0000	47.8	0.0
Boydton Plank Road Cogeneration	Dinwiddie	VA	0.0000	3.0	0.0	0.0000	3.0	0.0	0.0000	3.0	0.0	0.0000	3.0	0.0
Chesapeake	Chesapeake City	VA	0.0000	2.5	0.0	0.0000	2.4	0.0	0.0000	2.4	0.0	0.0000	2.6	0.0
Chesterfield	Chesterfield	VA	0.0210	1,205.1	4,786.4	0.0210	1,204.3	4,786.0	0.0210	1,204.4	4,786.1	0.0210	1,204.8	4,786.5
Clover	Halifax	VA	0.0274	9,120.8	3,234.3	0.0274	9,120.2	3,234.1	0.0274	9,120.3	3,234.2	0.0274	9,121.0	3,234.4
Commonwealth Chesapeake	Accomack	VA	0.0000	153.4	0.0	0.0000	150.1	0.0	0.0000	153.4	0.0	0.0000	148.1	0.0
Darbytown	Henrico	VA	0.0000	21.8	0.0	0.0000	21.7	0.0	0.0000	21.7	0.0	0.0000	21.8	0.0
Doswell Combined Cycle Facility	HANOVER	VA	0.0000	150.2	0.0	0.0000	150.0	0.0	0.0000	149.9	0.0	0.0000	150.0	0.0
Elizabeth River Combustion Turbine Station	Chesapeake City	VA	0.0000	20.9	0.0	0.0000	20.9	0.0	0.0000	20.9	0.0	0.0000	20.9	0.0
Gravel Neck	Surry	VA	0.0000	23.5	0.0	0.0000	23.4	0.0	0.0000	23.4	0.0	0.0000	23.5	0.0
Louisa Generating	Louisa	VA	0.0000	32.0	0.0	0.0000	31.9	0.0	0.0000	32.0	0.0	0.0000	32.0	0.0
Marsh Run Generating	Fauquier	VA	0.0000	32.8	0.0	0.0000	32.7	0.0	0.0000	32.7	0.0	0.0000	32.8	0.0
PJM Dominion	Buckingham	VA	0.0000	291.4	0.0	0.0000	291.5	0.0	0.0000	291.1	0.0	0.0000	291.4	0.0
PJM Dominion	Chesterfield	VA	0.0000	199.4	0.0	0.0000	199.6	0.0	0.0000	199.3	0.0	0.0000	199.4	0.0
PJM Dominion	Fluvanna	VA	0.0000	469.9	0.0	0.0000	470.2	0.0	0.0000	469.5	0.0	0.0000	469.9	0.0
PJM Dominion	HANOVER	VA	0.0000	334.0	0.0	0.0000	334.2	0.0	0.0000	333.7	0.0	0.0000	334.0	0.0
PJM Dominion	Hopewell City	VA	0.0000	175.0	0.0	0.0000	175.1	0.0	0.0000	174.8	0.0	0.0000	175.0	0.0
PJM Dominion	Louisa	VA	0.0000	109.5	0.0	0.0000	109.6	0.0	0.0000	109.4	0.0	0.0000	109.5	0.0
PJM Dominion	Prince William	VA	0.0000	267.3	0.0	0.0000	267.4	0.0	0.0000	267.0	0.0	0.0000	267.2	0.0
PJM Dominion	Richmond City	VA	0.0000	116.5	0.0	0.0000	116.6	0.0	0.0000	116.5	0.0	0.0000	116.5	0.0
Remington	Fauquier	VA	0.0000	40.6	0.0	0.0000	40.5	0.0	0.0000	40.6	0.0	0.0000	40.6	0.0

Figure 2-2a through c present emissions estimates by source sector for the 4-km grid for the 2010 base case, the 2020 Reference Case, the offshore wind scenario (S1), and the combined-cycle scenario (S3) for NO_x, SO_2, and mercury. Figures 2-3a through c present similar emission total by source sector for the State of Delaware. The figures present the large expected reduction in emissions between 2010 and 2020. They also illustrate the portion of overall emissions from the EGU sector and the relatively slight changes in emissions for the offshore wind and combined-cycle scenarios compared to the 2020 Reference Case.

Figure 2-2a. Emission Totals by Source Category for the 4-km Grid for the IRP Modeling Analysis Scenarios 2010 Base, 2020 Reference Case, Scenario S1 (Offshore Wind), and Scenario S3 (Combined-Cycle): NO_x.

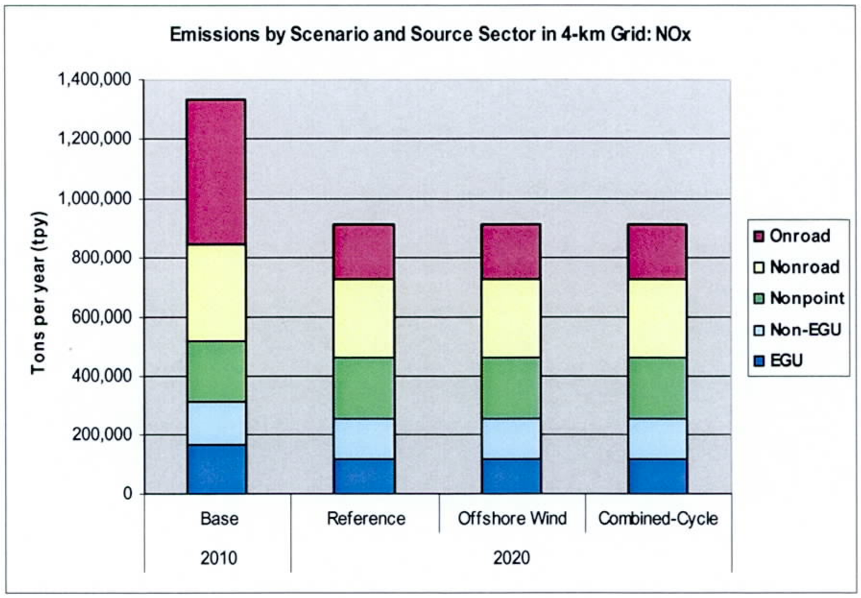


Figure 2-2b. Emission Totals by Source Category for the 4-km Grid for the IRP Modeling Analysis Scenarios 2010 Base, 2020 Reference Case, Scenario S1 (Offshore Wind), and Scenario S3 (Combined-Cycle): SO_2.

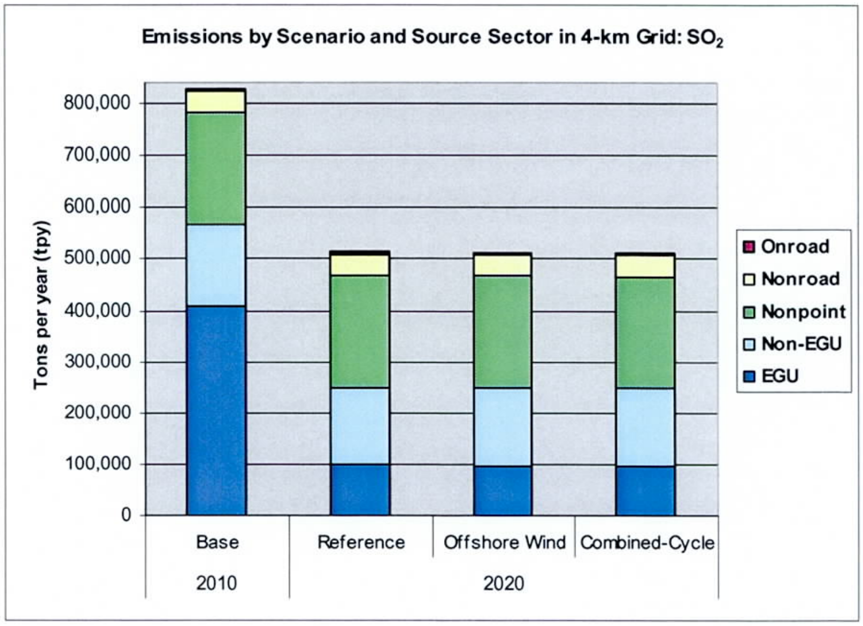


Figure 2-2c. Emission Totals by Source Category for the 4-km Grid for the IRP Modeling Analysis Scenarios 2010 Base, 2020 Reference Case, Scenario S1 (Offshore Wind), and Scenario S3 (Combined-Cycle): Hg.

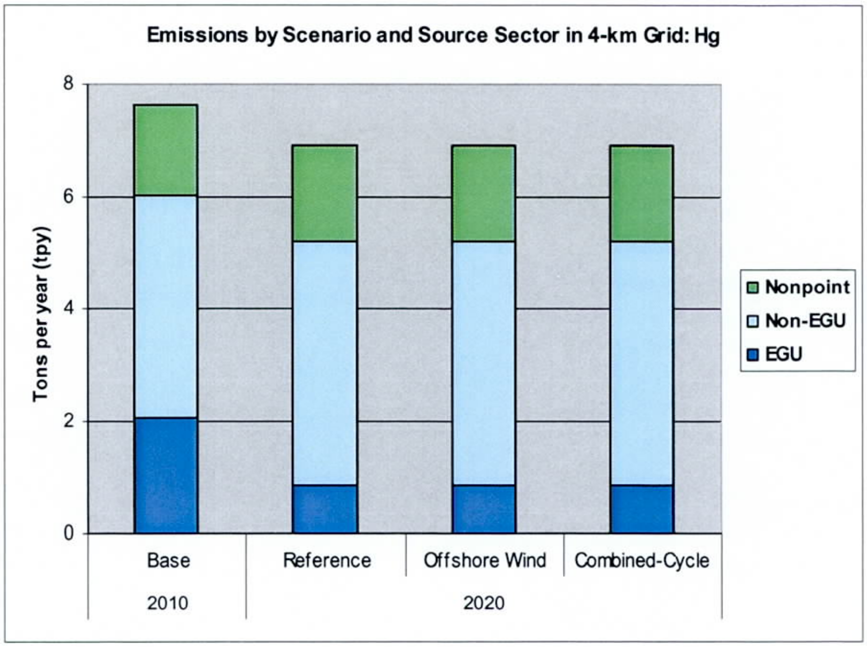


Figure 2-3a. Emission Totals by Source Category for Delaware for the IRP Modeling Analysis Scenarios 2010 Base, 2020 Reference Case, Scenario S1 (Offshore Wind), and Scenario S3 (Combined-Cycle): NO_x.

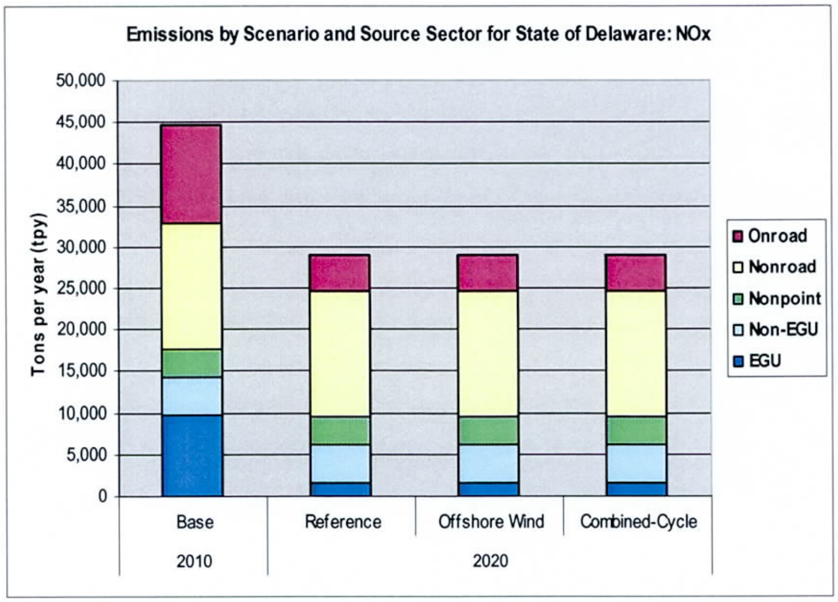


Figure 2-3b. Emission Totals by Source Category for Delaware for the IRP Modeling Analysis Scenarios 2010 Base, 2020 Reference Case, Scenario S1 (Offshore Wind), and Scenario S3 (Combined-Cycle): SO_2.

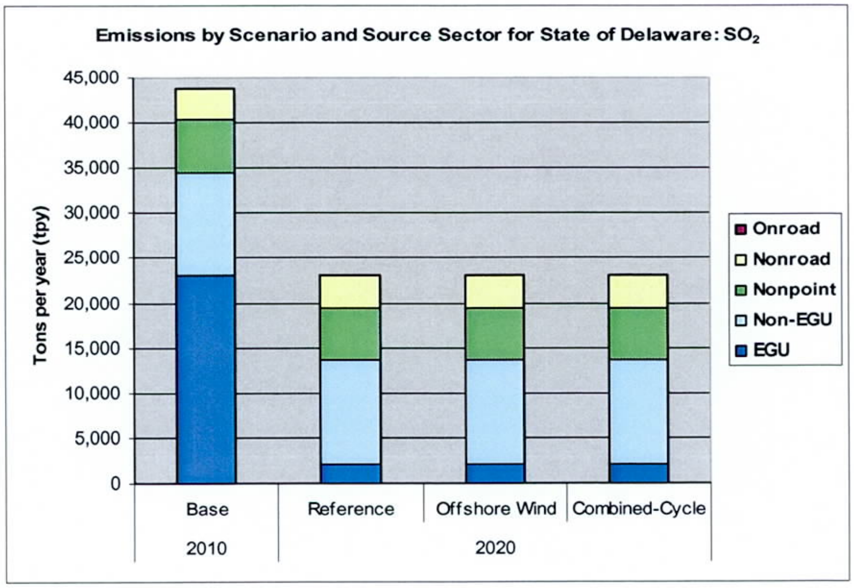
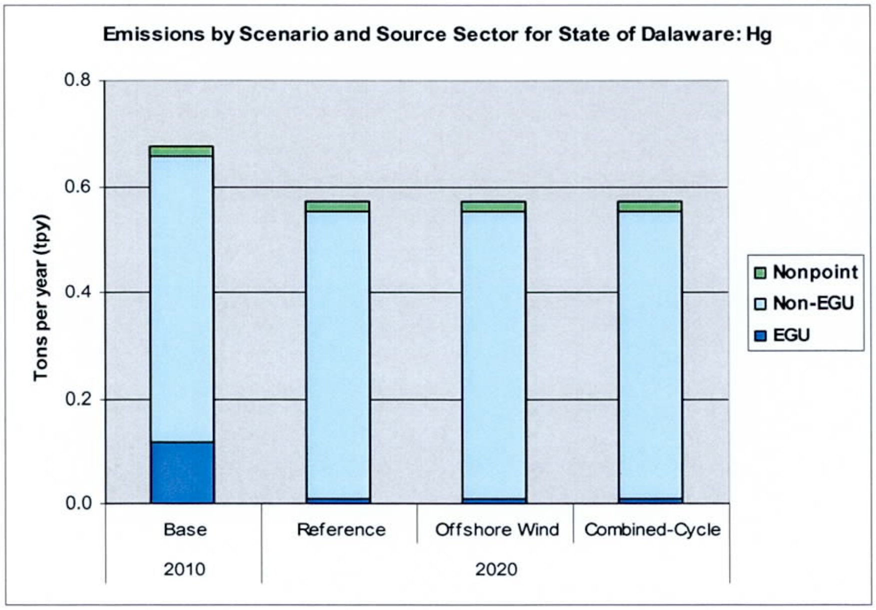


Figure 2-3c. Emission Totals by Source Category for Delaware for the IRP Modeling Analysis Scenarios 2010 Base, 2020 Reference Case, Scenario S1 (Offshore Wind), and Scenario S3 (Combined-Cycle): Hg.



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3. Air Quality Modeling

The air quality modeling methods and results are presented in this section. The CMAQ model was used in this study to simulate the air quality impacts associated with the addition of alternative power generation options. The model was applied at the regional scale for an annual simulation period. The CMAQ model requires information on the emissions, meteorology, and land-use characteristics of the modeling domain. Information about the emissions changes associated with selected alternative power generation scenarios were incorporated into the model through the emission input files for the modeled years 2010 and 2020. The CMAQ modeling results provide the basis for the health effects and benefits modeling.

3.1. Overview of the CMAQ Modeling System

The CMAQ model is a state-of-the-science, regional air quality modeling system that can be used to simulate the physical and chemical processes that govern the formation, transport, and deposition of gaseous and particulate species in the atmosphere (Byun and Ching, 1999). The CMAQ tool was designed to improve the understanding of air quality issues (including the physical and chemical processes that influence air quality) and to support the development of effective emission control strategies on both the regional and local scale. The CMAQ model was designed as a “one-atmosphere” model. This concept refers to the ability of the model to dynamically simulate ozone, particulate matter, and other species (such as mercury) in a single simulation. In addition to addressing a variety of pollutants, CMAQ can be applied to a variety of regions (with varying geographical, land-use, and emissions characteristics) and for a range of space and time scales.

Numerous recent applications of the model, for both research and regulatory air quality planning purposes, have focused on the simulation of ozone and $PM_{2.5}$. The CMAQ model was used by EPA to support the development of the Clean Air Interstate Rule (CAIR) (EPA, 2005). It was also used by EPA to support the second prospective analysis of the costs and benefits of the Clean Air Act (CAA) (Douglas et al., 2008b).

The CMAQ model numerically simulates the physical processes that determine the magnitude, temporal variation, and spatial distribution of the concentrations of gaseous and particulate species in the atmosphere and the amount, timing, and distribution of their deposition to the earth’s surface. The simulation processes include advection, dispersion (or turbulent mixing), chemical transformation, cloud processes, and wet and dry deposition. The CMAQ science algorithms are described in detail by Byun and Ching (1999).

According to Bullock et al. (2008 and 2009), the CMAQ model reflects the current state-of-the-science in simulating the atmospheric processes that influence the dispersion, advection, chemical transformation, and deposition of mercury. The CMAQ model includes three mercury (Hg) species: elemental mercury (HG0), reactive gaseous mercury (HG2), and particulate-bound mercury (HGP).

The CMAQ model also supports source attribution for ozone, particulate matter, and mercury as described by Douglas et al. (2007). The CMAQ Ozone and Particle Precursor Tagging

Methodologies (OPTM and PPTM) are designed to provide detailed, quantitative information about the *contribution* of selected sources, source categories, and/or source regions to simulated ozone and $PM_{2.5}$ concentrations, respectively. Emissions of precursor pollutants from selected sources, source categories, or source regions are (numerically) tagged and then tracked throughout a simulation. The contribution from each tag to the resulting simulated concentration of ozone, $PM_{2.5}$, or any of the $PM_{2.5}$ component species for any given location within the CMAQ modeling domain can be quantified. By tracking the emissions from selected sources or source locations, the methodology also provides information on the fate of the emissions from these sources. PPTM can also be applied for mercury.

The tagging methodology differs from the use of air quality model sensitivity simulations in which the emissions are modified or eliminated (zeroed-out). Sensitivity simulations typically provide information about the effects of changes in the emissions on the simulation results. In contrast, OPTM and PPTM provide information about the contribution of the emissions from the tagged sources, relative to the unmodified simulated conditions.

The CMAQ model requires several different types of input files. Gridded, hourly emission inventories characterize the release of anthropogenic, biogenic, and, in some cases, geogenic emissions from sources within the modeling domain. The emissions represent both low-level and elevated sources and a variety of source categories (including, for example, point, on-road mobile, non-road mobile, area, and biogenic). The amount and spatial and temporal distribution of each emitted pollutant or precursor species are key determinants to the resultant simulated air quality values.

The CMAQ model also requires hourly, gridded input fields of several meteorological parameters including wind, temperature, mixing ratio, pressure, solar radiation, fractional cloud cover, cloud depth, and precipitation. A full list of the meteorological input parameters is provided in Byun and Ching (1999). The meteorological input fields are typically prepared using a data-assimilating prognostic meteorological model, the output of which is processed for input to the CMAQ model using the Meteorology-Chemistry Interface Processor (MCIP). The prescribed meteorological conditions influence the transport, vertical mixing, and resulting distribution of the simulated pollutant concentrations. Certain of the meteorological parameters, such as mixing ratio, can also influence the simulated chemical reaction rates. Rainfall and near-surface meteorological characteristics govern the wet and dry deposition, respectively, of the simulated atmospheric constituents.

Initial and boundary condition (IC/BC) files provide information on pollutant concentrations throughout the domain for the first hour of the first day of the simulation, and along the lateral boundaries of the domain for each hour of the simulation. Photolysis rates and other chemistry-related input files supply information needed by the gas-phase and particulate chemistry algorithms.

CMAQ version 4.6 was used for this study (this work was begun before the release of CMAQ version 4.7.1). This version of the model supports several options for the gas-phase chemical mechanism, particle treatment, aerosol deposition, and cloud treatment. All simulations conducted as part of this study used the CB-05 chemical mechanism. For particles, the AERO4 particle treatment, which includes sea salt, was applied. For the 2020 Reference Case run, the CMAQ PPTM feature was used for to quantify the contribution of EGU emissions to the simulated PM2.5 concentrations.

3.2. CMAQ Application Procedures

The application of CMAQ, including the modeling domain, simulation period, input files (with the exception of the emission inventories), and post-processing and quality assurance procedures are discussed in this section. Preparation of the emission inventories for the application of CMAQ was discussed in detail in the previous section. Model performance evaluation for CMAQ for this simulation period (for a base year of 2001) was conducted as part of the Virginia Mercury Study (Douglas et al., 2008a) as well as several other EPA studies, and the results were found to be acceptable for use in air quality analysis.

