The Benefits and Costs of U.S. Air Pollution Regulations

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INTRODUCTION

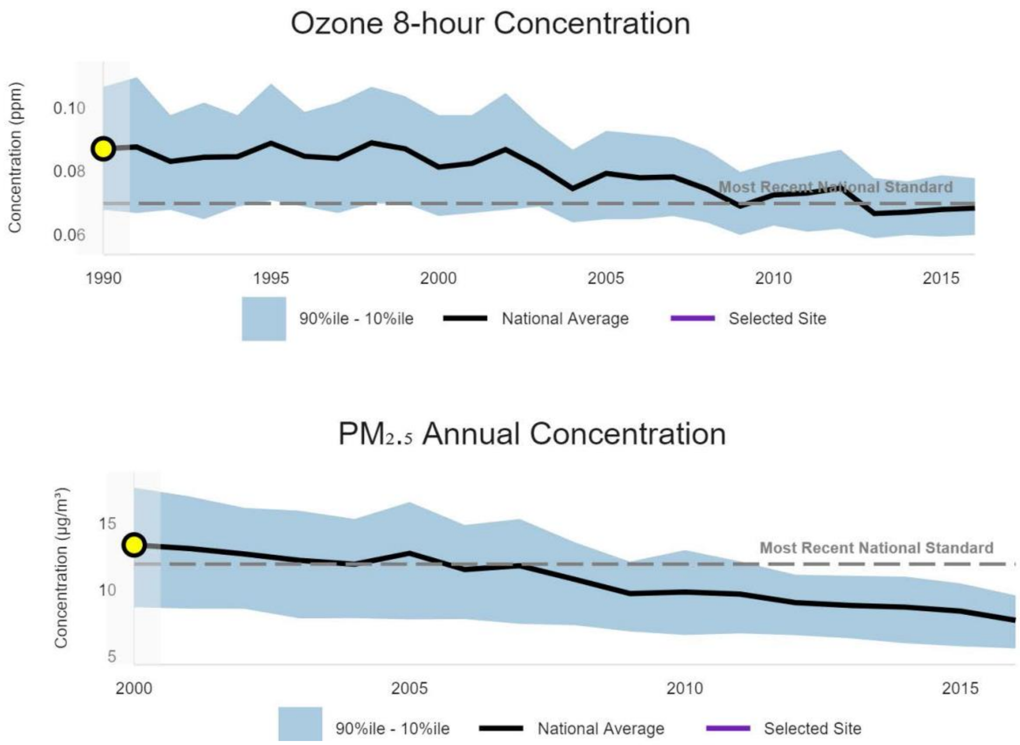
The passage of the 1970 Clean Air Act ushered in vast improvements in air quality across the United States and contributed significantly to improvements in Americans' public health. Under the authority of the Act, the newly created U.S. Environmental Protection Agency established the country's first National Ambient Air Quality Standards (NAAQS), which set minimum air quality requirements for pollutants such as suspended particulates (soot) and ozone (smog). The Act also required states to develop implementation plans describing how they would meet the standards, and established emissions standards for motor vehicles and for new emissions sources based on the best available technology. Building on the 1970 Act, the 1977 Clean Air Act Amendments created new requirements for areas in attainment with the NAAQS to prevent deterioration of air quality and established new mechanisms to help areas not in attainment with the NAAQS comply with the standards.

The Clean Air Act Amendments of 1990 significantly strengthened the protections established in the original Act and the 1977 Amendments. Related to the NAAQS, the 1990 Amendments created a graduated program for non-attainment areas to move toward attainment, reflecting the difficult and complex problems that some areas face in attaining the standards. The 1990 Amendments also established caps for power plant emissions responsible for the formation of acid rain. Under the cap-and-trade system established for these pollutants, power plants are able to trade emissions allowances to facilitate the achievement of emissions reductions at the lowest possible cost. Expanding upon the permitting requirements in place at the time, the 1990 Amendments established a new air permit program under which all major emissions sources are required to obtain an operating permit. In addition, the 1990 Amendments instituted emissions limits on 189 toxic air pollutants that had previously been uncontrolled at the federal level.

Due to the implementation of these and other Clean Air Act provisions, air quality across the U.S. has improved dramatically over the past several decades. This is particularly true when examining concentrations of fine particulate matter ($PM_{2.5}$) and tropospheric ozone (O_3), both of which increase the risk of premature mortality, asthma exacerbation, and a variety of other adverse health effects.[1] As shown in Figure 1 below, ambient concentrations of fine particulate matter ($PM_{2.5}$) have declined, on average, by approximately 42 percent since 2000 while ozone (O_3) concentrations have decreased by 21 percent since 1990.

[1] $PM_{2.5}$ is a mixture of solid particles and liquid droplets found in the air, with diameters that are generally 2.5 micrometers and smaller. $PM_{2.5}$ may be directly emitted into the air or formed from precursor pollutants. O_3 is formed in the atmosphere by chemical reactions between oxides of nitrogen (NO_x) and volatile organic compounds (VOCs).

FIGURE 1. RENDS IN OZONE AND $PM_{2.5}$ CONCENTRATIONS



Source: U.S. EPA (2017b)

As regulations have been developed to support and enable these improvements in air quality, administrations of both parties have developed a thorough accounting of the societal benefits and costs of these rules. In its annual report on the costs and benefits of new Federal regulations, the Office of Management and Budget (OMB) has consistently reported significant net benefits for the new Clean Air Act regulations that it reviews. Over the years 2002 through 2015, OMB reports that the benefits of the Clean Air Act regulations that it reviewed were between 3 and 18 times greater than the costs of these rules, depending on whether the low or high ends of the ranges reported by OMB were used.[2]

Expanding upon these benefit-cost analyses of individual regulations, the U.S. EPA developed a series of analyses assessing the benefits and costs of the full Clean Air Act. The most recent of these analyses, published in 2011, assessed the benefits and costs of the 1990 Clean Air Act Amendments (CAAA) over the 1990 to 2020 period, hereafter referred to as the EPA CAAA study.[3] The results of the analysis showed that the benefits of CAAA-related improvements in air quality (e.g., health benefits and improvements in visibility) were significant and will grow as emission control programs reach their full

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[2] See Office of Management and Budget (2002 through 2015).

[3] See U.S .EPA (2011a).

effect. By 2020, the analysis found that the annual benefits of the Amendments would grow to approximately $2.0 trillion, relative to compliance costs of approximately $65 billion that same year (2006$). Most of these benefits (approximately 85 percent) reflected reductions in premature mortality associated with reduced $PM_{2.5}$ concentrations. EPA's analysis estimated that the reduction in ambient $PM_{2.5}$ would prevent 230,000 cases of premature mortality in 2020. The remaining benefits were divided between other health improvements and improving the quality of ecological resources and other aspects of the environment.[4]

The purpose of this report is to update and expand upon previous analyses of the benefits and costs of the 1990 Clean Air Act Amendments. In particular, this report expands upon the EPA CAAA study to assess the impacts of the Amendments in the years 2020 and 2030. To provide a more comprehensive accounting of the benefits and costs of the Amendments, this report considers major rules developed or finalized after the cutoff date for inclusion in the EPA CAAA study, and thus were not reflected in the previous study.[5] The assessment of health benefits in this analysis is also updated to reflect the suite of health endpoints included in EPA's more recent regulatory impact analyses (RIAs). The specific health endpoints that EPA includes in its primary health benefits estimates have changed over time to reflect developments in the epidemiological literature and advice from the Agency's science advisors. Similarly, this report relies upon updated concentration-response functions and valuation estimates (e.g., the value of a statistical life) consistent with those used in more recent RIAs.

Building on EPA's previous analysis of the Amendments, this study also examines, to the extent feasible, the greenhouse gas (GHG) reductions that have resulted from the Amendments, as well as the attendant benefits. While data on GHG reductions is not available for most of the rules finalized during the two decades following passage of the Amendments, these data points are available for several more recent rulemakings.