Modeling Domain and Simulation Period

The modeling domain used for this analysis was presented in Figure 1-1. The domain consists of an outer, regional-scale grid that covers the Mid-Atlantic region and portions of some surrounding states and an inner, high-resolution grid that is focused on Delaware. The horizontal resolution is 12 kilometers (km) for the outer grid and 4 km for the inner grid. Air quality impacts and health effects were calculated for 4-km grid and Delaware.

The CMAQ model was applied for an annual simulation period, using meteorological inputs for a base year of 2001. This simulation period is characterized by typical meteorological conditions for the area of interest, with normal temperatures and precipitation amounts during the summer months, but less than normal precipitation during the fall period. For these reasons, it was also selected for use in the Virginia Mercury Study (Douglas et al. 2008a). In running the model, the annual simulation period was divided into two parts covering January through June and July through December, respectively. Each part of the simulation also included an additional five start-up simulation days, which were intended to reduce the influence of uncertainties in the initial conditions on the simulation results.

Meteorological Input Files

The 12-km resolution meteorological input files for the annual (2001) simulation period were originally prepared by EPA using the Pennsylvania State University/National Center for Atmospheric Research (PSU/NCAR) Fifth Generation Mesoscale Model (MM5) (EPA, 2005). The MM5 outputs were postprocessed by EPA for input to CMAQ using the MCIP program. The meteorological input preparation methodology and some information on MM5 model performance are provided by McNally (2003). The meteorological fields for the 12-km study domain were extracted from a larger 12-km domain used by EPA.

The 12-km meteorological inputs were also used as the basis for the 4-km meteorological fields. Interpolation and reanalysis methods were used to adapt the input files to the 4-km grid. The 12-

km fields were interpolated to the 4-km grid. For most parameters, objective analysis (based on bi-linear interpolation) was used to combine the interpolated fields with available observations and thus adjust the 12-km fields to the 4-km grid. Certain parameters such as radiation, rainfall, and land-use-based quantities, which are not expected to exhibit smooth variations in space, were not interpolated and the values used for the 4-km sub-cells were the same as for the encompassing 12-km grid cell.

Initial and Boundary Conditions and Geophysical Input Files

CMAQ was run once for 2010 and once for 2020 for the 36-km CONUS domain and the output from these runs was used to generate boundary conditions for the 12-km domain. Similarly, for each CMAQ scenario, the output from the 12-km grid was used to generate boundary conditions for the 4-km grid (one-way nesting). Gridded land-use and photolysis rate input files were prepared for the 12- and 4-km grids and the simulation period using standard CMAQ utility programs (CMAS, 2008).

Post-processing and Quality Assurance Procedures

Quality assurance of the CMAQ runs included the following steps:

- Scripts were routinely checked to ensure that the correct input files and output file names were used. Any error messages generated by CMAQ were checked and reconciled.
- For each simulation, plots of average $PM_{2.5}$ concentration, selected particulate species (e.g., sulfate, nitrate, organic carbon, and elemental carbon), and mercury deposition for each month and for the annual simulation period were prepared. In addition, plots of daily maximum 8-hour average ozone for the 15th day of each month were prepared. These were examined and compared with the results for other runs. The concentration patterns and values were checked for reasonableness.
- Difference plots comparing $PM_{2.5}$ and ozone concentrations and mercury deposition for each scenario versus the 2020 Reference Case simulation were also prepared. The results for each month and each alternative scenario were compared to ensure that differences in the CMAQ results were consistent with the emissions changes.

Following the quality assurance of the modeling results, the CMAQ results were post-processed for input to the health impacts and benefits modeling, as discussed in Section 4 of this report.

3.3. CMAQ Modeling Results

The CMAQ modeling results for the 2020 Reference Case and alternative energy generation scenarios are presented in this section. First, the CMAQ/PPTM-derived contributions from EGUs are presented. The estimated contributions were used to estimate the overall health-related costs associated with EGUs within the region encompassed by the 4-km modeling grid; the EGU-related costs are presented in Section 4 and are compared with results from a recent report by the National Academy of Sciences (NAS, 2009). Next, the 2020 Reference Case simulation results for ozone, $PM_{2.5}$, and mercury are presented for the 4-km grid. The simulated concentrations and deposition amounts were used to estimate health effects and monetized health benefits, as presented in Section 4.

$PM_{2.5}$ Source Contribution Analysis for 2020

As noted earlier, the CMAQ Ozone and Particle Precursor Tagging Methodologies (OPTM and PPTM) are designed to provide detailed, quantitative information about the *contribution* of selected sources, source categories, and/or source regions to simulated ozone and $PM_{2.5}$ concentrations, respectively. CMAQ/PPTM was used in this study to examine the contributions of emissions from the major source categories to simulated $PM_{2.5}$ concentrations and specifically to quantify the contributions from EGU sources.

CMAQ/PPTM was applied for the 2020 Reference Case scenario and the 12-km grid and the contributions from sources within the 12-km grid to specified receptor areas were estimated. Specifically, PPTM was used to examine the contributions to simulated PM for the following major emissions source categories/source areas:

- EGU point sources in Delaware
- EGU point sources in New Jersey, Pennsylvania, Maryland, Virginia, and Washington, D.C.
- EGU point sources in the remainder of the 12-km grid
- Non-EGU point sources in the 12-km grid
- All other emission sources in the 12-km grid combined (including on-road mobile, non-road, and area sources)
- Biogenic emissions
- Initial conditions and boundary conditions (IC/BCs).

Two key receptor areas were defined as follows: 1) the area encompassed by the 4-km grid (refer to Figure 1-1) and 2) Delaware. Figure 3-1a displays the simulation contribution from each of the seven tagged source categories/regions to annual average $PM_{2.5}$ for the 4-km grid. Figure 3-1b displays the simulation contribution from each of the tagged source categories/regions to annual average $PM_{2.5}$ for Delaware. The units for $PM_{2.5}$ concentration are micrograms per cubic meter (μgm^{-3}).

Figure 3-1a. CMAQ/PPTM-Derived Contributions to Annual Average $PM_{2.5}$ Concentration: 4-km Grid.

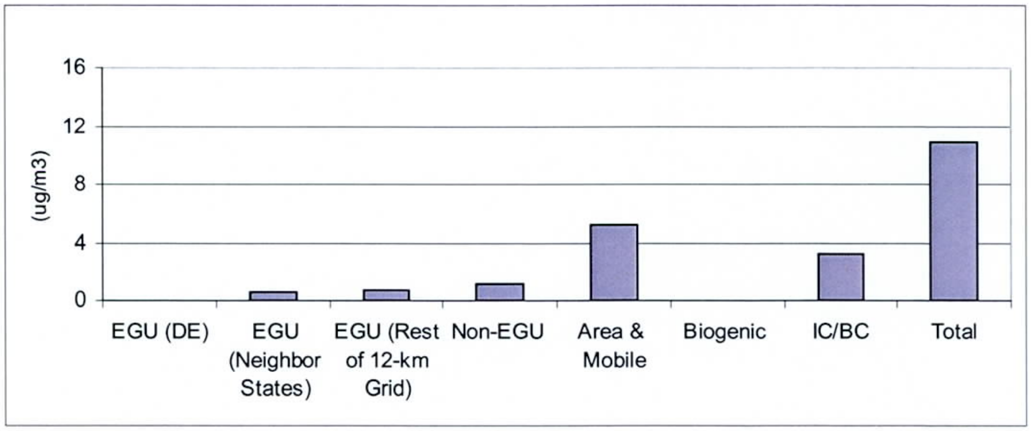
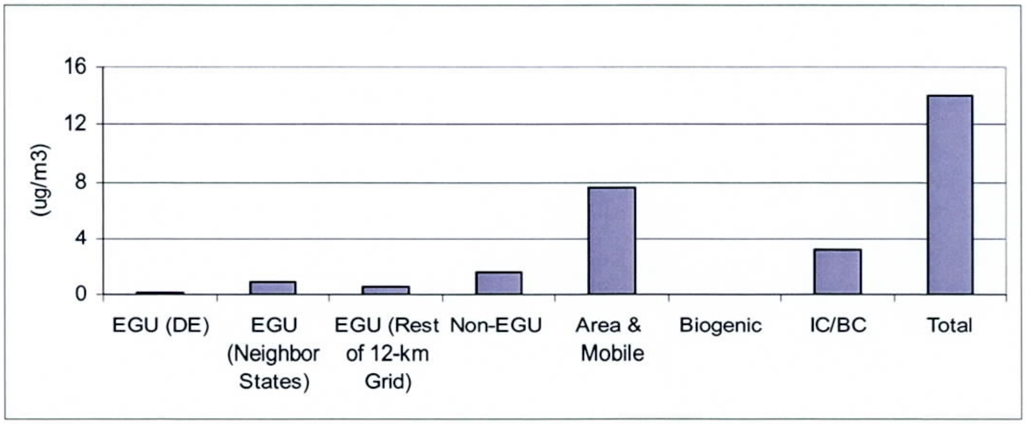


Figure 3-1b. CMAQ/PPTM-Derived Contributions to Annual Average $PM_{2.5}$ Concentration: Delaware.

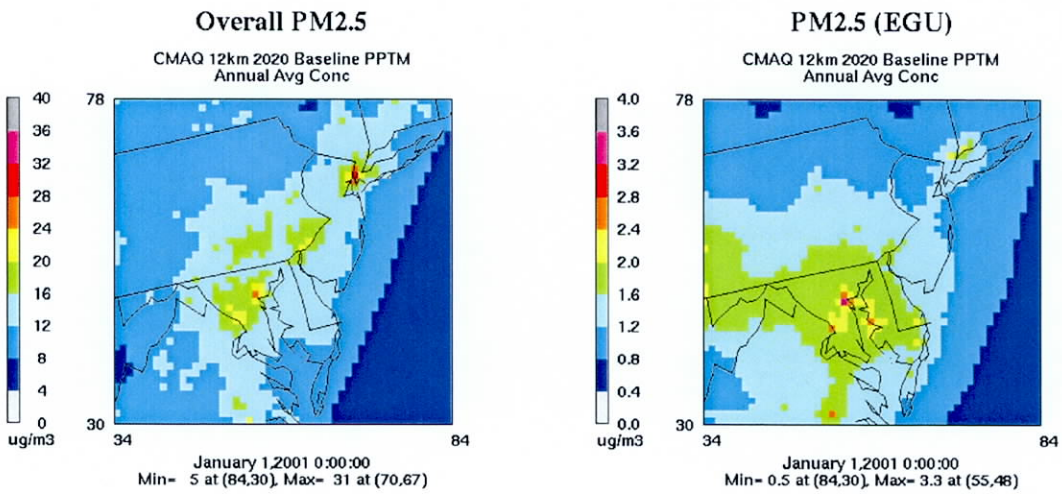


For both receptor regions, the tagging results indicate that among the tagged categories the area, on-road mobile, and non-road mobile sources (combined) are the largest contributor to the overall $PM_{2.5}$ concentration. They account for about 50 percent of the overall simulated concentration. IC/BCs, non-EGU sources, and EGU sources also contribute. The EGU sources (first three tags combined) account for 11 and 12 percent, respectively, of the simulated annual average $PM_{2.5}$ concentration for the 4-km grid and Delaware. The EGU contribution from sources located in Delaware is negligible when considered annual average $PM_{2.5}$ within the 4-km grid and very small when considering annual average $PM_{2.5}$ for Delaware. Note that the IC/BC contribution represents the contribution from all sources outside the 12-km grid (including EGUs located outside of the region), so the total EGU contribution may be slightly higher.

Spatial plots of the simulated annual average $PM_{2.5}$ concentration (all sources) and the corresponding contribution from EGU sources are provided in Figure 3-2. Note that the scales are different for the two plots.

Figure 3-2. CMAQ/PPTM Contribution to Simulated Annual Average $PM_{2.5}$ Species Concentration (μgm^{-3}) for the 4-km Grid from Emissions from (a) All Sources and (b) EGU Sources.

(a) Annual Average $PM_{2.5}$ (All Sources) (b) Annual Average $PM_{2.5}$ Contribution (EGU Sources)



The overall maximum simulated annual average $PM_{2.5}$ concentration from all sources is 31 μgm^{-3}. The maximum contribution from EGU sources is 3.3 μgm^{-3}.

2020 Reference Case Simulation Results

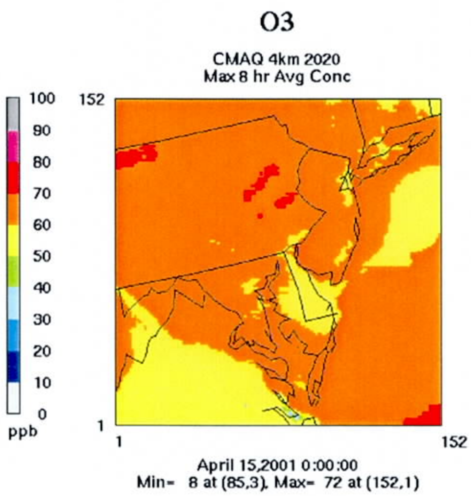
This section of the report provides an overview of the 2020 Reference Case CMAQ modeling results for the 4-km grid. These modeling results were generated for the assessment of air quality related health effects and the calculation of monetized health benefits.

Ozone

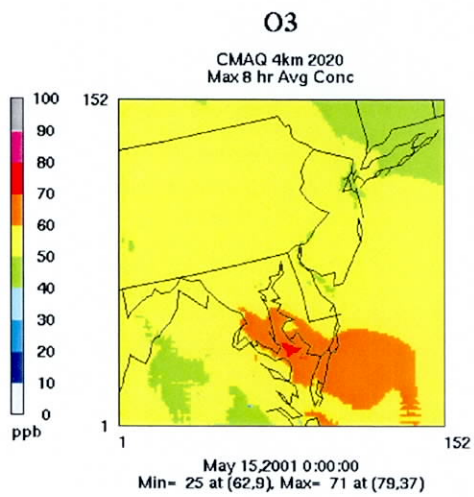
Figure 3-3 displays simulated daily maximum 8-hour ozone concentration (ppb) for the 4-km grid for the 15th of April, May, June, July, August, September, and October. These months represent the ozone season for the Mid-Atlantic states. The middle days of each month are used here to illustrate the month-to-month changes in ozone concentrations and to provide some perspective on the range of ozone concentration patterns simulated by CMAQ. The date and time given on this and all subsequent figures refer to the meteorological base year and start hour for the selected day or averaging period. The minimum and maximum values for any location within the domain are also provided, along with their grid cell (x,y) locations.

Figure 3-3. Simulated Daily Maximum 8-Hour Ozone Concentration (ppb) for the 4-km Grid for the 15th of April, May, June, July, August, September, and October: 2020 Reference Case Simulation.

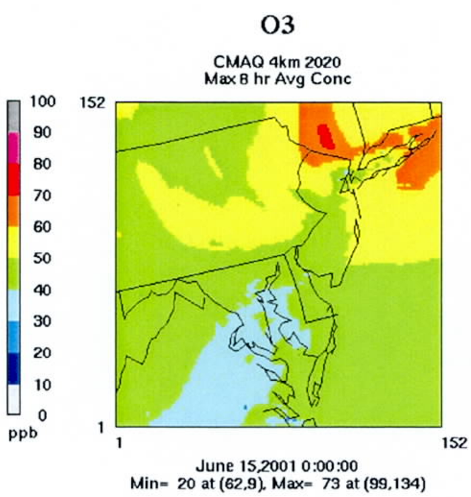
(a) April



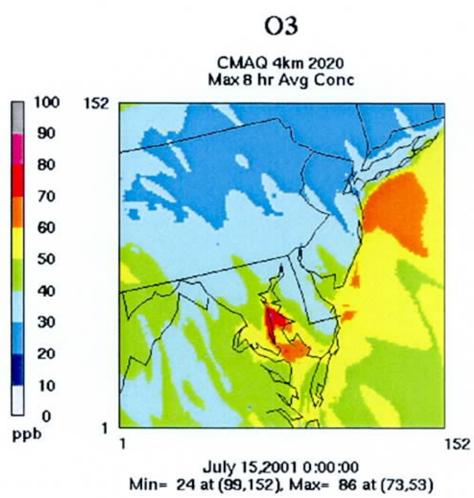
(b) May



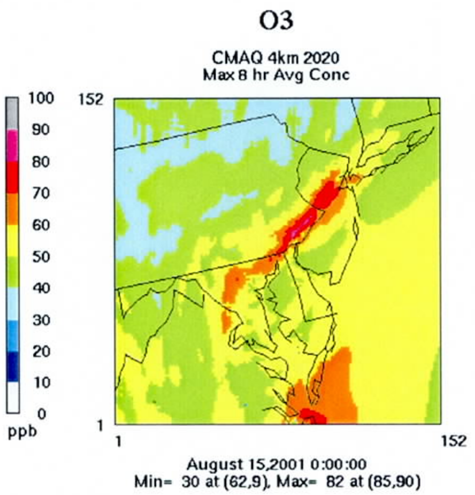
(c) June



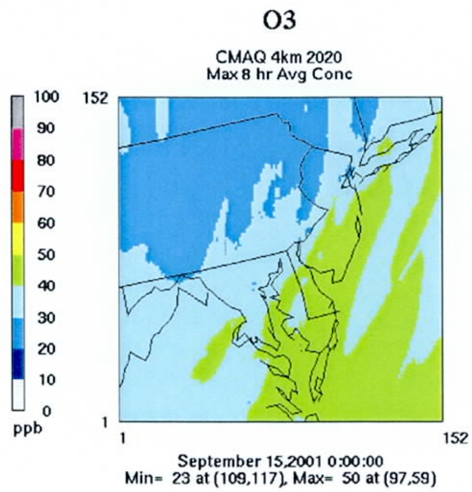
(d) July



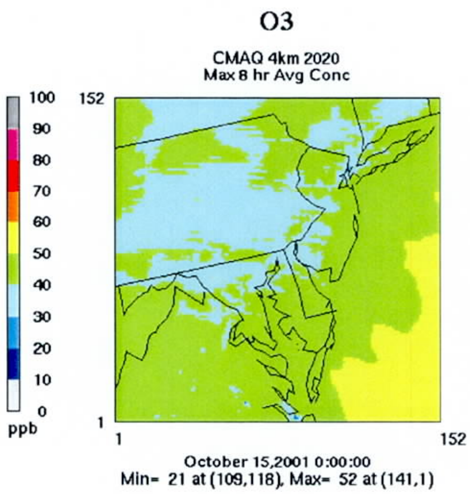
(e) August



(f) September



(g) October

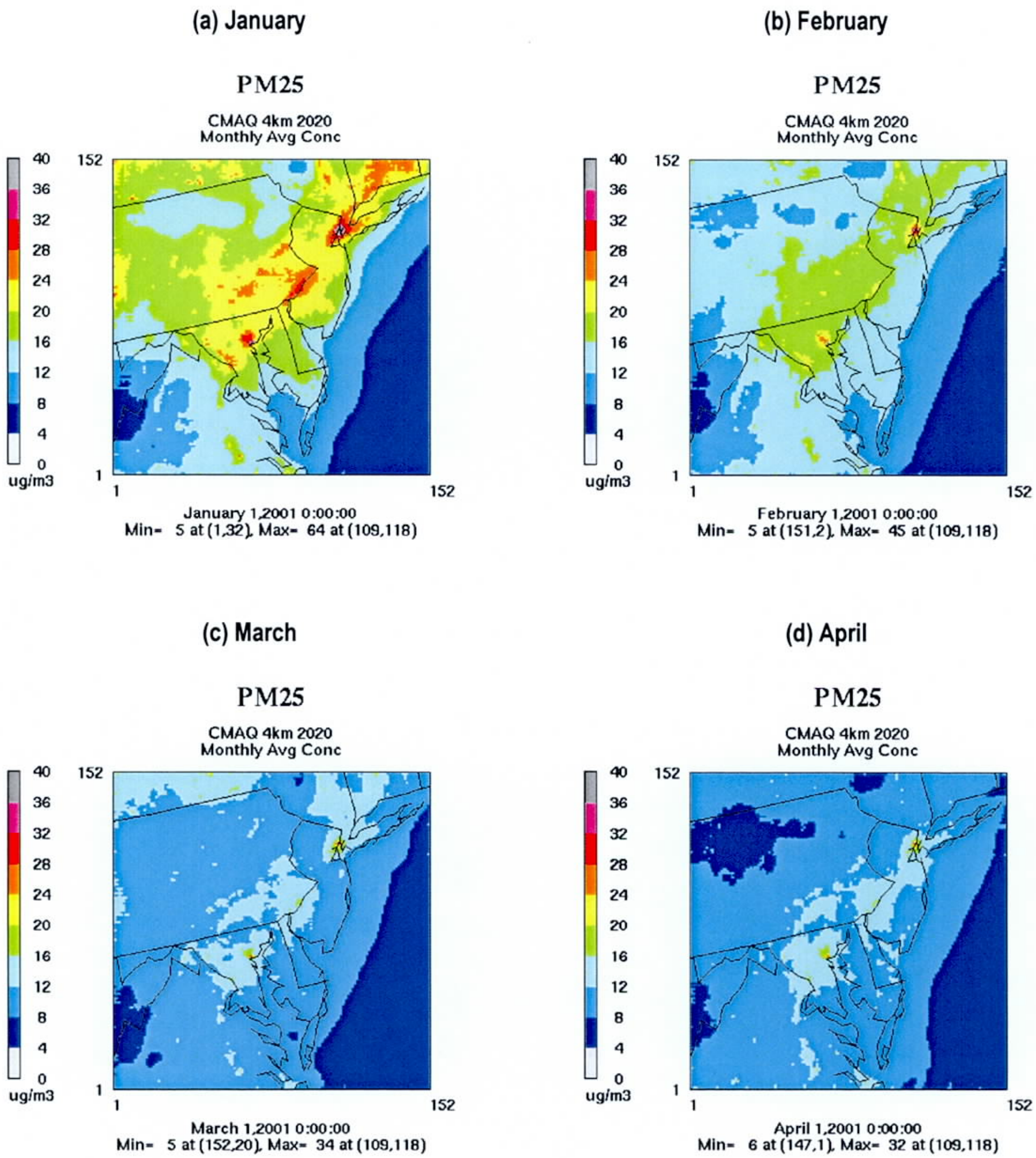


For this subset of days, daily maximum 8-hour ozone concentrations greater than 60 ppb are most widespread on April 15th, but the highest overall simulated daily maximum 8-hour average concentration (86 ppb) occurs on July 15th.

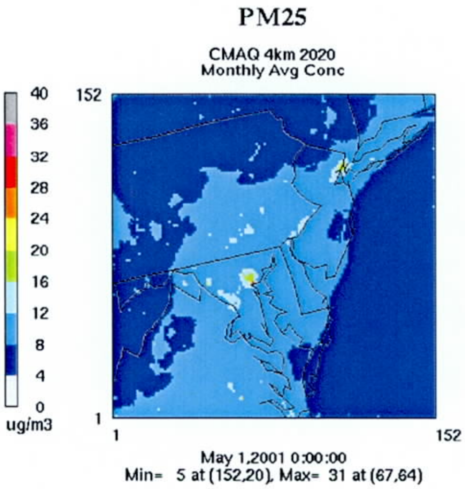
PM2.5

Figure 3-4 displays simulated monthly average $PM_{2.5}$ concentration (μgm^{-3}) for the 4-km grid for each month of the 2020 Reference Case simulation. The monthly plots are used here to illustrate the seasonal differences in $PM_{2.5}$ concentration and to highlight the concentration patterns simulated by CMAQ.

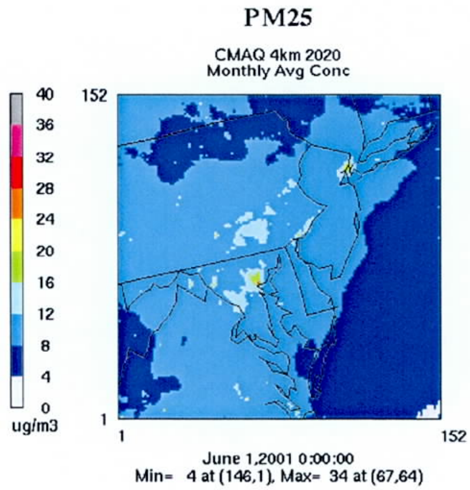
Figure 3-4. Simulated Monthly Average $PM_{2.5}$ (μgm^{-3}) for the 4-km Grid: 2020 Reference Case Simulation.



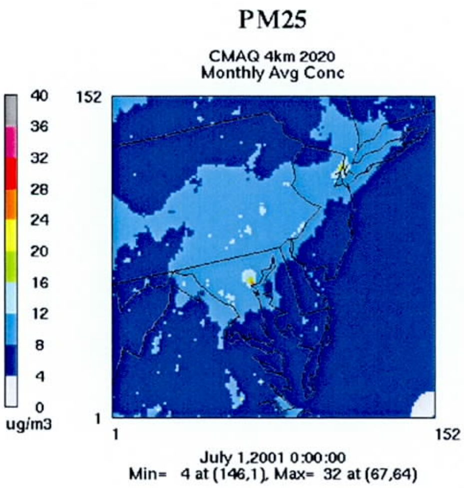
(e) May



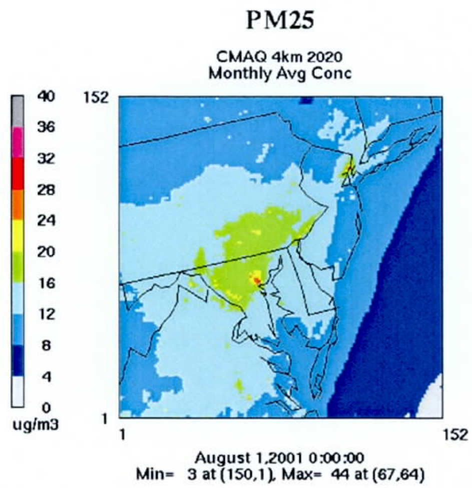
(f) June



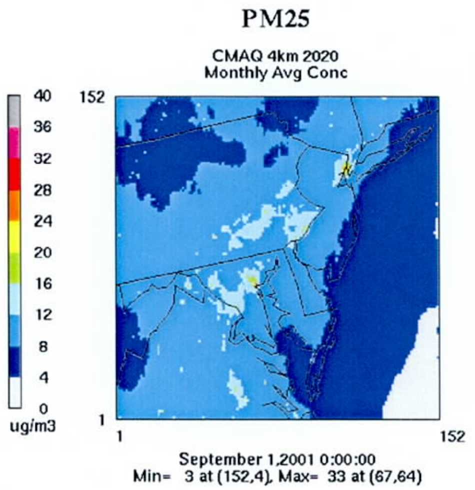
(g) July



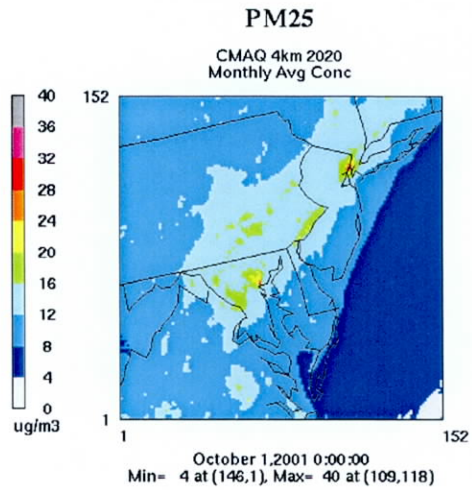
(h) August



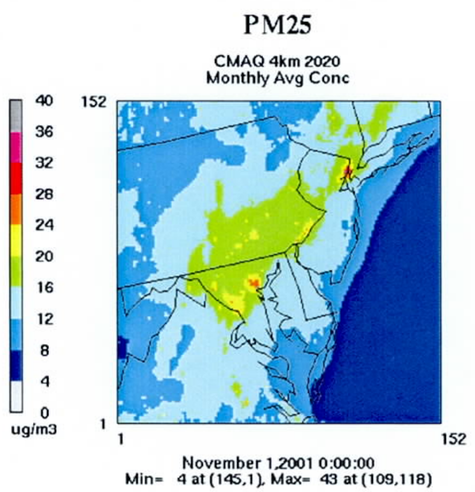
(i) September



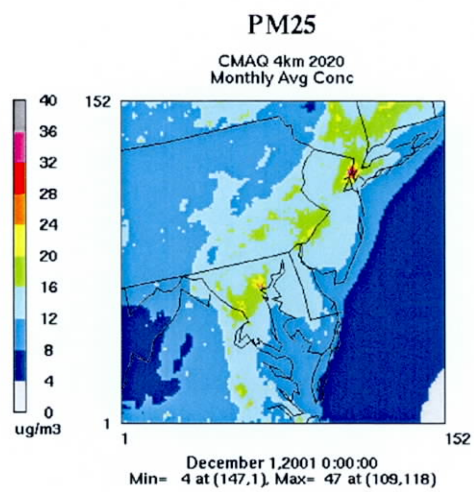
(j) October



(k) November



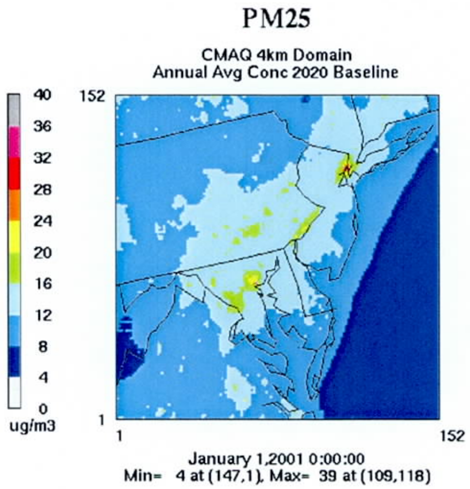
(l) December



The highest monthly average $PM_{2.5}$ concentrations tend to occur in the winter months, and are likely associated with low temperatures and stable atmospheric conditions. For example, the simulated concentrations are highest for Delaware in January. The concentration patterns for all months are characterized by relatively high $PM_{2.5}$ concentrations along the Northeast Corridor, and especially near Baltimore and New York City.

Figure 3-5 displays the simulated annual average $PM_{2.5}$ concentration (μgm^{-3}) for the 4-km grid for the 2020 Reference Case simulation. Note that the maximum concentration is slightly higher for the 4-km simulation, compared to the PPTM run (shown earlier), but that the patterns are very similar. The higher peak is due to the higher grid resolution.

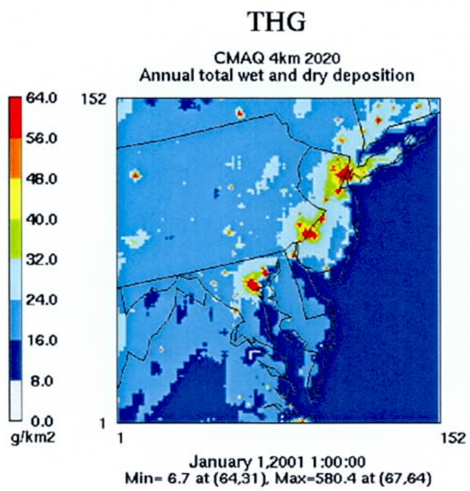
Figure 3-5. Simulated Annual Average $PM_{2.5}$ (μgm^{-3}) for the 4-km Grid: 2020 Reference Case Simulation.



Mercury

Figure 3-6 displays simulated annual mercury deposition (g km^{-2}) for the 4-km grid for the 2020 Reference Case simulation. The plot shows total mercury deposition, which includes both wet and dry deposition from all sources.

Figure 3-6. Total Annual Mercury Deposition (g km^{-2}) for the 4-km Grid: 2020 Reference Case Simulation.



The annual total mercury deposition pattern is characterized by widespread deposition of mercury in the range 8 to 24 g km^{-2}, greater deposition amounts along the Northeast Corridor, and a number of areas of high deposition (sometimes referred to as "hot spots"). The simulated deposition amounts for Delaware are relatively low compared to those for New Jersey and northeastern Maryland.

Alternative Energy Generation Scenarios

CMAQ results for Scenarios S1 and S3 are presented in this section. CMAQ was not run for Scenario S2, but the results are expected to be similar to those for S3. In fact, due to the integrated approach to estimating the changes in emissions using IPM and the small changes in emissions for each scenario, the results for S1, S2, and S3 are all very similar.

Scenario S1 (Offshore Wind)

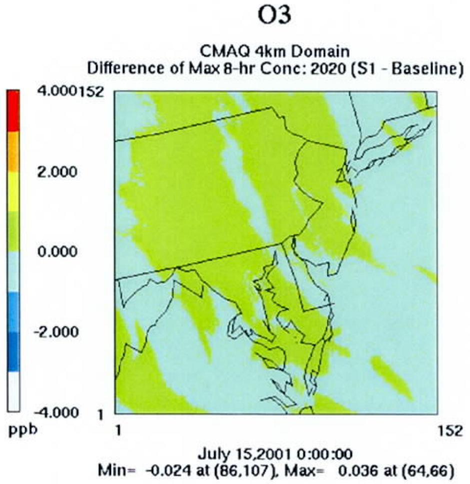
Scenario S1 examines the air quality impacts associated with the installation of additional offshore wind power generation facilities. The emissions changes due to the addition of offshore wind power facilities were estimated using the IPM model and are discussed in Section 2 of this report. IPM was used to estimate the *integrated* changes in emissions across the power grid and the emissions changes occur throughout the region (and affect facilities in both the 12- and 4-km modeling grids). The 2020 Reference Case emission inventories for both grids were modified to reflect the changes in emissions associated with the offshore wind power generation. The resulting emissions were used for the CMAQ application for S1. The CMAQ S1 simulation was run for both the 12- and 4-km grids (using a one-way nested-grid approach) and the annual simulation period.

CMAQ results for the S1 scenario are presented and compared in the remainder of this section.

Ozone

Figure 3-7 displays the difference in simulated daily maximum 8-hour ozone concentration (ppb) between the S1 and Reference Case scenarios for the 15th of July. July 15th was selected as an example ozone-season day for display of the ozone concentrations, primarily because of relatively higher ozone concentrations on this day compared to other days comprising the simulation period. The small increases and decreases in ozone concentration for S1 are characteristic of all simulation days examined. The differences in ozone concentration are projected to be very small (less than 0.1 ppb) and too small to be meaningful relative to the absolute simulated concentrations (which range from 24 to 86 ppb for this day) and the current ozone standard (75 ppb).

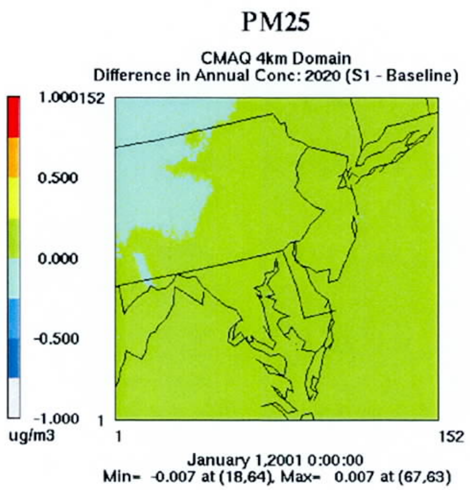
Figure 3-7. Difference in Simulated Daily Maximum 8-Hour Ozone Concentration (ppb) for 15 July (2020): S1 Minus Reference Case.



$PM_{2.5}$

Figure 3-8 displays the difference in simulated annual average $PM_{2.5}$ concentration (μgm^{-3}) between the S1 and Reference Case scenarios.

Figure 3-8. Difference in Simulated Annual Average $PM_{2.5}$ Concentration (μgm^{-3}) for 2020: S1 Minus Reference Case.

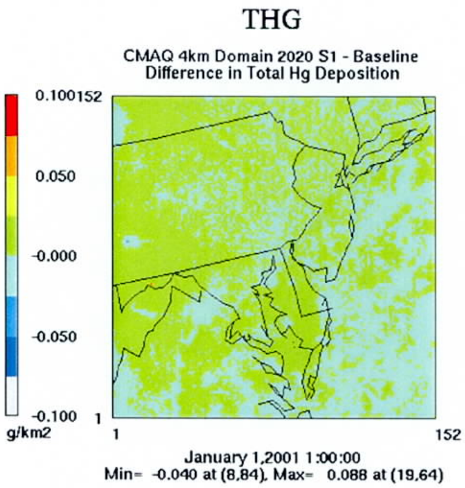


The absolute and relative differences are also projected to be small for $PM_{2.5}$. The difference plot shows that the S1 $PM_{2.5}$ concentrations are slightly higher throughout much of the 4-km grid compared to the baseline and the differences range from approximately -0.01 to 0.01 μgm^{-3}. This is compared to absolute $PM_{2.5}$ concentrations on the order of 4 to 40 μgm^{-3}.

Mercury

Figure 3-9 displays the difference in simulated total annual mercury deposition (g km^{-2}) between the S1 and Reference Case scenarios.

Figure 3-9. Difference in Simulated Total Annual Mercury Deposition (g km^{-2}) for 2020: S1 Minus Reference Case.



The differences in mercury deposition are a mix of very small decreases and increases. The maximum simulated decrease in annual mercury deposition for any grid cell in the domain is approximately 0.04 g km^{-2}, while the maximum increase is 0.09 g km^{-2}. This compared to absolute deposition amounts ranging from about 7 to greater than 100 g km^{-2}.

Scenario S3 (Combined Cycle)

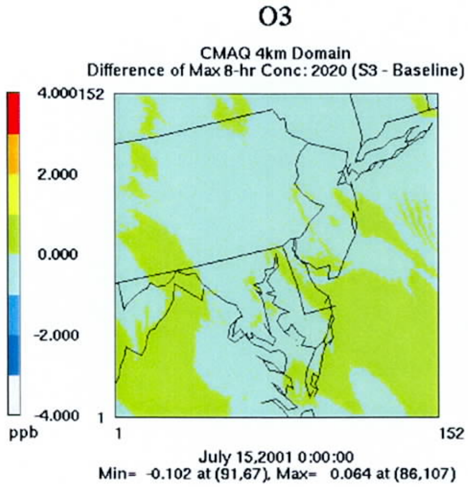
Scenario S3 examines the air quality impacts associated with the installation of a combined-cycle gas unit in Delaware. The emissions changes due to the addition of the combined-cycle unit were estimated using the IPM model and are discussed in Section 2 of this report. IPM was used to estimate the *integrated* changes in emissions across the power grid and the emissions changes occur throughout the region (and affect facilities in both the 12- and 4-km resolution modeling grids). The 2020 Reference Case emission inventories for both grids were modified to reflect the changes in emissions associated with the new facility. The resulting emissions were used for the CMAQ application for S3. The CMAQ S3 simulation was run for both the 12- and 4-km grids (using a one-way nested-grid approach) and the annual simulation period.

CMAQ results for the S3 scenario are presented and compared in the remainder of this section.

Ozone

Figure 3-10 displays the difference in simulated daily maximum 8-hour ozone concentration (ppb) between the S3 and Reference Case scenarios for the 15th of July. The small increases and decreases in ozone concentration for S3 are characteristic of all simulation days examined. As for S1, the differences in ozone concentration are projected to be very small (about 0.1 ppb) and too small to be meaningful relative to the absolute simulated concentrations.

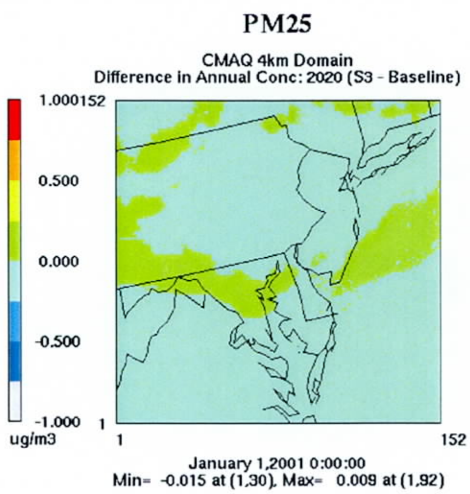
Figure 3-10. Difference in Simulated Daily Maximum 8-Hour Ozone Concentration (ppb) for 15 July (2020): S3 Minus Reference Case.



$PM_{2.5}$

Figure 3-11 displays the difference in simulated annual average $PM_{2.5}$ concentration (μgm^{-3}) between the S3 and Reference Case scenarios.

Figure 3-11. Difference in Simulated Annual Average $PM_{2.5}$ Concentration (μgm^{-3}) for 2020: S3 Minus Reference Case.

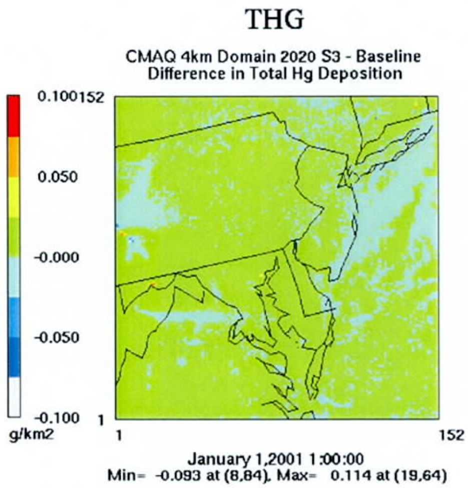


Overall the differences are similar in magnitude to those for S1. The difference plot shows that the S3 $PM_{2.5}$ concentrations are lower throughout most of the 4-km grid compared to the Reference Case and the differences range from approximately -0.02 to 0.01 μgm^{-3}. The relatively consistent pattern of decreases suggests that the small decreases in $PM_{2.5}$ are attributable to reductions in emissions throughout the modeling domain.

Mercury

Figure 3-12 displays the difference in simulated total annual mercury deposition (g km^{-2}) between the S3 and Reference Case scenarios.

Figure 3-12. Difference in Simulated Total Annual Mercury Deposition (g km^{-2}) for 2020: S3 Minus Reference Case.



The differences in mercury deposition are a mix of very small decreases and increases. The maximum simulated decrease in annual mercury deposition for any grid cell in the domain is approximately 0.09 g km^{-2}, while the maximum increase is 0.1 g km^{-2}. This compared to absolute deposition amounts ranging from about 7 to greater than 100 g km^{-2}.

3.4. Discussion of Attributes and Limitations

The CMAQ air quality modeling system provides a reliable platform for evaluating the expected responses to changes in precursor emissions. The detailed, quantitative modeling results provide an excellent basis for examining the effects of the changes in emissions on air quality and provide the requisite input for the health effects and benefits modeling.