As described in further detail below, this analysis finds that the Clean Air Act Amendments have led to net benefits ranging from $1.9 trillion to $3.8 trillion in 2020 and $2.5 trillion to $5.0 trillion in 2030. This value excludes cost savings associated with motor vehicle fuel efficiency improvements and avoided natural gas losses expected under rules finalized after the cutoff date for inclusion in the EPA CAAA study. These cost savings total $59.4 billion in 2020 and $231.0 billion in 2030.

OVERVIEW OF METHODS

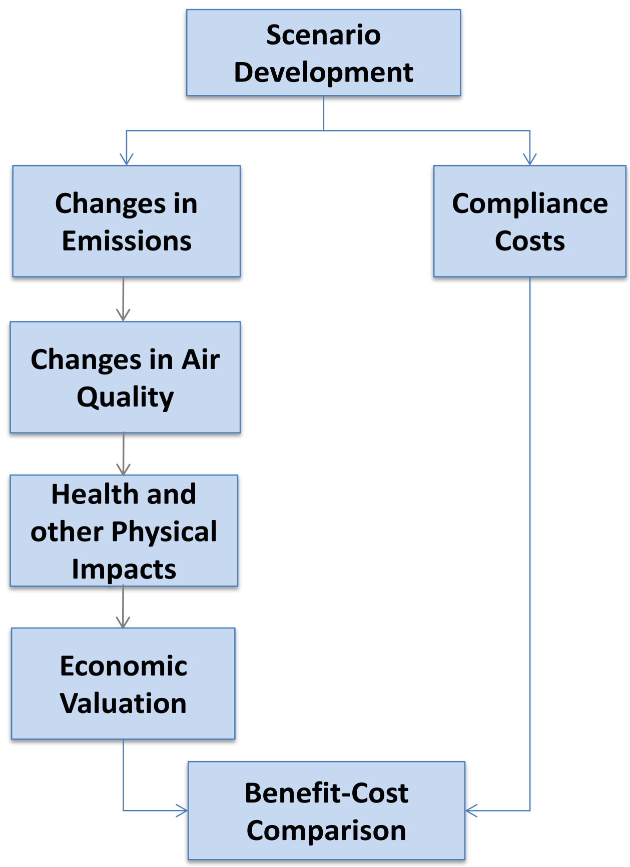
To assess the benefits and costs of Clean Air Act regulations, this study applies similar methods as those of other air quality analyses in the peer-reviewed literature, including EPA's CAAA study. Consistent with these previous analyses, this study reflects the analytic chain shown in Figure 2 linking changes in air policy to specific benefits and costs borne by society. Benefits include a variety of improvements in public health, while

[4] See U.S. EPA (2011a) for additional details.

[5] EPA's cutoff date for including a rulemaking in its analysis was September 2005.

costs reflect capital and operating expenditures for air pollution control devices, as well as other operational expenditures for process changes that reduce air pollution. The analysis of benefits presented here is limited to health benefits associated with reduced criteria pollutant emissions and climate benefits associated with reduced GHG emissions. Other benefits associated with cleaner air not examined here include: productivity benefits for agricultural crops; improved visibility in recreational and residential areas; reduced acidification of lakes, rivers, and streams; and avoided degradation of building materials.[6] The specific criteria pollutants that we examine in this study include sulfur dioxide (SO_2), fine particulate matter ($PM_{2.5}$), oxides of nitrogen (NO_x), and volatile organic compounds (VOCs). Because this analysis does not capture the benefits of reduced air toxics emissions (e.g., reduced cancer incidence from benzene exposure), the benefits presented in this document represent underestimates of actual CAAA-related health benefits.

FIGURE 2. ANALYTIC SEQUENCE FOR BENEFIT-COST ANALYSIS OF AIR POLICY



Source: Adapted from U.S. EP (2011a)

Consistent with Figure 2, our analysis of air policy benefits reflects:

[6] For the year 2020, the EPA CAAA Study estimated visibility benefits of $67 billion, agricultural and forest productivity benefits of $11 billion, and materials damage benefits of $110 million. All of these values are in year 2006 dollars.

- ***Policy-related emissions reductions:*** We estimate the emissions reductions associated with the regulations included in the EPA CAAA study, as well as reductions associated with major rules developed after the with-CAAA and without-CAAA scenarios were finalized for the EPA study. In addition, consistent with EPA's study, we estimate emissions reductions separately for five broad source categories: (1) electricity generating units (EGUs); (2) non-EGU point sources, such as refineries and other large industrial sources; (3) onroad vehicles; (4) nonroad vehicles; and (5) non-point sources (e.g., dry cleaners and roadway dust).
- ***Changes in air quality:*** Reductions in emissions of the pollutants specified above may affect ambient concentrations of $PM_{2.5}$ and tropospheric ozone.
- ***Changes in physical effects:*** Improvements in air quality may reduce the incidence of several adverse health effects.
- ***Economic value of avoided effects:*** We estimate the economic value of avoided health effects based on individuals' willingness to pay to avoid these effects, as well as data available on the treatment costs and lost earnings associated with these effects.

In addition to these benefits associated with criteria pollutants, we also assess CAAA-related benefits associated with reductions of GHGs. Our analysis of these benefits, however, is limited to those CAAA rules for which sufficient information was available to estimate GHG reductions.

Our estimates of the costs of CAAA regulations represent the incremental costs incurred to achieve the emissions reductions described above. Similar to our assessment of emissions impacts, we estimate costs by source category, based on data from EPA's CAAA study and regulatory impact analyses for more recent regulations that were not reflected in the EPA study. These cost estimates are based on detailed sector-specific modeling that, in many cases, reflects the characteristics of individual facilities (e.g., the emissions controls that they already have in place) and the least-cost compliance option for these facilities.

SCENARIO DEFINITION

The CAAA regulations examined in this study include the full suite of rules covered in EPA's CAAA study plus several other major regulations that were finalized after the cutoff date for inclusion in that study (late 2005). The specific rules selected for inclusion in this study, incremental to those reflected in the EPA study, are those with the most significant benefit and/or costs, as specified in later regulatory impact analyses. Rules were also only included if sufficient information was available to allocate rule-related emissions reductions to the county or state level, to facilitate the development of credible benefits estimates. Because this analysis excludes relatively minor rules, as well as regulations for which limited emissions data were available, we likely underestimate both the benefits and costs of the Clean Air Act Amendments.

Table 1 lists each of the 12 regulations included in this analysis that were not reflected in the EPA CAAA study. As indicated in the table, these rulemakings reduce emissions across all five of the major source categories, except for nonroad engines. Five of the 12 rules focus on onroad vehicle emissions, while three reduce emissions from the electric power sector. In addition, four of the five motor vehicle rules also affect upstream emissions from EGUs and/or non-EGU point sources. These upstream effects reflect reduced output from refineries due to increased vehicle fuel economy and increased generation from power plants to supply energy to electric vehicles (EVs).

EMISSIONS IMPACTS

To estimate CAAA-related emissions reductions in the years 2020 and 2030, we separately examine the emissions impacts of the rules included in the EPA CAAA study and the emissions impacts of the rules listed in Table 1. We then sum these two sets of emission reductions to estimate the total emissions reductions achieved in 2020 and 2030, by pollutant, source category, and county.

EMISSIONS REDUCTIONS FOR RULES IN THE EPA CLEAN AIR ACT STUDY

As part of its analysis of the benefits and costs of the 1990 Clean Air Act Amendments, EPA produced county-level emissions inventories for the years 2000, 2010, and 2020 under both the with-CAAA and without-CAAA scenarios. Both sets of inventories are organized by pollutant and source category. For the purposes of the present analysis, we rely on these data to estimate county-level emissions reductions in the year 2020 for the clean air regulations included in the EPA CAAA study. More specifically, we estimate reductions as the difference between without-CAAA emissions and with-CAAA emissions.