CMAQ is a three-dimensional, regional-scale, multi-pollutant model that simulates a) the emissions of precursor species (NO_x, SO_2, VOC, Hg, etc.) from various anthropogenic and biogenic sources, b) the transport, dispersion, and chemical transformation of these constituents into secondary products (ozone and particulate matter), and c) the deposition of such species to land surfaces. It well suited for use with IPM since the emissions changes estimated using IPM typically 1) involve point sources (with varying stack-height and plume-rise parameters) that require a three-dimensional representation of the atmosphere, 2) are distributed regionally (within the power grid), and 3) simultaneously affect multiple precursor species. All of these factors can be taken into account in a CMAQ simulation. CMAQ is also able to accommodate temporal variations in the emissions and changes to the temporal profiles of the emissions. In addition to a spatially and temporally detailed treatment of the emissions, CMAQ is also designed to account for other factors that affect air quality and the resulting health impacts at any given location, such as meteorology, topography, land-use, and atmospheric chemistry processes.

An important attribute of this application of CMAQ is the use of 4-km horizontal grid resolution. This grid resolution is consistent with current EPA modeling guidance and practice for urban-scale ozone modeling and exceeds that typically used for $PM_{2.5}$ and mercury modeling. This grid resolution should be sufficiently detailed to resolve both near-source and regional processes that influence point source emissions and provide an accurate response to small changes in precursor emissions.

All air quality modeling exercises are affected by inherent uncertainties that derive from model formulation (including numerical approximations and the parameterization of physical and chemical processes), and inaccuracies in the input fields (including the meteorological inputs and emission inventory estimates). A number of key limitations and uncertainties, both general and specific to this analysis, are discussed below.

Pollutants such as ozone and $PM_{2.5}$ are secondary pollutants that are formed through atmospheric chemical processes. There are many different reaction pathways and there are uncertainties associated with each pathway as represented in the CMAQ model.

There are inherent uncertainties in the Reference Case emission inventories as well as in the IPM emission estimates. Key areas of uncertainty in the Reference Case emissions include the accuracy and completeness of the National Emissions Inventory (NEI) base-year emission estimates (2005), the methods and assumptions used to project the emissions (e.g., economic indicators and forecasts), the use of spatial surrogates (e.g., population, land use) to allocate the emissions by grid cell, the use of estimated annual, seasonal, monthly, and diurnal temporal profiles to allocate the emissions temporally, and the use of chemical speciation profiles that are based on limited data to speciate the data for use in the model (particularly hydrocarbon data). Key areas of uncertainty in the IPM emission estimates are uncertainties in a) forecasting future economic growth and associated demands in electricity, b) changes in the future regulatory environment, c) market pricing, and d) the costs associated with construction and maintenance of electric generation facilities operated in a marine environment.

It is expected that there are also uncertainties in the other inputs that also contribute to biases in the CMAQ results; these have not been specifically examined or quantified as part of this analysis. In addition, there are uncertainties associated with modeling a future year. As noted above, the 2020 emissions are based on future estimates of population and economic and industrial activity and contain uncertainties due to potential unknown social, political, and/or economic factors that could affect growth/activity and future emissions. Also, the meteorological inputs might be representative of 2001 conditions but may not reflect any effects of potential climate change in 2020.

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4. Health Effects and Benefits Assessment

The methods and results of the health effects and benefits modeling related to ozone, fine particulate matter ($PM_{2.5}$), and mercury are presented in this section. Ozone and $PM_{2.5}$ are secondary pollutants that are formed in the atmosphere. Ozone is a secondary pollutant that is formed in the atmosphere by a series of reactions involving ultra violet radiation and precursor emissions of nitrogen oxides (NO_x) and volatile organic compounds (VOCs). Fine particulates in the atmosphere consist of primary particles that are emitted directly from sources and secondary particles that form in the atmosphere through chemical and physical processes. Pollutants that contribute to the formation of secondary aerosols include sulfur dioxide (SO_2), NO_x, and other species. Thus this assessment of the health effects and benefits for ozone and $PM_{2.5}$ addresses the effects of changes in NO_x and SO_2 emissions.

For ozone and $PM_{2.5}$, the BenMAP health effects analysis tool was used to quantify the health impacts and monetized health benefits associated with EGU emissions and specifically with the changes in emissions associated with the alternative power generation scenarios. For mercury, a more qualitative assessment is provided.

4.1. Ozone and $PM_{2.5}$

Following the application of CMAQ for the 2020 Reference Case and alternative power generation scenarios, the CMAQ-derived air quality estimates were processed for input to the BenMAP health effects analysis tool, and BenMAP was used to estimate the health impacts and monetized health-related benefits associated with the changes in air pollution simulated by CMAQ for each modeled alternative. The BenMAP tool includes health impact functions, which relate a change in the concentration of a pollutant to a change in the incidence of a health endpoint. BenMAP also calculates the economic value of health impacts.

Overview of the BenMAP Modeling System

BenMAP is a computer program developed by EPA that uses interpolation functions, population projections, health impact functions, and valuation functions to translate simulated changes in air pollution concentration into changes in health-related incidences and monetized health-related benefits. BenMAP is primarily intended as a tool for estimating the human health effects and economic benefits associated with changes in ambient air pollution. EPA originally developed this tool to analyze national-scale air quality regulations. The health benefits and monetary values derived using BenMAP are intended to inform policy makers by enabling the comparison of the benefits and costs of various regulatory measures (Abt Associates, 2008).

BenMAP relies on the input of air quality information that can be used to calculate the change in ambient air pollution associated with a change in emissions. Typically, the results from two air quality modeling simulations (with different emission inputs) are used. In some cases, measured ambient air quality data can also be used.

BenMAP calculates health effects based on expected relationships between the change in concentration and certain health effects (also known as health endpoints), using concentration-response (C-R) functions from epidemiology studies (Abt Associates, 2008). The response functions are used together with population data to estimate health effects. For a model-based application, health effects are calculated on a grid cell-by-grid cell basis and then summed to obtain regional and national-scale estimates. In its most basic form, the health effect for a given health endpoint is a function of the change in air concentration, concentration-response estimates, and population. Primary health endpoints include premature mortality, heart attacks, and chronic respiratory illnesses.

After estimating the change in adverse health effects associated with a given change in air quality, BenMAP calculates the monetary benefits associated with those changes (Abt Associates, 2008). Simply, the economic value is based on the change in the incidence of a certain adverse health effect multiplied by the value of the health effect (on a per-incident or per-case basis). For example, the value associated with avoided premature mortality is typically calculated using the Value of Statistical Life (VSL), which is the monetary amount that people are willing to pay to slightly reduce the risk of premature death. For other health effects, the medical costs of the illness are typically used to estimate value. The BenMAP database includes several different valuation functions for VSL and other health endpoints.

BenMAP Application Procedures

Prior to the application of BenMAP, the CMAQ model output files were reformatted for input into the BenMAP tool. The analysis period for ozone for the application of BenMAP is a subset of the CMAQ simulation period and includes only April through October. The input files for ozone contain 214 days of hourly average ozone concentrations for each grid cell in the CMAQ modeling domain. The analysis period for $PM_{2.5}$ for the application of BenMAP is the full annual CMAQ simulation period. The input files for $PM_{2.5}$ contain 365 days of 24-hour average $PM_{2.5}$ concentration for each grid cell. BenMAP was applied for both the 4-km CMAQ modeling domain and for the area covering the State of Delaware. BenMAP includes population data at the census-tract level and algorithms for characterizing demographic changes (age distribution) over time. For this analysis, population estimates for 2020 were used. This is consistent with the CMAQ simulation year of 2020. BenMAP was applied separately for ozone and $PM_{2.5}$.

BenMAP calculates the changes in health effects and monetized health-related benefits by comparing the results of two simulations. For this study, BenMAP was first used to estimate the monetized health costs associated with all EGUs in the analysis region. BenMAP was then used to calculate the change in health effects and monetized health-related benefits for each alternative power generation scenario compared to the 2020 Reference Case. For reference, difference plots of the CMAQ-derived ozone and $PM_{2.5}$ concentrations for each pair of simulations were presented in Section 3.

For each pollutant and simulation couple, the application of BenMAP included four steps:

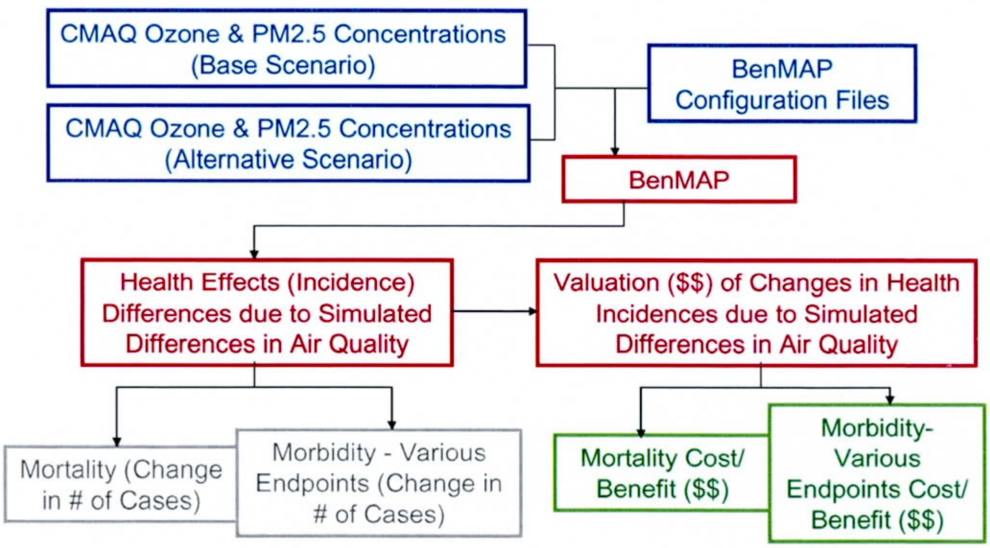
- Incorporation of the CMAQ modeling results into the air quality grid files required by BenMAP (air quality grid creation);

- Calculation of the change in the incidence of adverse health effects based on the differences in the CMAQ-derived ozone and $PM_{2.5}$ concentrations between the two simulations;
- Aggregation of the incidence results and calculation of the economic value of the aggregated incidences; and
- Preparation of tabular and graphical summaries; quality assurance and analysis of the results.

In the air quality grid creation step, the CMAQ model results were used directly.

Figure 4-1 illustrates the steps and components of the BenMAP application procedure.

Figure 4-1. Schematic Diagram of the BenMAP Health Effects and Benefits Analysis



Health Impact Functions

BenMAP was used to calculate reductions in both mortality and a range of non-fatal health effects (morbidity), based on epidemiological studies of a number of U.S. and non-U.S. (Canadian) populations.

BenMAP can estimate changes in a wide range of health impact "endpoints" associated with changes in ozone and $PM_{2.5}$ exposure. The endpoints are grouped broadly as "mortality" and "morbidity." Mortality endpoints include changes in "all-cause" mortality, as well as mortality due to specific causes, such as cardiopulmonary disease. Morbidity endpoints include specific illnesses and symptoms ("asthma exacerbations"); events requiring medical care (emergency room visits and hospital admissions); and adverse effects that involve lost work or restricted activity days.

EPA has evaluated the literature related to the adverse effects of ozone and particulate exposures and identified a set of endpoints for which the associations are considered to be well established, and for which reliable exposure-response relationships have been developed (Abt Associates, 2008). For this analysis, the EPA-recommended set of health endpoints for use with the latest version of BenMAP was used. These endpoints are listed in Table 4-1 and Table 4-2 for ozone and $PM_{2.5}$, respectively. The endpoints include changes in mortality (for both adults and infants), as well as a range of morbidity endpoints related to respiratory and cardiovascular diseases and symptoms, hospital admissions, and lost work or lost activity days. The age range for each endpoint, if available, is provided in the tables.

Table 4-1. Health Impact Functions Used in the BenMAP Application to Estimate Ozone-Related Health Effects.

Endpoint	Author/Study Location	Age Range	Notes
Mortality, Non-Accidental	Ito et al. (2005)	0-99	a, b
Mortality, Non-Accidental	Schwartz (2005) (14 U.S. cities)	0-99	a,c
Mortality, Non-Accidental	Bell et al. (2004) (95 U.S. Cities)	0-99	a,b
Mortality, All Cause	Levy et al. (2005) (US & non-U.S.)	0-99	a,c
Mortality, All Cause	Bell et al. (2005) (US & non-U.S.)	0-99	a,b
Mortality, Cardiopulmonary	Huang et al. (2005) (19 U.S. cities)	0-99	a,b
Emergency Room Visits, Asthma	Jaffe et al. (2003) (Ohio cities)	5-34	a
Emergency Room Visits, Asthma	Peel et al. (2005) (Atlanta, GA)	0-99	a
Emergency Room Visits, Asthma	Wilson et al. (2005) (Portland, ME)	0-99	a
Emergency Room Visits, Asthma	Wilson et al. (2005) (Manchester, NH)	0-99	a
Hospital Admissions, All Respiratory	Burnett et al. (2001) (Toronto, CAN)	0-1	a,c
Hospital Admissions, All Respiratory	Schwartz ((New Haven, CT)	65-99	a,b
Hospital Admissions, All Respiratory	Schwartz (Tacoma, WA)	65-99	a,b
Hospital Admissions, Chronic Lung Disease	Moolgavkar et al. (1997) (Minneapolis, MN)	65-99	a,d
Hospital Admissions, Pneumonia	Moolgavkar et al. (1997) (Minneapolis, MN)	65-99	a,d
Hospital Admissions, Pneumonia	Schwartz (1994) (Detroit, MI)	65-99	a,d
Hospital Admissions, Pneumonia	Schwartz (1994)(Minneapolis, MN)	65-99	a,d
Hospital Admissions, Chronic Lung Disease (less Asthma)	Schwartz (1994) (Detroit, MI)	65-99	a,d
School Loss Days, All	Chen et al. (2000) (Washoe Co, NV)	5-17	a,f
School Loss Days, All	Gilliland et al. (2001) (So. CA)	5-18	a,e
Worker Productivity	Crocker & Horst (Nationwide)	18-64	a,d
Minor Restricted Activity Days	Ostro & Rothschild (1989) (Nationwide)	18-64	a,g

a/ Metric is daily maximum 8-hour ozone.
b/ Metric is daily maximum 8-hour ozone. Warm season. 8-hour max from 24-hour mean.
c/ Metric is daily maximum 8-hour ozone. Warm season. 8-hour max from 1-hour mean.
d/ Metric is daily maximum 8-hour ozone. All year. 8-hour max from 24-hour mean.
e/ Metric is daily maximum 8-hour ozone. All year. 8-hour max from 8-hour mean.
f/ Metric is daily maximum 8-hour ozone. All year. 8-hour max from 1-hour mean.
g/ Metric is daily maximum 8-hour ozone. 8-hour max from 1-hour mean.

Table 4-2. Health Impact Functions Used in the BenMAP Application to Estimate PM2.5-Related Health Effects.

Endpoint	Author/Study Location	Age Range	Notes
Mortality, All Cause	Laden et al. (2006) (6 cities)	25-99	
Mortality, All Cause	Pope et al. (2002) (51 cities)	30-99	
Mortality, All Cause	Woodruff et al. (2006) (204 counties)	0-1	
Mortality, All Cause	Pope et al. (2002) (51 cities)	30-99	a
Mortality, All Cause	Pope et al. (2002) (51 cities)	30-99	b
Mortality, All Cause	Pope et al. (2002) (51 cities)	30-99	c
Mortality, All Cause	Pope et al. (2002) (51 cities)	30-99	d
Mortality, All Cause	Expert Elicitation (2006)	30-99	e
Mortality, All Cause	Expert Elicitation (2006)	30-99	f
Mortality, All Cause	Expert Elicitation (2006)	30-99	g
Mortality, All Cause	Expert Elicitation (2006)	30-99	h
Mortality, All Cause	Expert Elicitation (2006)	30-99	i
Mortality, All Cause	Expert Elicitation (2006)	30-99	j
Mortality, All Cause	Expert Elicitation (2006)	30-99	k
Chronic Bronchitis	Abbey et al. (1995)	27-99	
Acute Bronchitis	Dockery et al. (1996) (24 communities)	8-12	
Acute Myocardial Infarction, Nonfatal	Peters et al. (2001) (Boston, MA)	18-24	
Acute Myocardial Infarction, Nonfatal	Peters et al. (2001) (Boston, MA)	25-44	
Acute Myocardial Infarction, Nonfatal	Peters et al. (2001) (Boston, MA)	45-54	
Acute Myocardial Infarction, Nonfatal	Peters et al. (2001) (Boston, MA)	55-64	
Acute Myocardial Infarction, Nonfatal	Peters et al. (2001) (Boston, MA)	65-99	
Hospital Admissions, Chronic Lung Disease	Moolgavkar (2003) (Los Angeles, CA)	65-99	
Hospital Admissions, Chronic Lung Disease	Ito (2003) (Detroit, MI)	65-99	
Hospital Admissions, Chronic Lung Disease (less Asthma)	Moolgavkar (2000) (Los Angeles, CA)	18-64	
Hospital Admissions, Pneumonia	Ito	65-99	
Hospital Admissions, Asthma	Sheppard (2003) (Seattle, WA)	0-64	
Hospital Admissions, All Cardiovascular (less Myocardial Infarctions)	Moolgavkar	18-64	
Hospital Admissions, All Cardiovascular (less Myocardial Infarctions)	Moolgavkar	65-99	
Hospital Admissions, Ischemic Heart Disease (less Myocardial Infarctions)	Ito (2003) (Detroit, MI)	65-99	
Hospital Admissions, Dysrhythmia	Ito (2003) (Detroit, MI)	65-99	
Hospital Admissions, Congestive Heart Failure	Ito (2003) (Detroit, MI)	65-99	
Emergency Room Visits, Asthma	Norris et al. (1999) Seattle, WA	0-17	
Minor Restricted Activity Days	Ostro and Rothschild (1989) (Nationwide)	18-64	
Lower Respiratory Symptoms	Schwartz and Neas (2000) (6 U.S. Cities)	7-14	
Asthma Exacerbation, Cough	Ostro et al. (2001) (Los Angeles)	6-18	
Asthma Exacerbation, Wheeze	Ostro et al. (2001) (Los Angeles)	6-18	
Asthma Exacerbation, Shortness of Breath	Ostro et al. (2001) (Los Angeles)	6-18	
Work Loss Days	Ostro (1987) (Nationwide)	18-64	
Upper Respiratory Symptoms	Pope et al. (1987) (Utah Valley)	9-11	

a/ Adjusted Coefficient With 10 µg Threshold

b/ Adjusted Coefficient With 12 µg Threshold

c/ Adjusted Coefficient With 15 µg Threshold
d/ Adjusted Coefficient With 7.5 µg Threshold
e/ Full Range
f/ Range from > 10 to 30 µg
g/ Range from >16 to 30 (no threshold)
h/ Range from >7 to 30
i/ Range from 4 to 7 µg
j/ Range from 4 to 10 µg
k/ Range from 4 to 16 µg (no threshold)

The results options for this study include the mean value, incremental percentile values, and the standard deviation.

Valuation Metrics

BenMAP was also used to estimate reductions in monetized health-related benefits (based on value of statistical life studies, lost wages, and health care expenses) associated with the health impacts. These estimates are derived using a set of monetary surrogates for the various health effects developed by EPA and public health researchers. BenMAP also tracks changes over time in willingness-to-pay for reductions in health risks, and includes adjustment factors that incorporate the effect of inflation on health-related costs.

The assessment of monetized health-related benefits involves assigning monetary values to each health endpoint, and totaling the overall benefits associated with changes in pollutant exposures. Different valuation methods are used for the various health endpoints. The monetary surrogate value for mortality is derived using a Value of Statistical Life (VSL) approach, that is, the monetary cost of a single "statistical" death (Abt Associates, 2008). The VSL used for this analysis was $6.3 million (in 2000-equivalent dollars).

Valuation methods for morbidity endpoints (non-fatal health effects) include approaches referred to as cost-of-illness (COI), willingness-to-pay (WTP), and lost wages or productivity (Abt Associates, 2008). COI estimates comprise a range of approaches, which account for the costs of medical care, and in some cases lost wages. WTP approaches refer to methods where voluntary payments to avoid disease are directly or indirectly estimated and used to estimate monetized health-related benefits. Finally, lost productivity methods value the time lost to illness using wage rates or the estimated value of leisure or school time (Abt Associates, 2008). For all endpoints, the total monetized health-related benefit for a given endpoint is estimated by multiplying the monetary values for that endpoint by the estimated change in the number of "cases" of the endpoint. For most studies, morbidity values are small compared to the mortality values. Thus, the specific valuation methods used for morbidity have only a small effect on the overall monetized health-related benefits estimates.

For this analysis, the EPA-recommended set of valuation methods for the latest version of BenMAP was used. The endpoints and methods for the valuation portion of the analysis are listed in Table 4-3 and 4-4 for ozone and $PM_{2.5}$, respectively. The endpoints include monetized health-related benefits associated with changes in mortality, as well as a range of morbidity endpoints. All monetized health-related benefits results for this analysis are presented in 2008-equivalent dollars.

Table 4-3. Valuation Functions Used in the BenMAP Application to Estimate Ozone-Related Monetized Health-Related Benefits.