For 2030, we extrapolated the 2020 emissions reductions forward to 2030. Our methods for projecting these reductions to 2030 vary by source category as follows:

Onroad Vehicles

To extrapolate the year 2020 emissions reductions from the EPA CAAA study to 2030, we apply national projections of vehicle miles traveled (VMT) from the U.S. Energy Information Administration's *Annual Energy Outlook* (AEO) 2016 reference case.[7] Between 2020 and 2030, total VMT is projected to increase by 7.6 percent. We apply this factor to the total onroad sector emissions reductions achieved in 2020 to estimate nation-wide emissions reductions for 2030. To allocate the year 2030 reductions to the county level, we assume that the change in reductions between 2020 and 2030 is allocated to counties in direct proportion to their change in population between these two years. Thus, if a given county accounts for 0.1 percent of population growth between 2020 and 2030, its emissions reductions in 2030 are estimated as the sum of (1) its year 2020 reductions and (2) 0.1 percent of the additional reductions achieved nationally between 2020 and 2030.

[7] See EIA (2016).

TABLE 1. REGULATIONS INCLUDED IN ANALYSIS, INCREMENTAL TO THOSE IN EPA'S BENEFIT-COST ANALYSIS OF THE CAAA

RULE	YEAR FINALIZED	POLLUTANT(S)	SOURCE CATEGORY(S)
Mercury and Air Toxics Standards	2011	NO_x, SO_2, $PM_{2.5}$, VOCs, CO_2	EGUs
The Transport Rule	2011	NO_x, SO_2, $PM_{2.5}$, VOCs, CO_2	EGUs
The Clean Power Plan	2015	NO_x, SO_2, CO_2, CH_4	EGUs
Refinery Rule - National Emission Standards for Hazardous Air Pollutants (NESHAP) and New Source Performance Standards (NSPS)	2015	VOCs	Non-EGU point sources
Light-duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy (CAFE) Standards for Model Years 2012-2016	2010	NO_x, SO_2, $PM_{2.5}$, VOCs, CO_2, CH_4	Onroad, non-EGU point sources (upstream)
Greenhouse Gas Emissions Standards and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles	2011	NO_x, SO_2, $PM_{2.5}$, VOCs, CO_2, CH_4	Onroad, non-EGU point sources (upstream)
Greenhouse Gas Emissions and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles - Phase 2	2016	NO_x, SO_2, $PM_{2.5}$, VOCs, CO_2, CH_4	Onroad, non-EGU point sources (upstream)
Tier 3 Motor Vehicle Emission and Fuel Standards Final Rule	2014	NO_x, SO_2, $PM_{2.5}$, VOCs	Onroad
Light-duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy (CAFE) Standards for Model Years 2017-2025	2012	NO_x, SO_2, $PM_{2.5}$, VOCs, CO_2, CH_4	Onroad, non-EGU point sources (upstream), and EGUs (upstream)
NSPS and NESHAP Amendments for the Oil and Natural Gas Industry	2012	VOCs, CH_4	Nonpoint Sources
Final Oil and Natural Gas Sector: Emission Standards for New, Reconstructed, and Modified Sources	2016	VOCs, CH_4	Nonpoint Sources
NESHAP for Major Source and Area Source Boilers	2012	SO_2, $PM_{2.5}$	Non-EGU Point Sources and Nonpoint Sources

Electricity Generating Units

To project the year 2020 EGU emissions reductions from the EPA CAAA study to 2030, we apply two separate approaches: one for VOCs and $PM_{2.5}$ and a second for SO_2 and NO_x. For VOCs and $PM_{2.5}$, we apply an approach similar to that outlined above for onroad vehicles. Specifically, we assume that VOC and $PM_{2.5}$ emissions reductions grow at the same rate as electricity demand. For each county, we apply the corresponding regional growth rate for electricity demand as reflected in the base case (v. 5.15) specified in the U.S. EPA's Integrated Planning Model (IPM), which is the electricity sector model that EPA uses to assess the costs of most of its air rules affecting the electric power sector.[8]

Our approach for projecting the year 2020 EGU reductions of SO_2 and NO_x to 2030 differs somewhat from our approach for VOCs and $PM_{2.5}$. Rather than projecting year 2030 reductions directly from year 2020 reductions, we project year 2030 emissions separately under the without-CAAA and with-CAAA scenarios and calculate reductions as the difference between the two. Due to the emissions caps established under the Clean Air Act Amendments for SO_2 and NO_x, emissions of these pollutants under the with-CAAA and without-CAAA scenarios are unlikely to grow at the same rate over time (as would be implied by applying an activity growth rate to the year 2020 reductions). Therefore, applying a single activity-based growth rate to the emissions reductions achieved in 2020 is unlikely to provide an accurate estimate of reductions in 2030.

For the *without-CAAA* scenario, we hold SO_2 and NO_x emissions constant at their year 2020 levels, as estimated in the EPA CAAA study. While EGU emissions of SO_2 and NO_x would likely increase between 2020 and 2030 in the absence of the Clean Air Act Amendments, the data from the EPA study show that emissions of SO_2 and NO_x grow more slowly than electricity demand under the without-CAAA scenario.[9] While it would be possible to assume that the relationship between demand growth and emissions growth continues through 2030, it is uncertain whether this relationship would continue to hold over time. Therefore, to avoid the overestimation of SO_2 and NO_x emissions reductions, we hold year 2030 without-CAAA emissions of these pollutants constant at their year 2020 values.

Under the *with-CAAA* scenario, growth in SO_2 and NO_x emissions between 2020 and 2030 is likely to be constrained by EGU emissions caps established under the CAAA. For example, Title IV of the Clean Air Act Amendments limits power sector SO_2 emissions to 8.95 million tons per year. Even if electricity demand grows significantly, the power sector must find ways of keeping SO_2 emissions under this cap. Therefore, as an alternative to growing emissions in proportion to demand between 2020 and 2030, we specify 2030 SO_2 and NO_x emissions under the *with-CAAA* scenario as the lower of (1) *with-CAAA* scenario emissions in 2020, as estimated in the EPA CAAA study and or (2) emissions estimates from the 2014 National Emissions Inventory (NEI). Table 2

[8] See U.S. EPA (2015b).

[9] See Industrial Economics, Inc. and E.H. Pechan & Associates, Inc. (2011).

compares the emissions estimates from these sources, by pollutant. As shown in the table, SO_2 and NO_x emissions as estimated in the EPA CAAA study for the year 2020 are higher than the corresponding year 2014 values from the NEI. We therefore use the NEI 2014 emissions estimates as an approximation of *with-CAAA* emissions in 2030. We allocate these emissions to the county level in proportion to their distribution in the 2020 with-CAAA scenario emissions from the EPA CAAA study.

TABLE 2. COMPARISON OF EGU EMISSIONS FROM THE 2014 NATIONAL EMISSIONS INVENTORY (NEI) AND EPA CAAA STUDY *WITH-CAAA* SCENARIO FOR 2020

POLLUTANT	YEAR 2014 EGU EMISSIONS FROM NATIONAL EMISSIONS INVENTORY	YEAR 2020 EGU EMISSIONS FROM THE EPA CAAA STUDY
Total NO_x	1,647,139	1,986,463
Total SO_2	3,173,664	4,270,126

Notes:
1. See U.S. EPA (2018).
2. See U.S. EPA (2011a).

Non-EGU Point Sources, Nonroad Engines, and Nonpoint Sources

The year 2020 emissions reductions in EPA's CAAA study for non-EGU point sources, nonroad engines, and nonpoint sources reflect reductions for a variety of sub-sectors within each of these broad categories. For example, the emissions reductions for nonpoint sources include reductions from industrial fuel combustion, solvent utilization, waste disposal, and several other sources. To project changes in emissions over time for these various sub-sectors, the EPA CAAA study incorporated region-specific growth rates from the U.S. Energy Information Administration's AEO 2005.[10]

We apply a similar approach to extrapolate the non-EGU point source, nonroad engine, and nonpoint source emissions reductions from the EPA CAAA study to the year 2030. For each pollutant and sector (e.g., NO_x emissions from non-EGU point sources), we estimate a *single* emissions reductions growth factor for the 2020-to-2030 period. Each growth factor is a weighted average of the growth factors for the various sub-sectors that make up each source category. As an initial step in this process, we assign growth factors from the AEO 2016 to each of the various categories of non-EGU point sources, nonroad engines, and nonpoint sources identified in the EPA CAAA study.[11] For example, assuming that industrial fuel combustion will grow at the same rate as industrial GDP, we assign the estimated industrial output growth rate to the industrial fuel consumption subsector. After estimating the 2020-to-2030 growth factors for the sub-sectors that make

[10] See EIA (2005).

[11] Each individual source was assigned the AEO 2016 growth factor for population, real GDP, or total industrial output from EIA (2016).

up each source category, we calculated weighted average growth factors, by pollutant and source category, using the year 2020 reductions for each sub-category as weights. For example, given that industrial fuel combustion accounts for 48 percent of the non-EGU point source SO_2 reductions in 2020, the 2020-to-2030 growth factor for industrial fuel combustion has a weighting of 48 percent when calculating the growth rate for SO_2 emissions reductions from non-EGU point sources. Table 3 presents the estimated growth factors for non-EGU point sources, nonroad engines, and nonpoint sources for the 2020-2030 period. For example, based on the data in the table, we project that VOC emissions reductions from nonroad engines will grow by 12 percent between 2020 and 2030.

TABLE 3. GROWTH FACTORS FOR PROJECTING EMISSIONS REDUCTIONS FOR SELECT SECTORS

SECTOR NAME	POLLUTANT	2020-2030 WEIGHTED AVERAGE GROWTH FACTOR
Nonroad Engines	VOCs	**1.12**
	NO	**1.24**
	SO_2	**1.22**
	$PM_{2.5}$	**1.20**
Non-EGU Point Sources	VOCs	**1.17**
	NO_x	**1.18**
	SO_2	**1.17**
	$PM_{2.5}$	**Not applicable**
Nonpoint Sources	VOCs	**1.18**
	NO_x	**1.24**
	SO_2	**1.19**
	$PM_{2.5}$	**1.24**

Across all three of these source types, we assume that the spatial distribution of reductions is the same in 2030 as in 2020. For nonroad engines, this implies that the spatial distribution of year 2030 reductions is the same as in the EPA CAAA study for 2020. For non-EGU point sources and nonpoint sources, however, we made one refinement to the spatial distribution of year 2020 emissions reductions in the EPA CAAA study. In EPA's study, without-CAAA emissions for these sources are distributed to individual counties within a state in proportion to the spatial distribution of emissions in the 1990 National Emissions Inventory (NEI) while with-CAAA emissions are distributed in proportion to values in the 2002 NEI. When we reviewed EPA's county-level emissions data for these sources, it appeared that the methods for distributing emissions within a state changed between the 1990 and 2002 NEIs. For example, the 2002 NEI includes non-EGU point source emissions for significantly more counties than the 1990 NEI, suggesting that the 2002 NEI included a more refined approach for allocating emissions. Assuming that the 2002 NEI better reflects the spatial distribution of both emissions and emissions reductions within each state, we distributed the non-EGU point source and nonpoint source reductions for each state in proportion to the spatial distribution in the 2002 NEI, by pollutant and state. While this adjustment affects the assumed spatial distribution of emissions reductions, it does not affect our estimates of the emissions reductions achieved in a given state.

Local Controls

In addition to estimating the emissions reductions associated with various sector-specific policies, the EPA CAAA study also estimated emissions reductions associated with additional local controls expected to be adopted to achieve further progress toward compliance with the 8-hour ozone NAAQS, the $PM_{2.5}$ NAAQS, and the Clean Air Visibility Rule (CAVR). For the purposes of projecting reductions related to local controls to 2030, we assume that the reductions estimated for 2020 remain constant through 2030. Because reductions related to local controls depend, in part, on ambient ozone and $PM_{2.5}$ concentrations once other policies have been implemented, it was not possible to project how these reductions would change without conducting detailed air quality modeling.

EMISSIONS REDUCTIONS FOR RULES NOT REFLECTED IN THE EPA CLEAN AIR ACT STUDY

Building on the emissions reductions achieved as a result of the regulations reflected in the EPA CAAA study, EPA has issued several additional rulemakings to reduce air pollutant emissions across multiple sectors of the economy. For the purposes of this analysis, we focus on the emissions reductions associated with the rulemakings listed above in Table 1. We focus on these specific rules because (1) they have resulted in significant emissions reductions for multiple pollutants and (2) sufficient data is available for each rule to estimate emissions reductions at the county level.

To estimate the emissions reductions associated with each rule in Table 1 for the years 2020 and 2030, we relied extensively on the information available in each rule's regulatory impact analysis (RIA) and any accompanying analyses published by EPA. If the RIA for a rule included emissions reduction projections for 2020 or 2030, we applied these values directly in our analysis. In cases where a rule RIA did not include reduction estimates specific to 2020 or 2030, we interpolated or extrapolated from the values included in the RIAs for other years, using activity metrics specific to each sector as the basis for interpolation/extrapolation (e.g., refinery output projections for reductions from petroleum refineries). To allocate the emissions reductions for each rule to individual counties, we used any spatially-specific emissions data included in each rule's RIA, as well as data indicative of the spatial distribution of activity for each affected sector (e.g., data on vehicle miles traveled for motor vehicle emission reductions).

Electricity Generating Units

As shown in Table 1, we estimate emissions reductions for three EGU rules finalized following the development of the EPA CAAA study. For each of these rules, the projected reductions in NO_x, SO_2, and CO_2 emissions were available for both 2020 and

2030 from the Integrated Planning Model (IPM) simulations performed for each rule.[12] We apply these values in our analysis. The IPM projections do not include emissions data for $PM_{2.5}$ or VOCs, though the rules' RIAs report $PM_{2.5}$ and VOC reductions for 2014 (Transport Rule) or 2016 (Mercury and Air Toxics Rule).[13] Because $PM_{2.5}$ and VOCs are not the focus of the EGU rules listed in Table 1, we hold the $PM_{2.5}$ and VOC reductions from the rule RIAs constant through 2020 and 2030. We do not project changes in these reductions over time.

With respect to the spatial distribution of NO_x, SO_2, and CO_2 reductions, EPA's IPM data for 2020 and 2030 report emissions by NERC region. For each rule, EPA also released more detailed IPM "parsed" files that include emissions estimates for individual EGUs, though these parsed files were not available for 2020 or 2030.[14] Using the parsed file for the year closest to 2020 or 2030 for each rule, we estimated the distribution of emissions reductions (by pollutant) across the counties in each region and applied the resulting distribution to the 2020 and 2030 regional emissions reductions for NO_x, SO_2, and CO_2.

For $PM_{2.5}$ and VOCs, the rules' RIAs report reductions by state. In the absence of parsed data for these pollutants, we allocate $PM_{2.5}$ and VOC reductions based on the distribution of generation. Specifically, for $PM_{2.5}$, we allocate state-level emissions to the county level in proportion to each county's total coal-fired generation as modeled by IPM. For VOC emissions, we allocate according to each county's total fossil fuel-based generation.

Petroleum Refineries

Our expanded analysis of emissions reductions from the petroleum refining sector reflects the 2015 Refinery Sector Rule, which includes both National Emissions Standards for Hazardous Air Pollutants (NESHAP) and New Source Performance Standards (NSPS) for petroleum refineries. EPA's RIA of the rule reports VOC emissions reductions for 2017.[15] To project emissions reductions to 2020 and 2030, we assume that emissions reductions grow at the same rate as total U.S. crude petroleum supply, as measured by U.S. refinery throughput from the Energy Information Administration's *Annual Energy Outlook 2016*.[16] AEO 2016 projects a slight decrease of one percent in total U.S. refinery throughput between 2017 and 2020, and less than a one percent change between 2017 and 2030.