Endpoint	Author/Study Location	Valuation Method	Notes
Mortality, Non-Accidental	Ito et al. (2005)	VSL	a,c
Mortality, Non-Accidental	Schwartz (2005) (14 U.S. cities)	VSL	a,c
Mortality, Non-Accidental	Bell et al. (2004) (95 U.S. Cities)	VSL	a,c
Mortality, All Cause	Levy et al. (2005) (U.S. & non-U.S.)	VSL	a,c
Mortality, All Cause	Bell et al. (2005) (U.S. & non-U.S.)	VSL	a,c
Mortality, Cardiopulmonary		VSL	a,c
Hospital Admissions, Respiratory		COI	b,d
Hospital Admissions, Respiratory		COI	b,e
Emergency Room Visits, Respiratory	Smith et al. (1997)	COI	c
Emergency Room Visits, Respiratory	Stanford et al. (1999)	COI	c
School Loss Days			f
Worker Productivity			g
Acute Respiratory Symptoms	Cardio-vascular studies	WTP	h

a/ Based on 26 value-of life studies
b/ Med costs + wage loss
c/ Ages: 0-99
d/ Ages: 65-99
e/ Ages: 0-2
f/ Ages: 0-17
g/ Ages: 18-65
h/ Ages: 18-99

Table 4-4. Valuation Functions Used in the BenMAP Application to Estimate PM2.5-Related Monetized Health-Related Benefits.

Endpoint	Author/Study Location	Valuation Method	Notes
Mortality	Laden et al. (2006) (6 cities)	VSL	a, i
Mortality	Pope et al. (2002) (51 cities)	VSL	a, i
Mortality	Woodruff et al. (1997) (86 cities)	VSL	a, i
Chronic Bronchitis	Abbey et al. (1995) (CA)	WTP	b, k
Acute Myocardial Infarction	Peters et al. (2001) (Boston, MA)	COI	c,j,q
Hospital Admissions, Chronic Lung Disease	Ito (2003) (Detroit, MI)	COI	d,i
Hospital Admissions, Pneumonia	Ito (2003) (Detroit, MI)	COI	d,i
Hospital Admissions, Respiratory	Ito (2003) (Detroit, MI)	COI	d,p
Hospital Admissions, Cardiovascular	Moolgavkar (2000) (Los Angeles)	COI	d,p
Hospital Admissions, Cardiovascular	Moolgavkar (2000) (Los Angeles)	COI	d,i
Emergency Room Visits, Respiratory	Norris et al (1999) (Seattle, WA)	COI	i,s
Acute Bronchitis	Dockery et al. (1996) (24 communities)	WTP	e,f,m
Lower Respiratory Symptoms	Schwartz and Neas (2000) (6 U.S. cities)	WTP	e,f,m
Upper Respiratory Symptoms	Pope et al. (1991) (Utah Valley)	WTP	e,f,m
Acute Respiratory Symptoms	Ostro (2001) (Los Angeles)	WTP	e,f,n
Work Loss Days	Ostro (1987) (Nationwide)		g,o
Asthma Exacerbation	Ostro (2001) (Los Angeles)	WTP	h,m,r
Mortality, All Cause	Expert Elicitation (2006)	VSL	a,j

a/ Based on 26 value-of-life studies.

b/ Average severity

c/ 5 yrs med, 5 yrs wages, 3% DR

d/ med costs + wage loss

e/1 day illness

f/ CV studies

g/ Median daily wage, county-specific

h/ bad asthma day

i/ 0-99

j/ 30-99 k/ 0-24

l/ 65-99

m/ 0-17

n/ 18-99

o/ 18-65

p/ 20-64

q/ Russell (1998)

r/ Rowe Chestnut (1986)

s/ Stanford (1999)

In the aggregation and valuation step, the results were aggregated for the 4-km grid and for the State of Delaware. Default options were applied in the aggregation and pooling of the results. Similarly, EPA standard inflation values (defaults) were used for the valuation. The results are given in 2008-equivalent dollars.

Post-processing and Quality Assurance Procedures

As a first step in the quality assurance of the BenMAP application procedures and results, a protocol document outlining each step in the application of BenMAP was prepared. This was subsequently used as a checklist for each application and for quality assurance. Following the application of BenMAP for each pair of simulations, a subset of the BenMAP runs was duplicated by a second modeler using another computer and the results were confirmed to be the same. Finally, the results for each simulation pair were checked for consistency with emissions and the CMAQ modeling results.

Tabular summaries of the results were then prepared, as presented in the following sections. The contents of the tables were systematically checked by comparing the values with the raw BenMAP report files.

BenMAP Results

BenMAP was used to estimate the change in the incidence of various health-related endpoints, as well as a monetized estimate of the health-related costs or benefits for selected pairs of simulations. The incidence and valuation results are presented in the remainder of this section. The health incidence results presented in this section are the BenMAP-derived mean values. The valuation estimates reflect both an income growth adjustment and a time lag between exposure and $PM_{2.5}$ mortality.

BenMAP results for Scenarios S1 and S3 are presented in this section. BenMAP was not run for Scenario S2, but the results are expected to be similar to those for S3. In fact, due to the integrated approach to estimating the emissions changes using IPM and the small changes in emissions for each scenario, the results for S1, S2, and S3 are all very similar.

The income growth adjustment accounts for expected growth in real income over time. Economic theory suggests that WTP for most goods and services (such as environmental protection) will increase if income increases. To account for growth in income through 2020, BenMAP applied the following factors to the valuation results: 1.20 for long-term mortality, 1.23 for chronic health impacts, and 1.07 for minor health impacts.

The valuation results for $PM_{2.5}$ assume that there is a time lag between changes in $PM_{2.5}$ concentration and changes in $PM_{2.5}$ mortality. To account for this, monetized health-related benefits occurring in the future are discounted. For this analysis, the BenMAP-derived reductions were multiplied by 0.91 to achieve a 3% "discount rate" and by 0.82 to achieve a 7% "discount rate" (EPA pers. comm., 2010). Similar adjustments do not exist for ozone.

All of the incidence and valuation results are rounded to two significant figures (and also limited to a maximum of two decimal places).

Health Effects and Monetized Health Effects Attributable to Energy Generation

The overall health effects and costs attributed to emissions from EGUs located within the modeling domain (the 12-km grid) were estimated for the greater Mid-Atlantic region (the 4-km grid) and Delaware using the CMAQ/PPTM results summarized in Section 3. For this analysis, only the health effects and costs associated with $PM_{2.5}$ were calculated. The ozone effects were not calculated, but are expected to be much smaller than those for $PM_{2.5}$ (as will be demonstrated later in this section).

BenMAP results for $PM_{2.5}$ mortality are presented in Table 4-5. The mortality estimates are based on both epidemiology literature and expert elicitation in which experts were asked to develop estimates of the increment in mortality that would be associated with increments of $PM_{2.5}$ exposures, based on their understanding of the epidemiological literature taken as a whole (Abt Associates, 2008). The baseline case values presented in this table are a standard output from BenMAP and provide a point of reference for assessing the meaningfulness of the incidence results. The BenMAP baseline values (based on the BenMAP 2020 mortality incidence dataset for the mortality endpoints and on BenMAP 2000 incidence and prevalence dataset for the morbidity endpoints) represent deaths or health effects due to all causes, not just those related to air pollution, and these vary depending on the health impact function used for the referenced study.

Table 4-5. BenMAP Aggregated Incidence Results for $PM_{2.5}$-Related Mortality: Premature Mortality Associated with EGU Emissions Located within the Modeling Domain.

Epidemiology Literature	Greater Mid-Atlantic Region (4-km Grid)		Delaware	
	No of. Cases	Baseline Values	No. of Cases	Baseline Values
Harvard six-city study (Laden et al.)	9,200	451,789	640	25,592
ACS study (Pope et al.)	3,600	448,549	250	25,412
Infant mortality study (Woodruff et al.)	12	1,215	1	69
Expert Elicitation				
Expert A	9,800	448,549	680	25,412
Expert B	7,900	455,914	560	25,951
Expert C	8,100	448,549	570	25,412
Expert D	5,400	448,549	380	25,412
Expert E	12,000	448,549	860	25,412
Expert F	7,000	455,178	500	25,884
Expert G	6,200	448,549	430	25,412
Expert H	5,300	448,549	370	25,412
Expert I	7,700	448,549	540	25,412
Expert J	6,700	448,549	470	25,412
Expert K	4,200	451,134	300	25,578
Expert L	5,800	454,027	410	25,813

Overall, there is general consensus among the experts and among the studies. The differences are due to the use of different study populations and exposure-response relationships. For the 4-km grid the number of incidences of mortality attributed to EGU emissions in 2020 ranges from 3,600 to 12,000. For Delaware, the number of cases ranges from 250 to 860. Note that the estimated number of premature deaths associated with EGU emissions is small compared to the number of deaths due to all causes, as represented by the baseline values.

BenMAP results for other $PM_{2.5}$-related health effects and associated endpoints (morbidity) are presented in Table 4-6.

Table 4-6. BenMAP Aggregated Incidence Results for $PM_{2.5}$-Related Morbidity: Morbidity Endpoints Associated with EGU Emissions Located within the Modeling Domain.

Epidemiology Literature	Greater Mid-Atlantic Region (4-km Grid)		Delaware	
	No of. Cases	Baseline Values	No. of Cases	Baseline Values
Chronic bronchitis (age>=25)	2,500	135,178	160	6,949
Emergency room visits for asthma (age<19)	3,300	141,782	160	5,851
Acute bronchitis (age 8-12)	5,200	146,205	300	7,526
Asthma exacerbation (age 6-18)	160,000	76,631,498	9,800	3,911,320
Lower respiratory symptoms (age 7-14)	67,000	2,559,506	4,200	131,700
Upper respiratory symptoms (asthmatic children age 9-18)	51,000	15,485,265	3,200	796,333
Minor restricted-activity days (age 18-65)	2,800,000	272,121,536	170,000	13,749,218
Work loss days (age 18-65)	471,000	73,681,920	29,000	3,729,066
Nonfatal myocardial infarction (age>17)	4,300	131,165	310	7,789
Hospital admissions - respiratory (all ages)	1,300	338,888	98	20,720
Hospital admissions - cardiovascular (age>17)	1,800	847,978	120	47,751

For all endpoints considered here, the number of cases is small compared to the baseline values.

BenMAP valuation results for $PM_{2.5}$ related mortality are presented in Table 4-7. The monetized health-related costs represent regional costs, in millions of U.S. 2008-equivalent dollars.

Table 4-7. BenMAP-Derived Monetized Health-Related Costs for $PM_{2.5}$-Related Mortality with 3% and 7% Discount Rates: Estimated Monetized Costs (Millions U.S. Dollars/Year) Related to Premature Mortality Associated with EGU Emissions Located within the Modeling Domain.

Epidemiology Literature	Greater Mid-Atlantic Region (4-km Grid)		Delaware	
	3% Discount Rate	7% Discount Rate	3% Discount Rate	7% Discount Rate
Harvard six-city study (Laden et al.)	79,000	72,000	5,500	5,000
ACS study (Pope et al.)	31,000	28,000	2,200	2,000
Infant mortality study (Woodruff et al.)	100	91	7	6
Expert Elicitation				
Expert A	84,000	76,000	5,900	5,300
Expert B	68,000	61,000	4,800	4,400
Expert C	70,000	63,000	4,900	4,400
Expert D	46,000	41,000	3,200	2,900
Expert E	110,000	95,000	7,400	6,600
Expert F	60,000	54,000	4,300	3,900
Expert G	37,000	34,000	2,600	2,300
Expert H	46,000	41,000	3,200	2,900
Expert I	65,000	59,000	4,600	4,100
Expert J	58,000	52,000	4,000	3,600
Expert K	11,000	9,900	790	710
Expert L	49,000	45,000	3,500	3,200

For the 3% discount rate, the calculated monetized health-related costs for the 4-km grid region range from 31 to 79 billion dollars for premature mortality (not including infant mortality) based on epidemiological studies (Pope et al., 2002 and Laden et al., 2006 in Abt Associates) and from 11 to 110 billion dollars for the expert elicitation estimates. The calculated monetized health-related costs for Delaware range from 2.2 to 5.5 billion dollars for the premature mortality (not including infant mortality) based on epidemiological studies and from 790 million to 7.4 billion dollars for the expert elicitation estimates.

For the 7% discount rate, the calculated monetized health-related costs for the 4-km grid region range from 28 to 72 billion dollars for premature mortality (not including infant mortality) based on epidemiological studies and from 9.9 to 95 billion for the expert elicitation estimates. The calculated monetized health-related costs for Delaware range from 2 to 5 billion dollars for the premature mortality based on epidemiological studies and from 710 million to 6.6 billion dollars for the expert elicitation estimates.

BenMAP valuation results for other $PM_{2.5}$-related health effects and associated endpoints (morbidity) are presented in Table 4-8.

Table 4-8. BenMAP-Derived Monetized Health-Related Costs for $PM_{2.5}$-Related Morbidity: Estimated Monetized Costs (Millions U.S. Dollars/Year) Related to Various Morbidity Endpoints Associated with EGU Emissions Located within the Modeling Domain.

Epidemiology Literature	Greater Mid-Atlantic Region (4-km Grid)	Delaware
Chronic bronchitis (age>=25)	1,300	83
Emergency room visits for asthma (age<19)	1	<1
Acute bronchitis (age 8-12)	<1	<1
Asthma exacerbation (age 6-18)	4	<1
Lower respiratory symptoms (age 7-14)	1	<1
Upper respiratory symptoms (asthmatic children age 9-18)	2	<1
Minor restricted-activity days (age 18-65)	190	12
Work loss days (age 18-65)	76	5
Nonfatal myocardial infarction (age>17)	230	17
Hospital admissions - respiratory (all ages)	25	2
Hospital admissions - cardiovascular (age>17)	54	4

For both regions, the greatest costs in monetized health-related benefits are associated with chronic bronchitis and non-fatal myocardial infarctions.

The cost associated with EGU emission can also be presented in terms of dollars per kilowatt hour (kWh). Using the Harvard 6-city study mortality estimate with a 3% discount rate as the upper bound and the ACS study with a 7% discount rate as the lower bound, total costs (combining mortality and morbidity) were calculated for the 4-km grid. In this case, only those costs associated with EGU emissions in the 4-km grid (CMAQ/PPTM Tags 1 and 2) were used to ensure compatibility with the kWh estimates. The kWh estimates for states contained within this same grid were obtained from the IPM. Total costs and costs per kWh are summarized in Table 4-9.

Table 4-9. BenMAP-Derived Total Monetized Health-Related Costs for the 4-km Grid and Costs per kWh Associated with EGU Emissions Located within the 4-km Grid.

This	Overall Cost (Millions $2008)	Cost per KWh ($)
Lower Bound	15,000	0.02
Upper Bound	40,000	0.05

This estimate is in line with the estimate provided in the recent NAS report (NAS, 2009), which indicates that the cost per kWh associated with coal and natural-gas fired utilities on a national scale is approximately 3.3 cents ($0.03) in $2007. In the NAS study, the costs were inclusive of health, vegetative, and other damages. Although a direct comparison of the results from the two studies is not appropriate given that the costs represent different endpoints, it is expected that health effects comprise a majority of the costs for the NAS study. Thus, this comparison provides some assurance that the results of present study are quantitatively consistent ("in the ballpark") with the recent findings of the NAS.

Health Effects and Monetized Health Benefits Associated with Alternative Energy Generation Scenarios

Scenario S1 (Offshore Wind)

The health effects and monetized health-related benefits associated with the offshore wind scenario are presented in this section.

OZONE

BenMAP results for ozone mortality are presented in Table 4-10. The mortality estimates are based on epidemiology literature. The baseline values are a standard output from BenMAP and provide a point of reference for assessing the meaningfulness of the incidence results. The baseline values represent deaths or health effects due to all causes, not just those related to air pollution, and these vary depending on the health impact function used for the referenced study.

Table 4-10. BenMAP Aggregated Incidence Results for Ozone-Related Mortality: Reduction in Premature Mortality Associated with the Offshore Wind Scenario: Scenario S1.

Epidemiology Literature	Greater Mid-Atlantic Region (4-km Grid)		Delaware	
	No of. Cases Avoided	Baseline Values	No. of Cases Avoided	Baseline Values
Mortality, Non-Accidental (Ito et al.)	0	308,394	0	22,043
Mortality, Non-Accidental (Schwartz)	0	308,394	0	22,043
Mortality, Non-Accidental (Bell et al.)	0	308,394	0	22,043
Mortality, All Cause (Levy et al.)	0	326,204	0	23,332
Mortality, All Cause (Bell et al.)	0	326,204	0	23,332
Mortality, Cardiopulmonary (Huang et al.)	0	147,690	0	10,375

BenMAP results for other ozone-related health effects and associated endpoints (morbidity) are presented in Table 4-11.

Table 4-11. BenMAP Aggregated Incidence Results for Ozone-Related Morbidity: Reduction in Various Morbidity Endpoints Associated with the Offshore Wind Scenario: Scenario S1.

Epidemiology Literature	Greater Mid-Atlantic Region (4-km Grid)		Delaware	
	No of. Cases Avoided	Baseline Values	No. of Cases Avoided	Baseline Values
Emergency room visits for asthma (age 5-34)	0	135,027	0	7,673
Emergency room visits for asthma (all ages)	0	265,145	0	14,929
Hospital admissions for respiratory symptoms (infant)	0	38,683	0	2,698
Hospital admissions for respiratory symptoms (age 65-99)	0	267,707	0	20,826
Hospital admissions for chronic lung disease (age 65-99)	0	42,921	0	3,245
Hospital admissions for pneumonia (age 65-99)	0	100,923	0	8,163
School loss days (Chen) (age 5-17)	-9	956,155,200	1	62,390,936
School loss days (Gilliland) (age 5-17)	-21	45,991,544	3	3,001,035
Minor restricted-activity days (age 18-65)	-24	193,102,128	5	12,469,518
Work loss days (age 18-65)	34	1.5.E+09	42	1.8.E+08

The impacts for ozone for the S1 scenario are negligible. For the 4-km grid the morbidity impacts are a mix of benefits (positive values) and disbenefits (negative values).

BenMAP valuation results for ozone related mortality are presented in Table 4-12. The monetized health-related costs represent regional costs, in millions of U.S. 2008-equivalent dollars.

Table 4-12. BenMAP-Derived Monetized Health-Related Benefits for Ozone-Related Mortality: Estimated Monetized Benefits (Millions U.S. Dollars/Year) Related to Premature Mortality Associated with the Offshore Wind Scenario: Scenario S1.

Epidemiology Literature	Greater Mid-Atlantic Region (4-km Grid)	Delaware
Non-accidental (Ito et al.)	-0.21	0
Non-accidental (Bell et al. (U.S. cities))	-0.05	0
Non-accidental (Schwartz et al.)	-0.07	0
All causes (Levy et al.)	-0.23	0
All causes (Bell et al.)	-0.16	0
Cardiopulmonary	-0.07	0

BenMAP valuation results for other ozone-related health effects and associated endpoints (morbidity) are presented in Table 4-13.

Table 4-13. BenMAP-Derived Monetized Health-Related Benefits for Ozone-Related Morbidity: Estimated Monetized Costs (Millions U.S. Dollars/Year) Related to Various Morbidity Endpoints Associated with the Offshore Wind Scenario: Scenario S1.

Epidemiology Literature	Greater Mid-Atlantic Region (4-km Grid)	Delaware
Emergency room visits for respiratory symptoms (all ages)	0	0
Hospital admissions for respiratory symptoms (age 0-2)	0	0
Hospital admissions for respiratory symptoms (age 65-99)	0	0
School loss days (age 0-17)	0	0
Work loss days (age 18-65)	0	0
Acute respiratory symptoms (age 18-99)	0	0

The total costs due to changes in ozone associate with the S1 scenario are less than 1 million dollars for the 4-km grid and negligible for Delaware.

$PM_{2.5}$

BenMAP results for $PM_{2.5}$ mortality are presented in Table 4-14. The mortality estimates are based on both epidemiology literature and expert elicitation. Again the baseline values represent deaths or health effects due to all causes, not just those related to air pollution.

Table 4-14. BenMAP Aggregated Incidence Results for $PM_{2.5}$-Related Mortality: Reduction in Premature Mortality Associated with the Offshore Wind Scenario: Scenario S1.

Epidemiology Literature	Greater Mid-Atlantic Region (4-km Grid)		Delaware	
	No of. Cases Avoided	Baseline Values	No. of Cases Avoided	Baseline Values
Harvard six-city study (Laden et al.)	-6	449,790	0	22,986
ACS study (Pope et al.)	-2	446,536	0	22,820
Infant mortality study (Woodruff et al.)	0	1,229	0	62
Expert Elicitation				
Expert A	-6	446,536	-1	22,820
Expert B	-5	452,183	0	23,205
Expert C	-5	446,536	0	22,820
Expert D	-3	446,536	0	22,820
Expert E	-7	446,536	-1	22,820
Expert F	-4	451,499	0	23,156
Expert G	-4	446,536	0	22,820
Expert H	-3	446,536	0	22,820
Expert I	-5	446,536	0	22,820
Expert J	-4	446,536	0	22,820
Expert K	-3	448,313	0	22,956
Expert L	-4	450,734	0	23,106

BenMAP results for other $PM_{2.5}$-related health effects and associated endpoints (morbidity) are presented in Table 4-15.

Table 4-15. BenMAP Aggregated Incidence Results for $PM_{2.5}$-Related Morbidity: Reduction in Various Morbidity Endpoints Associated with the Offshore Wind Scenario: Scenario S1.

Epidemiology Literature	Greater Mid-Atlantic Region (4-km Grid)		Delaware	
	No of. Cases	Baseline Values	No. of Cases	Baseline Values
Chronic bronchitis (age>=25)	-2	134,439	0	6,268
Emergency room visits for asthma (age09)	-2	147,052	0	5,530
Acute bronchitis (age 8-12)	-3	145,372	0	6,865
Asthma exacerbation (age 6-18)	-98	76,204,440	-8	3,572,679
Lower respiratory symptoms (age 7-14)	-43	2,544,926	-3	120,138
Upper respiratory symptoms (asthmatic children age 9-18)	-32	15,397,102	-3	726,473
Minor restricted-activity days (age 18-65)	-1,728	270,586,464	-138	12,469,518
Work loss days (age 18-65)	-291	73,260,680	-23	3,381,771
Nonfatal myocardial infarction (age>17)	-3	130,475	0	7,194
Hospital admissions - respiratory (all ages)	-1	340,018	0	18,073
Hospital admissions - cardiovascular (age>17)	-1	847,653	0	43,616

The mortality and morbidity impacts related to $PM_{2.5}$ for the S1 scenario small and represent disbenefits (as indicated by the negative values).

BenMAP valuation results for PM2.5 related mortality are presented in Table 4-16. The monetized health-related costs represent regional costs, in millions of U.S. 2008-equivalent dollars.

Table 4-16. BenMAP-Derived Monetized Health-Related Benefits for $PM_{2.5}$-Related Mortality with 3% and 7% Discount Rates: Estimated Monetized Benefits (Millions U.S. Dollars/Year) Related to Premature Mortality Associated with the Offshore Wind Scenario: Scenario S1.

Epidemiology Literature	Greater Mid-Atlantic Region (4-km Grid)		Delaware	
	3% Discount Rate	7% Discount Rate	3% Discount Rate	7% Discount Rate
Harvard six-city study (Laden et al.)	-48	-43	-4.3	-3.9
ACS study (Pope et al.)	-19	-17	-1.7	-1.5
Infant mortality study (Woodruff et al.)	0	0	-0.01	0
Expert Elicitation				
Expert A	-51	-46	-4.5	-4.1
Expert B	-42	-38	-3.7	-3.4
Expert C	-42	-38	-3.8	-3.4
Expert D	-28	-25	-2.5	-2.2
Expert E	-64	-58	-5.7	-5.2
Expert F	-37	-33	-3.3	-3.0
Expert G	-22	-20	-2.0	-1.8
Expert H	-28	-25	-2.5	-2.2
Expert I	-39	-35	-3.5	-3.2
Expert J	-35	-31	-3.1	-2.8
Expert K	-7	-6	-0.58	-0.52
Expert L	-30	-27	-2.7	-2.5

For the 3% discount rate, the calculated monetized health-related costs (disbenefits) for the 4-km grid region range from 19 to 48 million dollars for premature mortality (not including infant mortality) based on the epidemiological studies. The calculated monetized health-related costs for Delaware range from 1.7 to 4.3 million dollars for the premature mortality (not including infant mortality) based on epidemiological studies.

For the 7% discount rate and using the same studies, the calculated monetized health-related costs range from 17 to 43 million dollars for the 4-km grid region and from 1.5 to 3.9 million dollars for Delaware.

BenMAP valuation results for other $PM_{2.5}$-related health effects and associated endpoints (morbidity) are presented in Table 4-17.

Table 4-17. BenMAP-Derived Monetized Health-Related Benefits for $PM_{2.5}$-Related Morbidity: Estimated Monetized Benefits (Millions U.S. Dollars/Year) Related to Various Morbidity Endpoints Associated with the Offshore Wind Scenario: Scenario S1.

Epidemiology Literature	Greater Mid-Atlantic Region (4-km Grid)	Delaware
Chronic bronchitis (age>=25)	-0.81	-0.07
Emergency room visits for asthma (age<19)	0	0
Acute bronchitis (age 8-12)	0	0
Asthma exacerbation (age 6-18)	0	0
Lower respiratory symptoms (age 7-14)	0	0
Upper respiratory symptoms (asthmatic children age 9-18)	0	0
Minor restricted-activity days (age 18-65)	0	-0.01
Work loss days (age 18-65)	0	0
Nonfatal myocardial infarction (age>17)	0	-0.01
Hospital admissions - respiratory (all ages)	0	0
Hospital admissions - cardiovascular (age>17)	0	0

Morbidity costs are less than 1 million dollars for both regions, and near zero for Delaware.

Scenario S3 (Combined Cycle)

The health effects and monetized health-related benefits associated with the offshore wind scenario are presented in this section.

OZONE

BenMAP results for ozone mortality are presented in Table 4-18. The mortality estimates are based on epidemiology literature. As noted earlier, the baseline values represent deaths or health effects due to all causes, not just those related to air pollution.

Table 4-18. BenMAP Aggregated Incidence Results for Ozone-Related Mortality: Reduction in Premature Mortality Associated with the Combined Cycle Scenario: Scenario S3.

Epidemiology Literature	Greater Mid-Atlantic Region (4-km Grid)		Delaware	
	No of. Cases Avoided	Baseline Values	No. of Cases Avoided	Baseline Values
Mortality, Non-Accidental (Ito et al.)	0	308,394	0	22,043
Mortality, Non-Accidental (Schwartz)	0	308,394	0	22,043
Mortality, Non-Accidental (Bell et al.)	0	308,394	0	22,043
Mortality, All Cause (Levy et al.)	0	326,204	0	23,332
Mortality, All Cause (Bell et al.)	0	326,204	0	23,332
Mortality, Cardiopulmonary (Huang et al.)	0	147,690	0	10,375

BenMAP results for other ozone-related health effects and associated endpoints (morbidity) are presented in Table 4-19.

Table 4-19. BenMAP Aggregated Incidence Results for Ozone-Related Morbidity: Reduction in Various Morbidity Endpoints Associated with the Combined Cycle Scenario: Scenario S3.

Epidemiology Literature	Greater Mid-Atlantic Region (4-km Grid)		Delaware	
	No of. Cases Avoided	Baseline Values	No. of Cases Avoided	Baseline Values
Emergency room visits for asthma (age 5-34)	0	135,027	0	7,673
Emergency room visits for asthma (all ages)	0	265,145	0	14,929
Hospital admissions for respiratory symptoms (infant)	0	38,683	0	2,698
Hospital admissions for respiratory symptoms (age 65-99)	0	267,707	0	20,826
Hospital admissions for chronic lung disease (age 65-99)	0	42,921	0	3,245
Hospital admissions for pneumonia (age 65-99)	0	100,923	0	8,163
School loss days (Chen) (age 5-17)	24	956,155,200	-2.2	62,390,936
School loss days (Gilliland) (age 5-17)	57	45,991,544	-5.3	3,001,035
Minor restricted-activity days (age 18-65)	79	193,102,128	-7.5	12,469,518
Work loss days (age 18-65)	170	1.5.E+09	-67.0	1.8.E+08

The impacts for ozone for S3 are negligible. The morbidity impacts represent benefits for the 4-km grid region and disbenefits for Delaware.

BenMAP valuation results for ozone related mortality are presented in Table 4-20. The monetized health-related costs represent regional costs, in millions of U.S. 2008-equivalent dollars.

Table 4-20. BenMAP-Derived Monetized Health-Related Benefits for Ozone-Related Mortality: Estimated Monetized Benefits (Millions U.S. Dollars/Year) Related to Premature Mortality Associated with the Combined Cycle Scenario: Scenario S3.

Epidemiology Literature	Greater Mid-Atlantic Region (4-km Grid)	Delaware
Non-accidental (Ito et al.)	0.47	-0.06
Non-accidental (Bell et al. (U.S. cities))	0.10	-0.01
Non-accidental (Schwartz et al.)	0.16	-0.02
All causes (Levy et al.)	0.47	-0.06
All causes (Bell et al.)	0.34	-0.04
Cardiopulmonary	0.15	-0.02

BenMAP valuation results for other ozone-related health effects and associated endpoints (morbidity) are presented in Table 4-21.

Table 4-21. BenMAP-Derived Monetized Health-Related Benefits for Ozone-Related Morbidity: Estimated Monetized Costs (Millions U.S. Dollars/Year) Related to Various Morbidity Endpoints Associated with the Combined Cycle Scenario: Scenario S3.

Epidemiology Literature	Greater Mid-Atlantic Region (4-km Grid)	Delaware
Emergency room visits for respiratory symptoms (all ages)	0	0
Hospital admissions for respiratory symptoms (age 0-2)	0	0
Hospital admissions for respiratory symptoms (age 65-99)	0	0
School loss days (age 0-17)	0	0
Work loss days (age 18-65)	0	0
Acute respiratory symptoms (age 18-99)	0.01	0

The monetized ozone health-related benefits and costs for the S3 scenario are very small.

$PM_{2.5}$

BenMAP results for $PM_{2.5}$ mortality are presented in Table 4-22. The mortality estimates are based on both epidemiology literature and expert elicitation. Again the baseline values represent deaths or health effects due to all causes, not just those related to air pollution.

Table 4-22. BenMAP Aggregated Incidence Results for $PM_{2.5}$-Related Mortality: Reduction in Premature Mortality Associated with the Combined Cycle Scenario: Scenario S3.

Epidemiology Literature	Greater Mid-Atlantic Region (4-km Grid)		Delaware	
	No of. Cases Avoided	Baseline Values	No. of Cases Avoided	Baseline Values
Harvard six-city study (Laden et al.)	7	449,790	0	22,986
ACS study (Pope et al.)	3	446,536	0	22,820
Infant mortality study (Woodruff et al.)	0	1,229	0	62
Expert Elicitation				
Expert A	7	446,536	0	22,820
Expert B	6	452,183	0	23,205
Expert C	6	446,536	0	22,820
Expert D	4	446,536	0	22,820
Expert E	9	446,536	0	22,820
Expert F	5	451,499	0	23,156
Expert G	5	446,536	0	22,820
Expert H	4	446,536	0	22,820
Expert I	6	446,536	0	22,820
Expert J	5	446,536	0	22,820
Expert K	3	448,313	0	22,956
Expert L	4	450,734	0	23,106

BenMAP results for other $PM_{2.5}$-related health effects and associated endpoints (morbidity) are presented in Table 4-23.

Table 4-23. BenMAP Aggregated Incidence Results for $PM_{2.5}$-Related Morbidity: Reduction in Various Morbidity Endpoints Associated with the Combined Cycle Scenario: Scenario S3.

Epidemiology Literature	Greater Mid-Atlantic Region (4-km Grid)		Delaware	
	No of. Cases	Baseline Values	No. of Cases	Baseline Values
Chronic bronchitis (age>=25)	2	134,439	0	6,268
Emergency room visits for asthma (age<19)	3	147,052	0	5,530
Acute bronchitis (age 8-12)	4	145,372	0	6,865
Asthma exacerbation (age 6-18)	120	76,204,440	2	3,572,679
Lower respiratory symptoms (age 7-14)	52	2,544,926	1	120,138
Upper respiratory symptoms (asthmatic children age 9-18)	39	15,397,102	1	726,473
Minor restricted-activity days (age 18-65)	2,100	270,586,464	42	12,469,518
Work loss days (age 18-65)	360	73,260,680	7	3,381,771
Nonfatal myocardial infarction (age>17)	3	130,475	0	7,194
Hospital admissions - respiratory (all ages)	1	340,018	0	18,073
Hospital admissions - cardiovascular (age>17)	1	847,653	0	43,616

The incidence values for $PM_{2.5}$ are larger than for ozone and represent reductions in the incidence of mortality and morbidity for the S3 scenario.

BenMAP valuation results for PM2.5 related mortality are presented in Table 4-24. The monetized health-related costs represent regional costs, in millions of U.S. 2008-equivalent dollars.

Table 4-24. BenMAP-Derived Monetized Health-Related Benefits for $PM_{2.5}$-Related Mortality with 3% and 7% Discount Rates: Estimated Monetized Benefits (Millions U.S. Dollars/Year) Related to Premature Mortality Associated with the Combined Scenario: Scenario S3.

Epidemiology Literature	Greater Mid-Atlantic Region (4-km Grid)		Delaware	
	3% Discount Rate	7% Discount Rate	3% Discount Rate	7% Discount Rate
Harvard six-city study (Laden et al.)	58	52	1.4	1.2
ACS study (Pope et al.)	23	20	0.53	0.48
Infant mortality study (Woodruff et al.)	0	0	0	0
Expert Elicitation				
Expert A	62	56	1.5	1.3
Expert B	50	45	1.2	1.1
Expert C	51	46	1.2	1.1
Expert D	34	30	0.79	0.71
Expert E	78	70	1.8	1.7
Expert F	45	40	1	0.96
Expert G	27	25	0.64	0.58
Expert H	33	30	0.79	0.71
Expert I	48	43	1.1	1
Expert J	42	38	1	0.90
Expert K	7.9	7.1	0.19	0.17
Expert L	36	33	0.87	0.79

For the 3% discount rate, the calculated monetized health-related benefits for the 4-km grid region range from 23 to 58 million dollars for premature mortality (not including infant mortality) based on the epidemiological studies. The calculated monetized health-related benefits for Delaware range from 0.5 to 1.4 million dollars for the premature mortality (not including infant mortality) based on epidemiological studies.

For the 7% discount rate and using the same studies, the calculated monetized health-related benefits range from 20 to 52 million dollars for the 4-km grid region and from 0.5 to 1.2 million dollars for Delaware.

BenMAP valuation results for other $PM_{2.5}$-related health effects and associated endpoints (morbidity) are presented in Table 4-25.

Table 4-25. BenMAP-Derived Monetized Health-Related Benefits for $PM_{2.5}$-Related Morbidity: Estimated Monetized Benefits (Millions U.S. Dollars/Year) Related to Various Morbidity Endpoints Associated with the Combined Cycle Scenario: Scenario S3.

Epidemiology Literature	Greater Mid-Atlantic Region (4-km Grid)	Delaware
Chronic bronchitis (age>=25)	1	0.02
Emergency room visits for asthma (age<19)	0	0
Acute bronchitis (age 8-12)	0	0
Asthma exacerbation (age 6-18)	0	0
Lower respiratory symptoms (age 7-14)	0	0
Upper respiratory symptoms (asthmatic children age 9-18)	0	0
Minor restricted-activity days (age 18-65)	0.14	0
Work loss days (age 18-65)	0.06	0
Nonfatal myocardial infarction (age>17)	0.18	0
Hospital admissions - respiratory (all ages)	0.02	0
Hospital admissions - cardiovascular (age>17)	0.04	0

Monetized health-related benefits associated with the morbidity endpoints are less than 2 million dollars for the 4-km grid region, and negligible for Delaware.

4.2. Mercury

The benefits assessment for mercury deposition was based on information from a comprehensive study of the benefits of controlling mercury emissions from coal fired power plants (NESCAUM, 2005). Compared to the application of BenMAP, the approach is much more qualitative.

Mercury Effects Estimation Methodology

The basis of the benefits calculations for this analysis are results obtained by NESCAUM (2005) for the Mid-Atlantic region, which is defined in the NESCAUM report as Delaware, Maryland, New Jersey, Pennsylvania, Virginia, West Virginia, and Washington, D.C. From the information provided in the NESCAUM report, the monetized benefit per μgm^{-2} reduction of mercury deposition was calculated for the Mid-Atlantic region. Details of this calculation are provided in the next section.

For the present analysis, the CMAQ-derived change in total mercury deposition rate for the Mid-Atlantic region, relative to the Reference Case scenario was calculated for both scenarios. This change in deposition rate was then multiplied by the benefit per μgm^{-3} for the Mid-Atlantic region (from the NESCAUM report). The resulting estimated benefits are summarized in the next section.

A key assumption in the NESCAUM study is that "…changes in mercury deposition rates result in proportional changes in human methylmercury intakes." The study provides estimated benefits for both neurotoxic and cardiotoxic effects. However, the report notes that the degree of confidence differs between the neurotoxic and cardiotoxic effects. According to this report, the neurological (e.g. IQ) effects associated with *in utero* methylmercury exposures have been thoroughly evaluated. In addition, there is no evidence of a threshold for neurotoxicity. Studies "...evaluating the association of cardiovascular events with adult methylmercury exposures have, as a group, not been as thoroughly evaluated. While high doses of methylmercury are clearly associated with neurological decrements, they have not been repeatedly shown to be associated with adverse cardiac events; in fact, fish consumption, which implies some methylmercury exposure, is recommended as protective of cardiovascular disease." Thus, the authors urge caution in interpreting the results related to monetized benefits associated with the cardiovascular endpoint.

For the present analysis, loss of IQ points with no neurotoxicity threshold is used as the primary value. Loss of IQ points with a threshold and combined neurotoxic and cardiotoxic benefit estimates provide lower and upper bounds for the calculations.

Assessment of Mercury Effects

The methodology outlined above was used to calculate monetized benefits associated with the change in mercury deposition for the Mid-Atlantic states for the S1 and S3 scenarios.

However, since the changes in mercury deposition are so small the estimated costs/benefits for both scenarios are negligible.

4.3. Discussion of Attributes and Limitations

The BenMAP tool incorporates a wide variety of recent studies that can be used to quantify and monetize health effects. The epidemiological studies address a variety of different health endpoints and, in some cases, multiple studies (involving different populations or concentration-response functions) are available allowing for some comparison. BenMAP includes up-to-date valuation methods and data for the monetization of health impacts. BenMAP also incorporates advanced statistical methods for aggregating and weighting the results to obtain both mean values as well as information about the likelihood (probability) that the value will be within a given range. A primary advantage of BenMAP is that it can incorporate the change in air quality directly from air quality model output files and thus takes into account spatial and temporal differences in the changes in air quality, and relates these to population. For this analysis, selection of the health effects studies and valuation methods were based on the latest BenMAP (configuration and aggregation, pooling and valuation) input files provided by EPA (which reference the studies and methods that EPA considers to be the most relevant and applicable to the U.S. population as a whole.)

Nevertheless, there are uncertainties associated with the estimation of changes in health effects and monetized health-related benefits associated with changes in ozone and $PM_{2.5}$ air quality. For the health incidence calculations, BenMAP includes an option to generate an average incidence estimate, as well as a range of results that assume there is variability in the inputs to the health impact functions. Variability is incorporated into most of the BenMAP exposure-response algorithms by prescribing a dose-response parameter that assumes a distribution about the mean value. In calculating the health effects, BenMAP samples this distribution to develop a probability distribution of effect. The result is expressed as the mean value of the distribution. For the $PM_{2.5}$ mortality expert elicitation functions, variability is accounted for in a variety of ways. For the valuation calculation, the valuation function is also specified as a probability distribution, accounting for different methods of estimating health costs and willingness to pay. BenMAP samples from probability distributions from single or multiple cost estimation models, and combines the results through Monte Carlo simulation. The resulting monetized benefit distributions therefore include contributions both from the uncertainty in the exposure-response relationships and in the valuation functions.

Finally, the mercury assessment is qualitative and the results are for the Mid-Atlantic region only. The assessment is based on the results the NESCAUM study, which considers many factors and includes numerous assumptions (see NESCAUM, 2005 for a discussion of the attributes and limitation of this study).

5. Simulated Air Quality Trends (2010 – 2020)

For this analysis, CMAQ was also applied for a prior year of 2010, in order to examine expected changes in air quality over time for the period 2010 – 2020. The NEI emissions for 2010 were obtained from EPA and processed using the procedures described in Section 2. The CMAQ 2010 base-case simulation was run for both the 12- and 4-km grids (using a one-way nested-grid approach) and the annual simulation period.

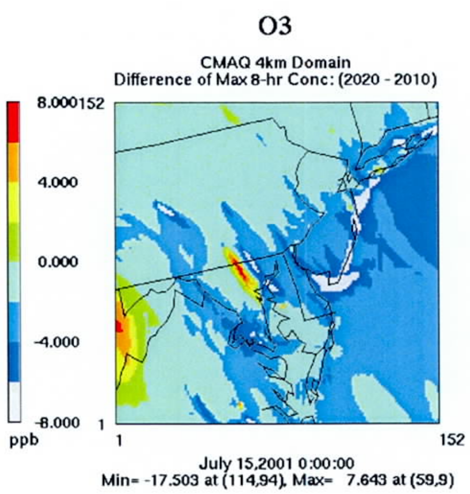
The 2010 base case and 2020 Reference Case results are presented and compared in the remainder of this section. The presentation of the results focuses on the 4-km grid.

5.1. CMAQ-Derived Changes in Air Quality

Ozone

Figure 5-1 displays the difference in simulated daily maximum 8-hour ozone concentration (ppb) between the 2020 Reference Case and 2010 base case scenarios for the 15th of July.

Figure 5-1. Difference in Simulated Daily Maximum 8-Hour Ozone Concentration (ppb) for 15 July: 2020 Reference Case Minus 2010 Base Case.

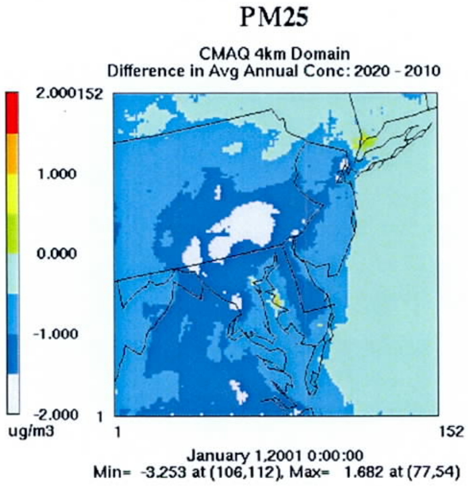


There are both increases and decreases in ozone concentration for 2020, compared to 2010. For this day, the differences range from approximately – 18 to 8 ppb. The decreases are fairly widespread, reflecting emissions reductions for a number of source categories throughout the domain. The increases are more isolated and reflect increases in emissions from specific sources. To some extent, both the increases and decreases may be due to different assumptions used in projecting the emissions for 2010 versus 2020. This is especially true for the EGU emissions. In both cases, the EGU emissions are based on the IPM, and inputs and assumptions vary by year. Nevertheless, for the remainder of this discussion, it is assumed that any changes due to differences in methodology are much smaller than the changes due to the different projection years.