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[12] IPM is a detailed model of the electricity sector that EPA uses to assess the emissions and cost impacts of rulemakings affecting electric power producers. For IPM data, see U.S. EPA (2011b, 2011c, and 2015c).

[13] No $PM_{2.5}$ or VOC data are available for the final Clean Power Plan.

[14] Parsed files for the Mercury and Air Toxics Rule and the Clean Power Plan were obtained from the docket for each rule. The docket/document IDs for the parsed files for the Mercury and Air Toxics Rule are EPA-HQ-OAR-2009-0234-19982 and EPA-HQ-OAR-2009-0234-19883. The docket/document IDs for the parsed files for the Clean Power Plan used for this analysis are EPA-HQ-OAR-2013-0602-36470, EPA-HQ-OAR-2013-0602-36471, EPA-HQ-OAR-2013-0602-36474, and EPA-HQ-OAR-2013-0602-36475. For parsed files for the Transport Rule, see U.S. EPA (2011b).

[15] See U.S. EPA (2015a).

[16] Total U.S. crude petroleum supply from 2016 AEO Reference Case Table 11: U.S. crude supply (line 16) + U.S. net imports of crude oil (line 19) + Other Crude Supply (line 22) + U.S. refinery processing gain (line 30).

We allocate the nation-wide VOC reductions to counties in proportion to recent refinery-specific estimates of refinery throughput. Using EIA's 2017 Refinery Capacity Report, we approximate total throughput by multiplying refinery-specific capacity by the capacity utilization factor for each Petroleum Administration for Defense District (PADD). We aggregate emissions reductions estimated from the 133 active refineries listed in the EIA Refinery Capacity Report to the county level to derive emissions reductions for 65 individual counties.[17]

Onroad Vehicles

The five onroad vehicle rules listed in Table 1 include tailpipe emission standards and motor vehicle fuel standards, as well corporate average fuel economy (CAFE) standards jointly developed between the U.S. EPA and the Department of Transportation. These rulemakings collectively affect light duty, medium-duty, and heavy-duty vehicles sold across the U.S. In addition, EPA's RIAs for these rules distinguish between downstream emissions and upstream emissions. Downstream emissions include emissions directly from vehicle tailpipes, while upstream emissions are produced by fuel refining and processing and the generation of electricity to power electric vehicles.

The RIAs for these motor vehicle and fuel rules differ in terms of the years for which they estimate a rule's emissions impacts. While some report emissions impacts for 2020 and/or 2030, others provide estimates of emissions impacts for other years. When available, we use the estimated emissions impacts provided for 2020 and 2030. When emissions projections for 2020 and/or 2030 were not available for a rule, we interpolated or extrapolated from the estimates for the year(s) reported.

Our approach for interpolating or extrapolating downstream emissions impacts varies by rule, depending on the extent to which the estimated reductions reflect fuel standards or vehicle standards. While fuel standards affect all vehicles on the road, vehicle standards affect new vehicles only and therefore have a cumulative impact on emissions over time. For example, if a fuel standard is fully implemented in 2020, all vehicles are immediately affected that year. In contrast, if a new vehicle standard goes into effect in 2020, only model year 2020 vehicles are affected that year; in 2021 the number of affected vehicles would grow to include model year 2020 and model year 2021 vehicles. Consistent with the immediate impact of fuel standards on all vehicles on the road, we use linear interpolation or extrapolation to project fuel standard emission impacts for 2020 and/or 2030. For vehicle standards, we apply a more nuanced approach that captures the cumulative nature of a rule's emissions impact over time. More specifically, we assume that affected VMT for a given year is based on sales that year, the cumulative sales of affected vehicles in prior years, and the gradual retirement of vehicle cohorts (e.g., model year 2020 vehicles) over time.

[17] See EIA (2017) for refinery capacity data. Locations information from US Energy Mapping System, available at: https://www.eia.gov/maps/layer_info-m.php.

To spatially allocate downstream emissions impacts, we follow a two-step process using data from publicly available sources. First, we allocate reductions to urban and rural areas in each state in proportion to each state's urban and rural VMT, as reported by the U.S. Federal Highway Administration for 2014.[18] For example, if a state's urban area VMT accounts for 5 percent of VMT nationally, we assign 5 percent of downstream emissions impacts to urban areas within that state. Second, we allocate the urban and rural reductions for each state to individual counties based on each county's share of the state's urban or rural population.[19]

Similar to our estimation of downstream emissions impacts for 2020 and 2030, our analysis of upstream emissions impacts relies on EPA estimates for these years if they are available. For rules for which estimates for 2020 and/or 2030 are unavailable, we assume that upstream emissions impacts change in direct proportion to fuel consumption for the vehicles affected by each rule. Fuel consumption projections for each relevant vehicle rule are included in the RIAs.

Our approach for spatially allocating upstream emissions impacts varies based on the type of upstream impact. We assume that emissions reductions related to reduced fuel consumption occur at refineries. We allocate these reductions using the same distribution of petroleum refining activity by county as described for the Refineries rule above. For changes in upstream EGU emissions, we allocate in proportion to county-level electricity generation, as specified in the IPM v5.15 base case described above.

Oil and Natural Gas Industry Rules

Our analysis of the oil and natural gas extraction sector covers two rulemakings promulgated since the publication of the EPA CAAA study: the 2012 New Source Performance Standards and National Emissions Standards for Hazardous Air Pollutants for the Oil and Natural Gas Industry (2012 NSPS/NESHAP)[20] and the 2016 New Source Performance Standards for the oil and gas industry (2016 NSPS).[21]For both rules, we rely on data from the final rule RIAs to estimate the emissions reductions achieved in 2020 and 2030. The RIA for the 2016 NSPS reports reductions for both 2020 and 2025. We use the year 2020 values in the RIA without any adjustment or modification. For 2030, we extrapolate from the year 2025 emissions reductions, which the RIA reports separately for one-time sources (well completions and recompletions) and sources with ongoing operations (e.g., pumps and compressors). For emissions from one-time sources, we assume that emissions between 2025 and 2030 grow in proportion to well completions.

[18] See Highway Statistics 2014: Table VM-2 and Table VM-4, available at: https://www.fhwa.dot.gov/policyinformation/statistics/2014/

[19] We derived county-level urban and rural population estimates from the county-level population projections in EPA's Ben-MAP model for 2020 and 2030 and 2010 U.S. Census Bureau estimates of county-level urban and rural population proportions.

[20] Emissions data from U.S. EPA (2012a).

[21] Emissions data from U.S. EPA (2016).

For sources with ongoing opertions, we assume that the change in emissions reductions between 2025 and 2030 is proportional to the change in the number of affected sources.

The RIA for the 2012 rule does not provide the same level of detail for affected sources by year. The RIA estimates emissions reductions for 2015 only, most of which are from unconventional natural gas well sites. The RIA also includes projections of the number of unconventional gas wells drilled each year through 2030.[22] In the absence of additional data, we assume that emissions reductions will grow post-2015 at the same rate as the increase in the number of unconventional natural gas wells drilled.

To allocate the emissions impacts of the oil and gas rules to the county level, we followed a two-step process. First, we distributed emissions reductions to Census regions in proportion to combined oil and gas production (measured in dollars) based on projections from AEO 2016.[23] We then allocated each region's reductions to counties within the region in proportion to oil and gas sector employment, as obtained from 2015 County Business Patterns data.[24]

Industrial, Commercial, and Institutional Boilers

Our analysis also accounts for emissions reductions associated with the 2012 final NESHAP for major source and area (nonpoint) source boilers. The RIA for the final rule presents the rule's estimated emissions impacts for just a single year: 2015.[25] While the reductions associated with the rule may increase over time, the trajectory of these changes is highly uncertain. To avoid overestimation of the emissions reductions associated with the rule, we assume that these reductions remain flat from 2015 through 2030.