$PM_{2.5}$

Figure 5-2 displays the difference in simulated annual average $PM_{2.5}$ concentration (μgm^{-3}) between the 2020 Reference Case and 2010 base case scenarios.

Figure 5-2. Difference in Simulated Annual Average $PM_{2.5}$ Concentration (μgm^{-3}): 2020 Reference Case Minus 2010 Base Case.

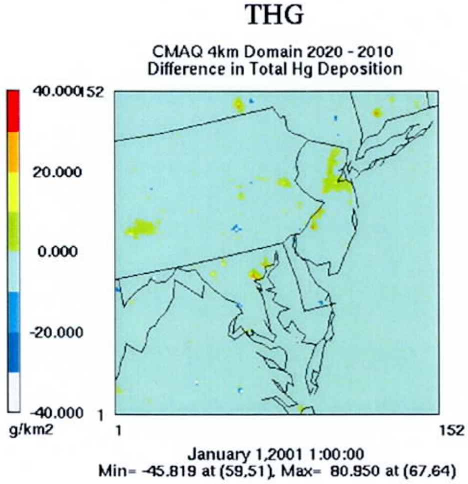


Except for a few isolated areas of increase, the simulated $PM_{2.5}$ concentrations for 2020 are lower than those for 2010 throughout much of the region. Concentrations are especially lower over southeastern Pennsylvania and over the New York, Philadelphia, Washington, D.C., and Richmond urban areas. The maximum decrease is approximately 3.3 μgm^{-3}. The difference pattern shows widespread reductions and the decreases in $PM_{2.5}$ are consistent with reductions in emissions from a variety of source categories throughout the region between 2010 and 2020.

Mercury

Figure 5-3 displays the difference in simulated total annual mercury deposition (g km^{-2}) between the 2020 Reference Case and 2010 base case scenarios.

Figure 5-3. Difference in Simulated Total Annual Mercury Deposition (g km^{-2}): 2020 Reference Case Minus 2010 Base Case.



The difference pattern is characterized by small areas of increases and decreases in mercury deposition for 2020, compared to 2010. Averaged across the domain, the simulated decrease in mercury deposition is approximately 1 g km^{-2}.

5.2. Health-Related Benefits

Ozone and $PM_{2.5}$

BenMAP was used to estimate the change in the incidence of various health-related endpoints, as well as a monetized health-related benefits associated with improvements in ozone and PM2.5 air quality between 2010 and 2020.

The incidence and valuation results are presented in this section and are rounded to two significant figures.

Ozone

BenMAP results for ozone mortality, based on epidemiology literature, are presented in Table 5-1. As a reminder, the baseline values represent deaths or health effects due to all causes, not just those related to air pollution, and these vary depending on the health impact function used for the referenced study.

Table 5-1. BenMAP Aggregated Incidence Results for Ozone-Related Mortality: Reduction in Premature Mortality Associated with the Changes in Air Quality from 2010 to 2020.

Epidemiology Literature	Greater Mid-Atlantic Region (4-km Grid)		Delaware	
	No of. Cases Avoided	Baseline Values	No. of Cases Avoided	Baseline Values
Mortality, Non-Accidental (Ito et al.)	390	308,394	36	22,043
Mortality, Non-Accidental (Schwartz)	140	308,394	12	22,043
Mortality, Non-Accidental (Bell et al.)	88	308,394	8	22,043
Mortality, All Cause (Levy et al.)	400	326,204	37	23,332
Mortality, All Cause (Bell et al.)	280	326,204	26	23,332
Mortality, Cardiopulmonary (Huang et al.)	130	147,690	12	10,375

The reduction in the mortality rate ranges from 88 to approximately 400 cases per year for the 4-km grid and from 8 to 37 for Delaware.

BenMAP results for other ozone-related health effects and associated endpoints (morbidity) are presented in Table 5-2.

Table 5-2. BenMAP Aggregated Incidence Results for Ozone-Related Morbidity: Reduction in Various Morbidity Endpoints Associated with the Changes in Air Quality from 2010 to 2020.

Epidemiology Literature	Greater Mid-Atlantic Region (4-km Grid)		Delaware	
	No of. Cases Avoided	Baseline Values	No. of Cases Avoided	Baseline Values
Emergency room visits for asthma (age 5-34)	370	135,027	32	7,673
Emergency room visits for asthma (all ages)	220	265,145	20	14,929
Hospital admissions for respiratory symptoms (infant)	320	38,683	31	2,698
Hospital admissions for respiratory symptoms (age 65-99)	1,000	267,707	99	20,826
Hospital admissions for chronic lung disease (age 65-99)	230	42,921	22	3,245
Hospital admissions for pneumonia (age 65-99)	330	100,923	34	8,163
School loss days (Chen) (age 5-17)	160,000	956,155,200	14,000	62,390,936
School loss days (Gilliland) (age 5-17)	360,000	45,991,544	32,000	3,001,035
Minor restricted-activity days (age 18-65)	510,000	193,102,128	45,000	12,469,518
Work loss days (age 18-65)	3.5.E+06	1.5.E+09	4.5.E+05	1.8.E+08

There are also some reductions in the morbidity endpoints due to the change in ambient ozone from 2010 to 2020.

BenMAP valuation results for ozone related mortality are presented in Table 5-3. The monetized health-related costs represent regional costs, in millions of U.S. 2008-equivalent dollars.

Table 5-3. BenMAP-Derived Monetized Health-Related Costs for Ozone-Related Mortality: Estimated Monetized Benefits (Millions U.S. Dollars/Year) Related to Premature Mortality Associated with the Changes in Air Quality from 2010 to 2020.

Epidemiology Literature	Greater Mid-Atlantic Region (4-km Grid)	Delaware
Non-accidental (Ito et al.)	3,700	340
Non-accidental (Bell et al. (U.S. cities))	830	76
Non-accidental (Schwartz et al.)	1,300	120
All causes (Levy et al.)	3,800	350
All causes (Bell et al.)	2,700	250
Cardiopulmonary	1,200	110

Monetized health-related benefits for mortality range from 830 million to 3.8 billion dollars for the 4-km grid and from 76 to 350 million dollars for Delaware, depending on the study used to calculate the benefits.

BenMAP valuation results for other ozone-related health effects and associated endpoints (morbidity) are presented in Table 5-4.

Table 5-4. BenMAP-Derived Monetized Health-Related Benefits for Ozone-Related Morbidity: Estimated Monetized Benefits (Millions U.S. Dollars/Year) Related to Various Morbidity Endpoints Associated with the Changes in Air Quality from 2010 to 2020.

Epidemiology Literature	Greater Mid-Atlantic Region (4-km Grid)	Delaware
Emergency room visits for respiratory symptoms (all ages)	0	0
Hospital admissions for respiratory symptoms (age 0-2)	3	0
Hospital admissions for respiratory symptoms (age 65-99)	14	1
School loss days (age 0-17)	15	1
Work loss days (age 18-65)	4	1
Acute respiratory symptoms (age 18-99)	34	3

For other health effects associated with ozone, the monetized benefits for mortality range from 0 to 34 million dollars for the 4-km grid and from 0 to 3 million dollars for Delaware.

$PM_{2.5}$

BenMAP results for $PM_{2.5}$ mortality are presented in Table 5-5. The mortality estimates are based on both epidemiology literature and expert elicitation.

Table 5-5. BenMAP Aggregated Incidence Results for $PM_{2.5}$-Related Mortality: Reduction in Premature Mortality Associated with the Changes in Air Quality from 2010 to 2020.

Epidemiology Literature	Greater Mid-Atlantic Region (4-km Grid)		Delaware	
	No of. Cases Avoided	Baseline Values	No. of Cases Avoided	Baseline Values
Harvard six-city study (Laden et al.)	6,900	449,790	460	22,986
ACS study (Pope et al.)	2,700	446,536	180	22,820
Infant mortality study (Woodruff et al.)	9	1,229	1	62
Expert Elicitation				
Expert A	7,300	446,536	490	22,820
Expert B	5,900	452,183	400	23,205
Expert C	6,100	446,536	400	22,820
Expert D	4,100	446,536	270	22,820
Expert E	9,200	446,536	610	22,820
Expert F	5,300	451,499	360	23,156
Expert G	4,600	446,536	310	22,820
Expert H	4,000	446,536	270	22,820
Expert I	5,800	446,536	380	22,820
Expert J	5,000	446,536	340	22,820
Expert K	3,200	448,313	220	22,956
Expert L	4,300	450,734	290	23,106

For the 4-km grid, the reduction in mortality rate due to emissions changes from 2010 to 2020 ranges from 2,700 to 6,900 based on epidemiological studies and from 3,200 to 9,200 for the expert elicitation estimates. For Delaware, the reduction ranges from 180 to 460 based on epidemiological studies and from 220 to 610 for the expert elicitation estimates. Note that in all cases the reductions are small compared to the number of deaths due to all causes, as represented by the baseline values.

BenMAP results for other $PM_{2.5}$-related health effects and associated endpoints (morbidity) are presented in Table 5-6.

Table 5-6. BenMAP Aggregated Incidence Results for $PM_{2.5}$-Related Morbidity: Reduction in Various Morbidity Endpoints Associated with the Changes in Air Quality from 2010 to 2020.

Epidemiology Literature	Greater Mid-Atlantic Region (4-km Grid)		Delaware	
	No of. Cases	Baseline Values	No. of Cases	Baseline Values
Chronic bronchitis (age>=25)	1,900	134,439	110	6,268
Emergency room visits for asthma (age<19)	2,800	147,052	120	5,530
Acute bronchitis (age 8-12)	4,000	145,372	240	6,865
Asthma exacerbation (age 6-18)	120,000	76,204,440	7,100	3,572,679
Lower respiratory symptoms (age 7-14)	50,000	2,544,926	3,000	120,138
Upper respiratory symptoms (asthmatic children age 9-18)	39,000	15,397,102	2,300	726,473
Minor restricted-activity days (age 18-65)	2,100,000	270,586,464	120,000	12,469,518
Work loss days (age 18-65)	360,000	73,260,680	21,000	3,381,771
Nonfatal myocardial infarction (age>17)	3,200	130,475	230	7,194
Hospital admissions - respiratory (all ages)	1,000	340,018	69	18,073
Hospital admissions - cardiovascular (age>17)	1,300	847,653	89	43,616

The BenMAP results indicate reductions for all of the morbidity endpoints due to emissions changes from 2010 to 2020. Averaged over all endpoints, the reduction in morbidity is about 1 percent for the 2020 Reference Case.

BenMAP valuation results for $PM_{2.5}$ related mortality are presented in Table 5-7. The monetized health-related costs represent regional benefits, in millions of U.S. 2008-equivalent dollars.

Table 5-7. BenMAP-Derived Monetized Health-Related Benefits for $PM_{2.5}$-Related Mortality with 3% and 7% Discount Rates: Estimated Monetized Benefits (Millions U.S. Dollars/Year) Related to Premature Mortality Associated with the Changes in Air Quality from 2010 to 2020.

Epidemiology Literature	Greater Mid-Atlantic Region (4-km Grid)		Delaware	
	3% Discount Rate	7% Discount Rate	3% Discount Rate	7% Discount Rate
Harvard six-city study (Laden et al.)	59,000	54,000	3,900	3,600
ACS study (Pope et al.)	23,000	21,000	1,500	1,400
Infant mortality study (Woodruff et al.)	80	72	5	4
Expert Elicitation				
Expert A	63,000	57,000	4,200	3,800
Expert B	51,000	46,000	3,400	3,100
Expert C	52,000	47,000	3,500	3,100
Expert D	34,000	31,000	2,300	2,100
Expert E	79,000	71,000	5,300	4,700
Expert F	45,000	41,000	3,100	2,800
Expert G	28,000	25,000	1,900	1,700
Expert H	34,000	31,000	2,300	2,100
Expert I	49,000	44,000	3,300	2,900
Expert J	43,000	39,000	2,900	2,600
Expert K	8,300	7,500	560	500
Expert L	37,000	34,000	2,500	2,300

For the 3% discount rate, the calculated monetized health-related benefits for the 4-km grid region range from 23 to 59 billion dollars for premature mortality (not including infant mortality) based on epidemiological studies and from 8.3 to 79 billion dollars for the expert elicitation estimates. The calculated monetized health-related benefits for Delaware range from 1.5 to 3.9 billion dollars for the premature mortality (not including infant mortality) based on epidemiological studies and from 560 million to 5.3 billion dollars for the expert elicitation estimates.

For the 7% discount rate, the calculated monetized health-related benefits for the 4-km grid region range from 21 to 54 billion dollars for premature mortality (not including infant mortality) based on epidemiological studies and from 7.5 to 71 billion for the expert elicitation estimates. The calculated monetized health-related benefits for Delaware range from 1.4 to 3.6 billion dollars for the premature mortality (not including infant mortality) based on epidemiological studies and from 500 million to 4.7 billion for the expert elicitation estimates.

BenMAP valuation results for other $PM_{2.5}$-related health effects and associated endpoints (morbidity) are presented in Table 5-8.

Table 5-8. BenMAP-Derived Monetized Health-Related Benefits for $PM_{2.5}$-Related Morbidity: Estimated Monetized Benefits (Millions U.S. Dollars/Year) Related to Various Morbidity Endpoints Associated with the Changes in Air Quality from 2010 to 2020.

Epidemiology Literature	Greater Mid-Atlantic Region (4-km Grid)	Delaware
Chronic bronchitis (age>=25)	1000	59
Emergency room visits for asthma (age<19)	1	0
Acute bronchitis (age 8-12)	0	0
Asthma exacerbation (age 6-18)	3	0
Lower respiratory symptoms (age 7-14)	1	0
Upper respiratory symptoms (asthmatic children age 9-18)	1	0
Minor restricted-activity days (age 18-65)	140	8
Work loss days (age 18-65)	58	3
Nonfatal myocardial infarction (age>17)	170	12
Hospital admissions - respiratory (all ages)	19	1
Hospital admissions - cardiovascular (age>17)	41	3

The monetized health-related benefits associated with morbidity total 1.4 billion dollars for the 4-km grid and 86 million dollars for Delaware, with the majority of the benefits associated with a reduction in the incidence of chronic bronchitis and nonfatal myocardial infarctions.

Mercury

Using the methodology outlined in Section 4 for the calculation of monetized benefits associated with a reduction in mercury deposition, the estimated value for the Mid-Atlantic states is 1.5 million dollars (in $2008). If we assume that Delaware represents about 5% of the total (based roughly on the BenMAP results) the estimated benefit for Delaware is 75 thousand dollars.

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6. Discussion of Climate Change

The assessment and estimation of environmental impacts for electric generation facilities in Delaware related to climate change follow methodologies and recommendations provided by the National Academy of Sciences (NAS) in their recent report entitled "Hidden Costs of Energy: Unpriced Consequences of Energy Production and Use", (NAS, 2009). The report recognizes that the production of energy from electric generation facilities will continue to be a major source of greenhouse gas (GHG) emissions, including CO_2 and methane, and "…damages from these emissions will result as their increased atmospheric concentrations affect climate, which in turn will affect such things as weather, freshwater supply, sea-level, biodiversity, and human society and health (NAS, 2009). However, the report further states that because of the complexities of climate change and the different time-scales over which the damages could occur, estimating and quantifying damages, which are based on the prediction of climate-change effects "is an intricate and uncertain process."

To prepare recommendations for how to assess climate change related damages, the NAS committee relied on a review of existing integrated assessment models (IAMs) and associated climate change literature. IAMs attempt to quantify damages of greenhouse gas emissions by estimating physical and monetary impacts associated with three main areas: 1) temperature changes, 2) impacts on weather, 3) impacts on various market sectors, as well as non-market sectors including agriculture, water resources, coastal infrastructure, health, and ecosystems (NAS, 2009). The IAMs examined by NAS include the Regional Integrated Model of Climate and Economy (RICE), the Dynamic Integrated Model of Climate and the Economy (DICE), the Framework for Uncertainty, Negotiation, and Distribution (FUND), and the Policy Analysis of the Greenhouse Effect (PAGE), which differ somewhat in their inputs, assumptions, and marginal damage formulas. Marginal damages are defined as damages per ton of emissions "associated with a particular climate change scenario at a particular future time." One of the difficulties in attempting to quantify damages due to GHG emissions, as opposed to criteria pollutant emissions (SO_2 or NO_x), is that the impacts of GHG's differ greatly in both spatial and atmospheric residence time scales, and the variety of potential impacts related to resulting temperature change. Due to the uncertainties in estimating potential future changes in climate and their effects on physical and economic resources, the NAS concluded that "only rough order-of-magnitude estimates of marginal damages were possible at this time." Their estimates range from \$1 to \$100 per ton CO_2-eq.

Table 6-1 presents a listing of oil, coal, and gas-fired EGUs located within the State of Delaware and the neighboring Mid-Atlantic states and the associated changes in CO_2 emissions from the 2020 Reference Case and for each of the scenarios, including the onshore wind scenario (S2). The table lists only those EGUs in these states for which IPM specifies changes in CO_2 emissions. Table 6-2 presents total CO_2 emissions for all EGUs located in the Mid-Atlantic states for the 2020 Reference Case and the scenarios. From the 2020 Reference Case total of 236,053,528 tpy of CO_2 emissions for all EGUs in the Mid-Atlantic states, the offshore wind scenario represents a reduction of 165,857 tpy, the onshore wind scenario represents a reduction of 32,465 tpy, and the combined cycle scenario results in an increase of 21,163 tpy. Using the NAS estimates for costs/benefits, the offshore scenario represents a range in benefits from $165,857 to $16,585,700 for the Mid-Atlantic states, while the onshore scenario represents a range of benefits from $32,465 to $3,246,500. Due to the estimated increase in CO_2 emissions, the combined cycle case represents a cost of $21,163 to $2,116,300.

Table 6-1. Changes in EGU CO_2, Emissions for the Offshore Wind, Combined-cycle and Onshore Wind Cases for EGU's Located within the Mid-Atlantic States.