To allocate the emissions reductions associated with the rule to the county level, we applied separate approaches for major source boilers and area source boilers. For the former, we relied on data from the database of major source boilers that EPA compiled to inform development of the rulemaking. Using information from this database, we allocated major source boiler emissions reductions to counties in proportion to total boiler fuel consumption.[26] For area source boilers, we allocated emissions reductions to the

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[22] See Table 2-13 in U.S. EPA (2012a). Total unconventional gas wells is calculated as the sum of tight sands, Devonian shale, and coalbed methane gas wells.

[23] We calculate annual oil and gas sales by Census region as the sum of oil sales (total onshore crude oil production and wellhead price from AEO Table 60) and natural gas sales (total dry natural gas production and onshore price from AEO Table 61). Alaska oil and gas sales calculated from Table 14 (Onshore crude oil production and dry natural gas production) and average prices in the lower 48 states.

[24] We estimate oil and gas employment using data for the NAICs codes identified in the 2016 RIA: NAICS codes 211111 (Crude Petroleum and Natural Gas Extraction), 211112 (Natural Gas Liquid Extraction), 213111 (Drilling Oil and Gas Wells), 213112 (Support Activities for Oil and Gas Operations), and 486210 (Pipeline Transportation of Natural Gas).

[25] See U.S. EPA (2912b).

[26] Total fuel consumption is calculated as the product of the number of units, capacity per unit (mmbtu/hr), and operating hours per unit, summed by county. Boiler MACT database available at: https://www.epa.gov/stationary-sources-air-pollution/industrial-commercial-and-institutional-boilers-and-process-heaters.

county level in proportion to county-level area source boiler emissions in the 2014 National Emissions Inventory.[27]

EMISSIONS RESULTS

Based on the methods outlined above, Table 4 presents the estimated emissions reductions associated with regulations developed under the CAAA. The table shows reductions in both criteria pollutant and GHGs. As noted above, however, information on the GHG reductions resulting from Clean Air Act regulations was not available for the regulations reflected in the EPA CAAA study. The GHG reduction estimates presented in Table 4 are therefore likely to understate the actual reductions likely to materialize as a result of the CAAA. Overall, the results in Table 4 show that the Clean Air Act Amendments have resulted in significant reductions in criteria pollutant emissions, particularly for SO_2 and NO_x, with reductions of 26.8 million tons and 24.6 million (short) tons, respectively, in 2030.

TABLE 4. EMISSIONS REDUCTIONS RELATED TO CLEAN AIR ACT REGULATIONS

POLLUTANT		2020	2030
CRITERIA POLLUTANTS (1,000 short tons)	NO_x	21,974	24,582
	SO_2	24,937	26,837
	$PM_{2.5}$	1,299	1,489
	VOC	17,760	20,468
GREENHOUSE GASES (MMT CO2eq)	CO_2	384	1,033
	CH_4	24	46

To provide additional insights on these reductions, Figure 3 presents the distribution of the estimated emissions reductions by source category and pollutant for the four criteria pollutants shown in Table 4. As shown in Figure 3, EGUs and onroad sources account for a significant portion of the estimated emissions reductions in both 2020 and 2030. EGUs represent approximately three-quarters of the SO_2 reductions in both 2020 and 2030 and more than 30 percent of NO_x reductions. Similarly, measures to limit emissions from onroad sources make up more than 40 percent of NO_x reductions in 2020 and 2030 and between 25 and 30 percent of VOC reductions. Figure 3 also shows that nonpoint sources account for more of the VOC and $PM_{2.5}$ reductions than any other source category, while non-EGU and nonroad sources make up a relatively small portion of reductions across all criteria pollutants.

[27] We identified area source boilers in the National Emissions Inventory nonpoint file based on the source classification codes (SCCs) representing the boilers affected by the rule. See Table II-5 from the Air Quality Modeling Technical Support Document, available on the docket: EPA-HQ-OAR-2002-0058.

FIGURE 3. CRITERIA POLLUTANT EMISSIONS REDUCTIONS BY POLLUTANT AND SOURCE CATEGORY

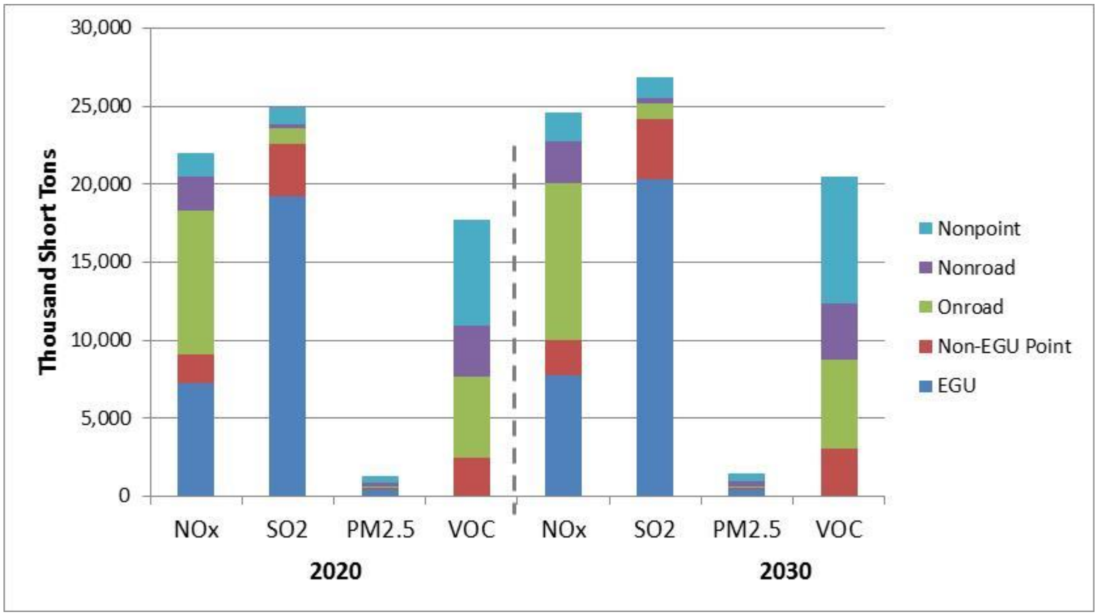
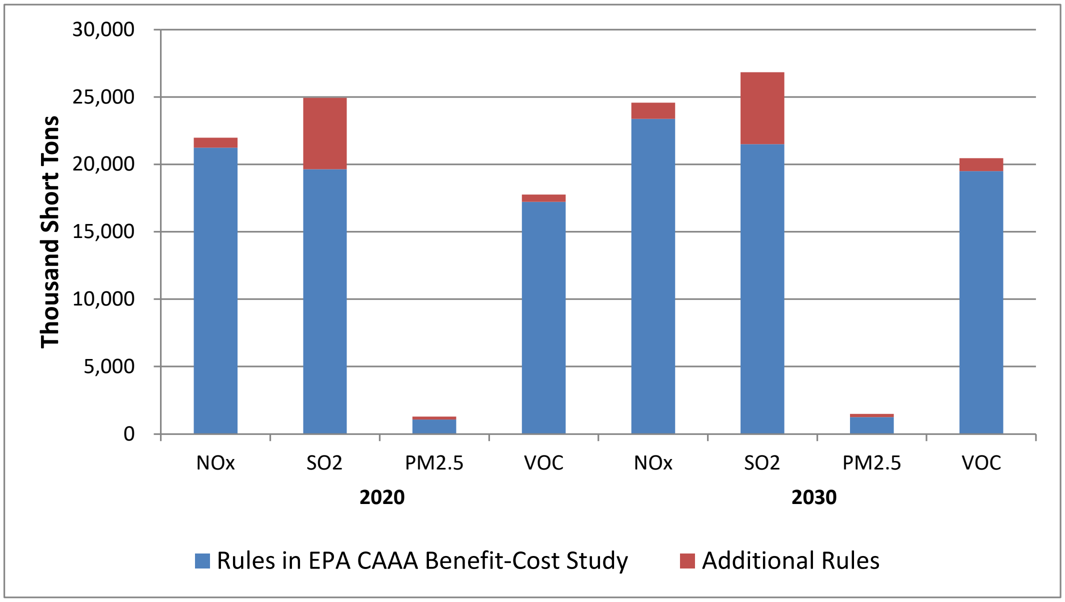


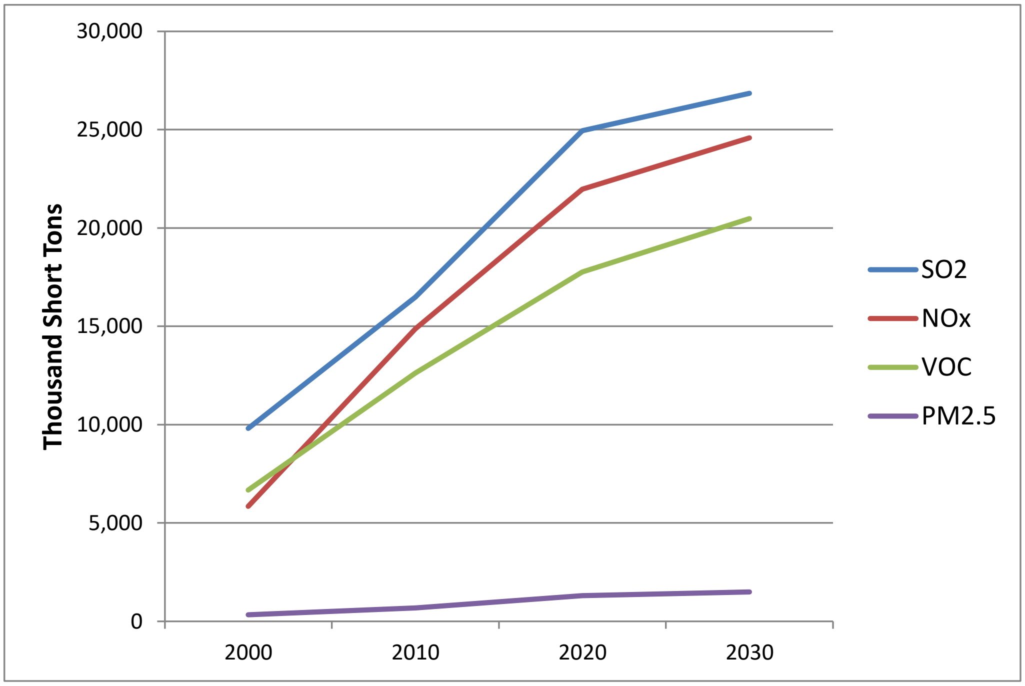
Figure 4 presents the distribution of the estimated emissions reductions between the Clean Air Act regulations reflected in the EPA CAAA study and the additional regulations listed in Table 1. Across all four criteria pollutants, the regulations reflected in the EPA study account for most of the estimated emissions reductions in both 2020 and 2030. This reflects the significant policy investments made in the 15 years following the enactment of CAAA, such as implementation of the Acid Rain program, which significantly reduced EGU emissions of SO_2; the Tier 1 and Tier 2 tailpipe standards for motor vehicles; various rulemakings under Title I of CAAA that reduced VOC emissions from nonpoint sources; and further strengthening of the NAAQS for both $PM_{2.5}$ and O_3. The emissions reductions associated with rules developed after the development of the EPA CAAA study are most significant for SO_2, due to the SO_2 reductions projected as a result of the Transport Rule and MATS. Combined, these two rules account for approximately 4.5 million tons of SO_2 reductions in both 2020 and 2030, based on the projections included in the RIAs for both rules.

FIGURE 4. EMISSIONS REDUCTIONS ASSOCIATED WITH RULES IN EPA'S CAAA BENEFIT-COST STUDY AND ADDITIONAL RULES



While the above results highlight the emissions reductions achieved as a result of the Amendments over the 2020-2030 timeframe of our analysis, Figure 5 puts these reductions in context by presenting CAAA-related criteria pollutant reductions dating back to 2000. As shown in the figure, the estimated emissions reductions for SO_2, NO_x, and VOCs increased significantly between 2000 and 2020 and are projected to increase at a lower rate between 2020 and 2030. This slowing in the growth of emissions reductions in part reflects the conservative assumptions made in this analysis. For example, to project SO_2 and NO_x reductions in 2030 associated with the power sector regulations reflected in EPA's CAAA study, this analysis holds without-CAAA emissions from EGUs constant between 2020 and 2030. In reality, EGU emissions of these pollutants would likely grow between 2020 and 2030 in the absence of the Clean Air Act Amendments. Due to uncertainty regarding the rate of growth, however, we assumed a flat trajectory for this period. Similarly, we assume that reductions related to local controls for NAAQS compliance remain constant at year 2020 levels through 2030, although such reductions may grow over time as areas not in compliance with the NAAQS implement additional control measures to demonstrate reasonable further progress in attaining the NAAQS.

FIGURE 5. EMISSIONS REDUCTIONS ASSOCIATED WITH THE 1990 CLEAN AIR ACT AMENDMENTS: 2000-2030



ESTIMATION OF HEALTH IMPACTS

To quantify and monetize the health benefits associated with the criteria pollutant reductions achieved as a result of the 1990 Clean Air Act Amendments, we applied pollutant-specific impact-per-ton values as calculated by the AP2 integrated air quality assessment model.[28] For a marginal ton of emissions from a given source county, AP2 estimates the monetized air quality impact for that county and every other county in the contiguous U.S., accounting for dispersion and prevailing winds.[29] For example, as shown in Table 5 below, a marginal ton of SO_2 emissions from County A may result in a monetized impact of $50,000. Approximately $20,000 of this impact is realized in County A, but the remainder is distributed across Counties B through E. AP2 generates these impact-per-ton values separately for ground level emissions sources (e.g., motor vehicles) and emissions sources of varying stack heights.

[28] For more information on the AP2 model visit https://sites.google.com/site/nickmullershomepage/home/ap2-apeep-model-2.

[29] AP2's estimation of air quality changes is calibrated to air quality and emissions data for 2011.

TABLE 5. HYPOTHETICAL DISTRIBUTION OF SO_2 IMPACT PER TON VALUES ACROSS RECEPTOR COUNTIES

SOURCE COUNTY	RECEPTOR COUNTIES					TOTAL DAMAGE PER TON
	COUNTY A	COUNTY B	COUNTY C	COUNTY D	COUNTY E	
County A	$20,000	$10,000	$6,000	$12,000	$2,000	**$50,000**
County B	$12,000	$35,000	$3,000	$16,000	$4,000	**$70,000**
County C	$2,000	$1,000	$24,000	$3,000	$5,000	**$35,000**
County D	$1,000	$2,000	$4,000	$29,000	$7,000	**$43,000**
County E	$500	$500	$2,000	$3,000	$8,000	**$14,000**

Developed by Dr. Nicholas Muller of Carnegie Mellon University, AP2 is an integrated air quality assessment model designed to estimate damages associated with changes in emissions of $PM_{2.5}$, VOC, NO_x, and SO_2. AP2's assessment of the damages from air pollution includes the following components:

- ***Emissions:*** For a given scenario, use of AP2 begins by allocating the change in emissions to the appropriate source location and source type. The AP2 model runs for this project altered emissions by one ton for every combination of pollutant and county in the contiguous U.S.
- ***Ambient air quality:*** AP2 uses a streamlined air quality model to translate emissions into ambient concentrations of $PM_{2.5}$ and ozone in every county in the contiguous U.S. The accuracy of the air quality model's predictions has been statistically tested against the EPA's monitoring network.
- ***Exposure assessment:*** After estimating changes in ambient pollutant concentrations, AP2 computes exposures to pollution levels predicted by the model. County-level inventories of human populations are used in conjunction with the predicted pollution levels in order to estimate county-level exposures.
- ***Application of concentration-response relationships to estimate physical effects:*** The exposures of human populations at the county level are translated into physical effects using concentration-response relationships from the peer-reviewed epidemiological literature.
- ***Valuation:*** AP2 assigns a monetary value to the estimated physical effects based on a combination of market and non-market data. For several health effects, valuation information is available in terms of individuals' willingness to pay to avoid the effect. For other health impacts, cost-of-illness data (i.e., the cost of treating a condition) represent the only valuation information available.