Plant Name	County	State	2020 Reference (tpy)	2020 Offshore Wind (S1) (tpy)	2020 Onshore Wind (S2) (tpy)	2020 Combined Cycle (S3) (tpy)
Hay Road	New Castle	DE	1,047,617	1,047,430	1,046,306	1,043,851
Indian River Generating Station (DE)	Sussex	DE	2,151,756	2,151,634	2,151,761	2,151,770
Seaford	Sussex	DE	1,175	1,175	1,175	1,159
Warren F Sam Beasley Generation	Kent	DE	16,954	16,954	16,954	13,118
Delmarva CC unit	Kent	DE	0	0	0	55,676
Berlin	Worcester	MD	531	531	531	445
C P Crane	Baltimore	MD	2,376,274	2,376,290	2,376,292	2,376,275
Chalk Point	Prince Georges	MD	4,716,446	4,717,501	4,716,606	4,713,891
Dickerson	Montgomery	MD	3,653,683	3,654,547	3,653,935	3,652,114
Easton	Talbot	MD	8,576	8,576	8,576	8,519
Easton 2	Talbot	MD	9,426	9,426	9,426	9,342
Morgantown Generating Station	Charles	MD	7,810,843	7,812,044	7,810,958	7,810,843
PJM - BGE	Baltimore	MD	10,094,329	9,919,597	10,060,454	10,056,690
PJM - PEPCO	Prince Georges	MD	6,531,899	6,533,020	6,538,863	6,539,997
Rock Springs Generating Facility	Cecil	MD	69,284	68,438	72,768	81,253
Bergen	Bergen	NJ	1,290,136	1,296,709	1,287,698	1,299,824
Calpine Parlin Inc	Middlesex	NJ	117,017	117,187	116,984	117,384
Carlls Corner	Cumberland	NJ	2,175	2,021	2,089	2,945
Carneys Point Generating Plant	Salem	NJ	1,821,240	1,816,518	1,821,240	1,821,240
Cumberland (NJ)	Cumberland	NJ	75,042	74,865	74,943	75,928
Essex (NJ PSEG)	Essex	NJ	15,242	15,507	14,671	15,107
Forked River	Ocean	NJ	3,205	3,185	3,212	3,254
Gilbert	Hunterdon	NJ	82,104	86,064	84,597	71,534
Lakewood Cogeneration LP	Ocean	NJ	222,228	222,587	222,160	223,003
Linden Cogen Plant	Union	NJ	1,274,802	1,274,973	1,274,871	1,274,705

Plant Name	County	State	2020 Reference (tpy)	2020 Offshore Wind (S1) (tpy)	2020 Onshore Wind (S2) (tpy)	2020 Combined Cycle (S3) (tpy)
Mickleton Station	Gloucester	NJ	1,758	1,634	1,688	2,381
Middle Station	Cape May	NJ	1,770	1,692	1,726	2,160
Ocean Peaking Power LP	Ocean	NJ	15,810	15,712	15,845	16,054
PJM - AE	Cumberland	NJ	90,405	89,903	89,341	87,705
PJM - AE	Cape May	NJ	29,108	28,946	28,765	28,238
PJM - AE	Ocean	NJ	23,286	23,157	23,012	22,591
PJM - AE	Atlantic	NJ	20,547	20,432	20,305	19,933
PJM - AE	Gloucester	NJ	20,204	20,092	19,966	19,601
PSEG Linden Generating Station	Union	NJ	1,161,065	1,167,284	1,160,757	1,154,269
Red Oak	Middlesex	NJ	829,309	834,949	832,406	833,614
Sayreville	Middlesex	NJ	11,071	11,002	11,096	11,242
Sayreville Cogeneration Facility	Middlesex	NJ	294,452	294,927	294,360	295,478
Sherman Avenue	Cumberland	NJ	2,414	2,243	2,318	3,268
West Station	Cumberland	NJ	775	720	744	1,049
Allegheny Energy Units 3 4 & 5	Allegheny	PA	569,590	569,647	569,959	569,594
Armstrong (PA)	Armstrong	PA	95,786	93,883	95,141	89,761
Delta Power Plant	York	PA	1,564,591	1,564,591	1,564,591	1,563,152
ECAR-First Energy	Lawrence	PA	1,596	1,618	1,610	1,578
Fairless Energy Center	Bucks	PA	2,820,755	2,818,893	2,821,529	2,823,516
Fayette Energy Facility	Fayette	PA	625,762	625,817	626,124	625,766
Grays Ferry Cogeneration Partnership	Philadelphia	PA	231,367	230,185	232,077	232,047
Liberty Electric Power LLC	Delaware	PA	1,274,677	1,273,836	1,275,026	1,275,924
Marcus Hook Refinery Cogeneration	Delaware	PA	1,227,040	1,221,060	1,230,632	1,230,479
PJM West Central	Northampton	PA	1,764,638	1,764,638	1,764,638	1,766,437
PJM West Central	Adams	PA	894,985	894,985	894,985	895,897
PJM West Central	Lebanon	PA	700,287	700,287	700,287	701,000
PJM West Central	York	PA	626,071	626,071	626,071	626,709
PJM West Central	Berks	PA	540,131	540,131	540,131	540,682
York Cogeneration Facility	York	PA	34,660	34,660	34,643	33,886
Bellmeade	Richmond City	VA	163,697	163,519	163,469	163,568
Chesapeake	Chesapeake City	VA	1,252	1,181	1,194	1,273

Plant Name	County	State	2020 Reference (tpy)	2020 Offshore Wind (S1) (tpy)	2020 Onshore Wind (S2) (tpy)	2020 Combined Cycle (S3) (tpy)
Chesterfield	Chesterfield	VA	5,004,623	5,003,596	5,003,775	5,004,434
Clover	Halifax	VA	6,640,082	6,639,635	6,639,716	6,640,215
Commonwealth Chesapeake	Accomack	VA	128,261	125,538	128,261	123,930
Darbytown	Henrico	VA	39,810	39,757	39,756	39,820
Doswell Combined Cycle Facility	Hanover	VA	484,038	483,475	483,321	483,653
Elizabeth River Combustion Turbine Station	Chesapeake City	VA	38,279	38,228	38,227	38,289
Gravel Neck	Surry	VA	41,148	41,095	41,094	41,159
Louisa Generating	Louisa	VA	58,503	58,425	58,424	58,518
Marsh Run Generating	Fauquier	VA	59,906	59,827	59,825	59,922
PJM Dominion	Fluvanna	VA	2,751,019	2,752,378	2,748,438	2,750,533
PJM Dominion	Hanover	VA	1,955,182	1,956,148	1,953,348	1,954,837
PJM Dominion	Buckingham	VA	1,705,784	1,706,627	1,704,184	1,705,484
PJM Dominion	Prince William	VA	1,564,616	1,565,389	1,563,148	1,564,340
PJM Dominion	Chesterfield	VA	1,167,580	1,168,157	1,166,485	1,167,374
PJM Dominion	Hopewell City	VA	1,024,353	1,024,859	1,023,392	1,024,172
PJM Dominion	Richmond City	VA	682,314	682,651	681,674	682,193
PJM Dominion	Louisa	VA	641,140	641,456	640,538	641,027
Remington	Fauquier	VA	74,261	74,163	74,161	74,280

Table 6-2. Total CO_2, Emissions for the 2020 Reference Case, and the Offshore Wind, Combined-cycle and Onshore Wind Cases for all EGU's Located within the Mid-Atlantic States.

	2020 Reference (tpy)	2020 Offshore Wind (S1) (tpy)	2020 Onshore Wind (S2) (tpy)	2020 Combined Cycle (S3) (tpy)
Total for All EGUs	**236,053,528**	**235,887,670**	**236,021,063**	**236,074,690**
Difference (tpy)		-165,857	-32,465	21,163
Difference (%)		-0.07%	-0.01%	0.01%

7. Summary and Conclusions

The objective of this analysis was to examine and quantify the air quality impacts and related health benefits associated with future power generation alternatives for the State of Delaware. The CMAQ air quality model was used to quantify the air quality changes for the different power generation scenarios and BenMAP was used to assess the health-related impacts of the simulated changes in air quality over the ten-year planning horizon. The analysis focused on two geographical regions including a 4-km resolution modeling grid covering the Mid-Atlantic states (see Figure 1-1) and the State of Delaware.

The CMAQ simulations included a 2020 Reference Case simulation and two alternative power-generation scenarios: one in which the emissions were adjusted to reflect the addition of offshore wind energy (Scenario S1) and a second scenario to reflect the addition of a combined-cycle gas unit (Scenario S3). Note that due to time constraints of the IRP submittal, an onshore wind energy scenario (Scenario S2) was examined based on the offshore wind scenario (S1), but not modeled with CMAQ. Two additional CMAQ simulations were run to examine the contributions from all EGU emissions to overall air quality as well as the expected changes in air quality with time (from 2010 to 2020).

The health effects analysis focused primarily on the effects of ozone and fine particulate matter ($PM_{2.5}$). Ozone and $PM_{2.5}$ are secondary pollutants that are formed in the atmosphere. Ozone is a secondary pollutant that is formed in the atmosphere by a series of reactions involving ultra violet radiation and precursor emissions of nitrogen oxides (NO_x) and volatile organic compounds (VOCs). Fine particulates in the atmosphere consist of primary particles that are emitted directly from sources and secondary particles that form in the atmosphere through chemical and physical processes. Pollutants that contribute to the formation of secondary aerosols include sulfur dioxide (SO_2), NO_x, and other species. Thus this assessment of the health effects and benefits for ozone and $PM_{2.5}$ addresses the effects of changes in NO_x and SO_2 emissions. Mercury and greenhouse gases (CO_2) were also considered using qualitative methods.

For the air quality modeling analysis, the EGU emissions were estimated using the IPM and emissions for all other source sectors were obtained from future-year estimates prepared by EPA. These emissions have been used recently by EPA in similar air quality modeling exercises supporting national rulemaking analyses. The EGU emissions from IPM for the 2020 Reference Case reflect estimates of future economic and population growth and corresponding electric generation demand, any planned shutdowns of existing facilities, inclusion of new facilities to meet future generation demands, and application of emission controls on existing facilities associated with applicable state and national rules.

The CMAQ Particle and Precursor Tagging Methodology (CMAQ/PPTM) was used to examine the contributions of emissions from the major source categories to simulated $PM_{2.5}$ concentrations and specifically to quantify the contributions from EGU sources. The specific tags included:

- EGU point sources in Delaware
- EGU point sources in New Jersey, Pennsylvania, Maryland, Virginia, and Washington, D.C.

- EGU point sources in the remainder of the 12-km grid
- Non-EGU point sources in the 12-km grid
- All other emission sources in the 12-km grid combined (including on-road mobile, non-road, and area sources)
- Biogenic emissions
- Initial conditions and boundary conditions (IC/BCs).

For both receptor regions, the tagging results indicate that among the tagged categories the area, on-road mobile, and non-road mobile sources (combined) are the largest contributors to the overall $PM_{2.5}$ concentration. The EGU sources (three EGU tags combined) account for 11 and 12 percent, respectively, of the simulated annual average $PM_{2.5}$ concentration for the 4-km grid and Delaware. The EGU contribution from sources located in Delaware is negligible when considering the annual average $PM_{2.5}$ within the 4-km grid and very small when considering annual average $PM_{2.5}$ for Delaware.

The IPM EGU emission estimates for the offshore wind (S1), onshore wind (S2), and combined cycle (S3) scenarios show a mix of increases and decreases at various facilities in Delaware and surrounding states. In most cases, the changes in emissions at any one facility are very small, and the overall change in EGU emissions from the 2020 Reference Case in each of the scenarios is also very small.

The CMAQ modeling results for both of the modeled alternative power generation scenarios show small increases and decreases in ozone concentration associated with the changes in emissions associated with Scenarios S1 and S3. The differences in ozone concentrations for both the 4-km grid and Delaware are projected to be very small (less than 0.1 ppb). Reference Case values for ozone range from approximately 20 to 100 ppb.

The absolute and relative differences attributable to the emissions changes for Scenarios S1 and S3 are also projected to be small for $PM_{2.5}$. For the offshore wind scenario (S1), the $PM_{2.5}$ concentrations are slightly higher throughout much of the 4-km grid compared to the Reference Case and the differences range from approximately -0.01 to 0.01 μgm^{-3}. The increases appear to be due primarily to increases in emissions outside of the 4-km domain (as projected by the IPM). For the combined cycle (S3) scenario, the simulated $PM_{2.5}$ concentrations are lower throughout most of the 4-km grid compared to the Reference Case and the differences range from approximately -0.02 to 0.01 μgm^{-3}. Reference Case values for $PM_{2.5}$ range from approximately 4 to 40 μgm^{-3}. The results are similar for Delaware.

For both scenarios, the CMAQ results indicate a mix of very small decreases and increases in mercury deposition throughout the region. For S1 (offshore wind), the maximum simulated decrease in annual mercury deposition for any grid cell in the domain is approximately 0.04 g km^{-2}, while the maximum increase is 0.09 g km^{-2}. For S3 (combined cycle), the maximum simulated decrease in annual mercury deposition for any grid cell in the domain is approximately 0.09 g km^{-2}, while the maximum increase is 0.1 g km^{-2}. These are compared to absolute deposition amounts ranging from about 7 to greater than 100 g km^{-2}.

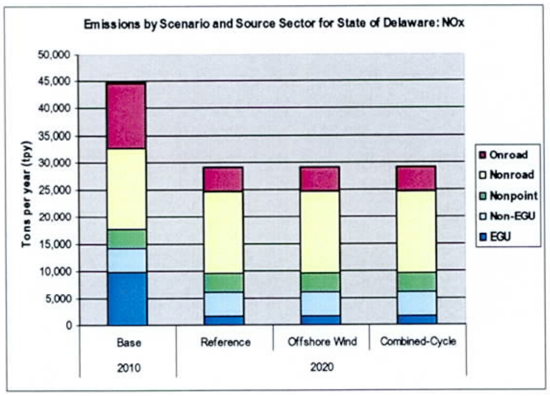
The increases and decreases in the modeling results reflect increases and decreases in the emissions at the various EGU facilities, including those outside of the 4-km grid. In addition, the variability in the response suggests that changes in certain emissions is quite complex and that reductions in precursor emissions such as nitric oxide (NO) can lead to increases in secondary pollutants. A good example of this is the relationship between NO_x and ozone. Under certain conditions (usually characterized by a high VOC to NO_x ratio), decreases in NO_x emissions can lead to increases in ozone. This is typically expected to occur in urban areas. Similarly, since the formation of particulate species (such as nitrate and sulfate) depends on reactions involving NO, NO_2, ozone, and hydrogen peroxide (H_2O_2), among other species, many of the complex interactions that affect ozone formation also affect particulate formation. Formation of particulate species is further complicated by the interaction of ammonia with nitric acid and sulfuric acid. Changes in the amount of sulfuric acid that is present can have an inverse effect on the amount of ammonium nitrate that forms.

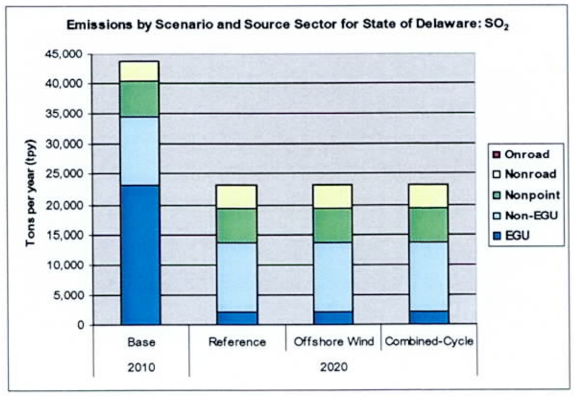
It is useful to compare the changes in concentration and deposition for Scenarios S1 and S3 with those associated with the larger emissions changes projected to occur between 2010 and 2020, which reflect implementation of emission control technologies following state and federal rule requirements, the shutting down of older facilities, fleet turnover of on-road motor vehicles and off-road equipment, the introduction of cleaner engine technologies, and the use of cleaner fuels. The CMAQ-simulated differences in pollutant concentrations between 2010 and 2020 are consequently primarily reductions. Within the region of interest, daily maximum 8-hour ozone is lower by as much as 20 ppb and annual average $PM_{2.5}$ is lower by more than 3 μgm^{-3}. Mercury deposition differences are characterized by small areas of increase and decrease with an average decrease of approximately 1 g km^{-2}.

These changes are consistent with the changes in emissions between 2010, 2020, S1, and S3 as illustrated for Delaware (for NO_x and SO_2) in Figures 7-1 (a) through (c).

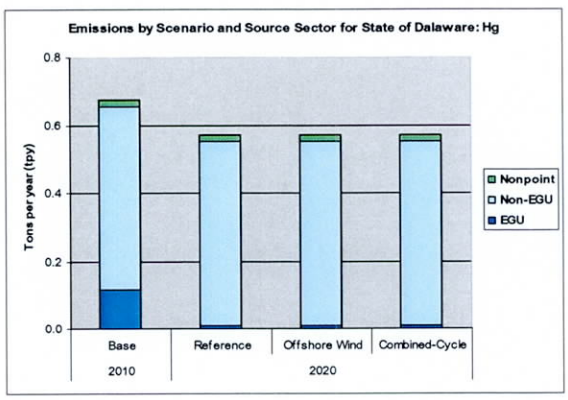
Figure 7-1. Emission Totals by Source Category for the State of Delaware for the IRP Modeling Analysis Scenarios 2010 Base, 2020 Reference Case, Scenario S1 (Offshore Wind), and Scenario S3 (Combined-Cycle): NO_x, SO_2 and Hg.

(a) NO_x (b) SO_2





(c) Hg



The relative contribution of the electric generation sector (EGU emissions) to overall air quality is expected to decrease considerably from 2010 to 2020 in both Delaware and the 4-km grid. Based on the 2010 emissions estimates, EGU NO_x emissions comprise 22% of the NO_x emissions for Delaware and 13% of the NO_x emissions for the 4 km grid. EGU SO_2 emissions represent 53% of the SO_2 emissions for Delaware and 49% of the SO_2 emissions for the 4 km grid. For 2020, EGU NO_x emissions represent 5% of the NO_x emissions in Delaware and 13% of the NO_x emissions in the 4 km grid. EGU SO_2 emissions account for 9% of the SO_2 emissions for Delaware and19% of the SO_2 emissions for the 4 km grid. The CMAQ/PPTM results indicate that the simulated relative contribution of EGU emissions to annual average $PM_{2.5}$ concentration is 12% for Delaware and 11% for the 4-km grid for 2020. PPTM was not applied for the 2010 simulation, but based on the emissions percentages, the relative contribution of EGU emissions to annual average $PM_{2.5}$ for 2010 is estimated to be greater for 2010, possibly on the order of 30 to 50% or more.

Total monetized benefits (or disbenefits) for Scenario S1, Scenario S3, all EGU emissions, and 2010 - 2020 (ozone and $PM_{2.5}$) are presented in Table 7-1. The ranges given below encompass the different health-incidence studies used in this analysis (but limited to, in this case, Laden et al. and Pope et al., for $PM_{2.5}$ mortality and Levy for ozone mortality) and different assumptions regarding cessation lag (discount rate) for $PM_{2.5}$ mortality. The monetized health-related benefits are given in 2008-equivalent U.S. dollars. Estimated mercury deposition costs/benefits do not change the totals given here.

Table 7-1. Total BenMAP Aggregated Valuation Results for $PM_{2.5}$ and Ozone for Scenario S1, Scenario S3, all EGU Emissions, and 2010 - 2020 ($2008). The High End Total Includes $PM_{2.5}$ Mortality from Laden et al. with a 3% Discount Rate and the Low End Total Includes $PM_{2.5}$ Mortality from Pope et al. with a 7% Discount Rate.

	Greater Mid-Atlantic Region (4-km Grid)		Delaware	
	High End	Low End	High End	Low End
Scenario S1				
PM-Mortality (Laden, 3% discount rate)	-48.00	—	-4.30	—
PM-Mortality (Pope, 7% discount rate)	—	-17.00	—	-1.50
PM-Morbidity	0.81	0.81	0.09	0.09
Ozone-Mortality (Levy)	-0.23	-0.23	0	0
Ozone-Morbidity	0.01	0.01	0	0
Total	*-47.41*	*-16.41*	*-4.21*	*-1.41*
Total (2 significant figures)	**-47**	**-16**	**-4.2**	**-1.4**
Scenario S3				
PM-Mortality (Laden, 3% discount rate)	58.00	—	1.40	—
PM-Mortality (Pope, 7% discount rate)	—	20.00	—	0.48
PM-Morbidity	1.44	1.44	0.02	0.02
Ozone-Mortality (Levy)	0.47	0.47	-0.06	-0.06
Ozone-Morbidity	0.01	0.01	0	0
Total	*59.92*	*21.92*	*1.36*	*0.44*
Total (2 significant figures)	**60**	**22**	**1.4**	**0.44**
EGU Emissions				
PM-Mortality (Laden, 3% discount rate)	79,000	--	5,500	—
PM-Mortality (Pope, 7% discount rate)	—	28,000	—	2,000
PM-Morbidity	1883	1883	123	123
Ozone-Mortality (Levy)	0	0	0	0
Ozone-Morbidity	0	0	0	0
Total	*80,883*	*29,883*	*5,623*	*2,123*
Total (2 significant figures)	**81,000**	**30,000**	**5,600**	**2,100**
2010-2020				
PM-Mortality (Laden, 3% discount rate)	59,000	—	3,900	—
PM-Mortality (Pope, 7% discount rate)	—	21,000	—	1,400
PM-Morbidity	1434	1434	86	86
Ozone-Mortality (Levy)	3800	3800	350	350
Ozone-Morbidity	70	70	6	6
Total	*64,304*	*26,304*	*4,342*	*1,842*
Total (2 significant figures)	**63,000**	**26,000**	**4,300**	**1,800**

As shown in Table 7-1, from 2010 to 2020 health benefits arising from the improving air quality associated with the Reference Case are expected to provide significant positive health impacts for Delaware. Scenario S1 which provides additional offshore wind resources in Delaware has a relatively small but negative impact on health benefits for Delaware in 2020 mainly due to increased emissions outside of the 4-km grid. Scenario S3, which provides additional gas-fired generation in Delaware, also has a small but positive impact on health benefits for Delaware in 2020. In any event, the health impacts of either scenario for 2020 are very small individually when compared to the health benefits expected to be achieved from 2010 to 2020.

The estimated total *cost* associated with Scenario S1 ranges from 16 to 47 million dollars for the 4-km grid and from 1.4 to 4.2 million dollars for Delaware. The estimated total *benefit* associated with Scenario S3 ranges from 22 to 60 million dollars for the 4-km grid and from 0.4 to 1.4 million dollars for Delaware. The corresponding values for Scenario S2 are expected to be similar to those for S3. The overall costs/benefits associated with mercury deposition are a small fraction of the overall totals.

Based on data from a recent National Academy of Sciences (NAS) report, the *benefits* associated with changes in carbon dioxide (CO_2) for the offshore wind scenario (S1) range from 0.17 to 16 million dollars, and the *benefits* for the onshore wind scenario (S2) range from 0.03 to 3 million dollars. Due to the estimated increase in CO_2 emissions, estimated *costs* associated with the combined cycle case (S3) range from 0.02 to 2 million dollars. These estimates are for the Mid-Atlantic states.

For perspective, it is useful to compare these values with estimated costs and benefits associated with larger emissions changes. As noted earlier, additional simulations were run to examine the contributions from all EGU emissions to overall air quality and changes in air quality with time (from 2010 to 2020). The estimated total cost associated with EGU emissions alone (based on their contribution to simulated ozone and $PM_{2.5}$ concentrations for the 2020 Reference Case simulation) ranges from 30 to 81 billion dollars for the 4-km grid and from 2.1 to 5.6 billion dollars for Delaware. Note the change from million to billion. The estimated total benefit associated with the expected emissions changes between 2010 and 2020 range from 26 to 63 billion dollars for the 4-km grid and from 1.8 to 4.3 billion dollars for Delaware.

In summary, the air quality and health effects modeling results indicate improvements in air quality between 2010 and 2020 due to expected changes in emissions from all sources, including EGUs. The simulated improvements in air quality result in a lower incidence of adverse health effects and substantial monetized health-effects benefits for Delaware and the surrounding region. The modeling results also indicate that the environmental impacts and health-related costs/benefits associated with the alternative energy production sources considered in this study are small compared to the changes from 2010 to 2020.

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