CONCENTRATION-RESPONSE FUNCTIONS

To parameterize AP2 to capture the health effects referenced above, the model requires concentration-response functions that link ambient pollutant concentrations with the incidence of these effects. For this application, AP2 uses concentration-response functions from the peer-reviewed epidemiological literature that were applied in recent regulatory impact analyses by the U.S. EPA.[30] Table 6 presents the specific concentration-response functions used in AP2, by health endpoint, along with their functional form and associated effect estimate, or beta value. The concentration-response functions presented in the table for premature mortality related to $PM_{2.5}$ and ozone exposure are particularly important to the estimation of air quality benefits, given the significant value placed on human life. These studies are based on populations in several locations observed a period of several years. For example, the Krewski et al. (2009) study for PM mortality reflects the relationship between $PM_{2.5}$ exposure and mortality over 116 US urban areas and addresses spatial confounding through incorporation of community-level covariates. The lowest measures of $PM_{2.5}$ pollution measured in the Krewski et al. (2009) and Lepeule et al. (2012) studies are 5.8 $\mu g/m^3$ and 8.0 $\mu g/m^3$, respectively. Both of these values are lower than the current $PM_{2.5}$ NAAQS of 12 $\mu g/m^3$.

Application of the concentration-response functions identified in Table 6 requires projections of the baseline incidence rates for each health effect. For mortality effects, AP2 relies upon county-specific baseline incidence rates derived from the Centers for Disease Control (CDC) WONDER database and the U.S. Census Bureau's American Community Survey for 2012-2014 (the most recently available years for averaging). Baseline morbidity incidence rates were extracted from the U.S. EPA's BenMAP-CE model.[31]

Application of the health impact concentration-response functions specified above also requires specification of the population. For this application, AP2 uses the population projections included in EPA's Ben-MAP model, by age group and county. These projections are based on Woods & Poole (2015)[32] population growth factors applied to 2010 U.S. Census Bureau data.

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[30] See U.S. EPA (2013) and U.S. EPA (2015c).

[31] EPA's BenMAP-CE is an open-source program that calculates health and economic impacts associated with changes in air pollution. EPA uses BenMAP-CE for its analyses of air quality changes for policy analysis. More information is available at https://www.epa.gov/benmap.

[32] Woods & Poole Economics. Washington, D.C. Available at https://www.woodsandpoole.com/.

TABLE 6. HEALTH ENDPOINT CONCENTRATION-RESPONSE FUNCTIONS

POLLUTANT	HEALTH ENDPOINT	AGE RANGE	STUDY	FUNCTIONAL FORM	BETA VALUE*
$PM_{2.5}$	All-cause mortality (high)	>24	Lepeule et al., 2012	Log-linear	0.013
$PM_{2.5}$	All-cause mortality (low)	>29	Krewski et al., 2009	Log-linear	0.0058
$PM_{2.5}$	Non-fatal heart attack	>18	Zanobetti and Schwartz, 2006	Log-linear	0.0053
$PM_{2.5}$	Hospital Admissions, Respiratory	>64	Kloog et al., 2012	Log-linear	0.0007
$PM_{2.5}$	Hospital Admissions, Respiratory	18-64	Moolgavkar, 2000a	Log-linear	0.0022
$PM_{2.5}$	Hospital Admissions, Respiratory	<19	Babin et al., 2007	Log-linear	0.002
$PM_{2.5}$	Hospital Admissions, Cardiovascular	>64	Zanobetti et al., 2009	Log-linear	0.0019
$PM_{2.5}$	Hospital Admissions, Cardiovascular	20-64	Moolgavkar, 2000b	Log-linear	0.0014
$PM_{2.5}$	Asthma ED Visits	All ages	Glad et al., 2012	Log-linear	0.00392
$PM_{2.5}$	Work loss days	18-65	Ostro et al., 1987	Log-linear	0.0046
$PM_{2.5}$	Acute Respiratory Symptoms	18-65	Ostro and Rothschild, 1989	Log-linear	0.0074
$PM_{2.5}$	Upper respiratory symptoms	9-11	Pope et al., 1991	Logistic	0.0036
$PM_{2.5}$	Lower respiratory symptoms	7-14	Schwartz and Neas, 2000	Logistic	0.019
$PM_{2.5}$	Asthma exacerbation	6-18	Mar et al., 2004	Log-linear	0.01906
O_3	All-cause mortality (high)	All ages	Zanobetti and Schwartz, 2008	Log-linear	0.00051
O_3	All-cause mortality (low)	All ages	Smith et al., 2009	Log-linear	0.00032
O_3	Hospital Admissions, Respiratory	>65	Katsouyanni et al., 2009	Log-linear	.00064
O_3	Asthma ED Visits	0-17	Mar and Koenig, 2010	Log-linear	0.01044
O_3	Asthma ED Visits	18-99	Mar and Koenig, 2010	Log-linear	0.0077
O_3	Asthma exacerbation	6-18	Schildcrout et al., 2006	Logistic	0.00222
O_3	School loss days	5-17	Gilliland et al., 2001	Log-linear	0.00782
O_3	Acute Respiratory Symptoms	18-65	Ostro and Rothschild, 1989	Log-linear	0.0026

**The beta value represents the natural log of the concentration-response relationship between the ambient concentration of $PM_{2.5}$ or O_3 to a particular health effect.*

HEALTH VALUATION ESTIMATES

After AP2 estimates the change in incidence for the health effects outlined above, the model applies valuation estimates from the peer-reviewed literature to monetize these impacts. Specifically, AP2 applies valuation estimates for each of the health endpoints listed in Table 6, calculated in 2015 dollars, to the estimated change in incidence for each health effect. These valuation estimates are provided as either willingness to pay (WTP) or cost of illness (COI) estimates. WTP is the maximum amount an individual would voluntarily pay to obtain an improvement. As such, WTP estimates are the conceptually appropriate measure of value for benefits that represent an improvement from status quo, such as reductions in morbidity or mortality risk associated with improved air quality.

For many of the morbidity effects estimated by AP2, WTP values are not available in the literature. In the absence of such values, AP2 uses COI estimates, which represent the real costs of incurred cases of illness, injury, or death. COI estimates generally include direct medical costs and indirect productivity losses, but do not account for quality of life impacts (i.e., pain and suffering).

In applying the WTP values, AP2 also adjusts for anticipated income changes over time. Economic theory maintains that individuals' willingness to pay for goods, including the avoidance of an adverse health effect, increases as real income increases. Given that incomes are projected to increase between 2020 and 2030, AP2 (where possible) uses income-adjusted valuation estimates to assess the value of the adverse health effects associated with changes in ambient pollutant concentrations. The model makes these adjustments only for those health effects for which WTP valuation estimates were used. Adjusted COI estimates were not used because the cost of treating an illness is not dependent upon income.

To develop income-adjusted estimates, income elasticities were used from EPA's BenMAP model that represent the percentage change in WTP associated with a 1 percent change in real income.[33] Table 7 below summarizes these values. These elasticity estimates were then applied to projected GDP per capita, as derived from EIA's *Annual Energy Outlook* (AEO).

Table 8 summarizes the health valuation functions used in the AP2 model.

TABLE 7. INCOME ELASTICITY ESTIMATES BY HEALTH ENDPOINT

HEALTH ENDPOINT CATEGORY	HEALTH ENDPOINT	INCOME ELASTICITY ESTIMATE
Mortality	Mortality	0.40
Severe morbidity	Asthma, non-fatal heart attack	0.45
Minor morbidity	All other health endpoints	0.14
Source: Table 4-15, U.S. EPA (2017a).		

[33] See U.S. EPA (2017a).

TABLE 8. HEALTH EFFECT VALUATION ESTIMATES FOR THE U.S. (2015$)

HEALTH EFFECT	STUDY	VALUE IN 2020	VALUE IN 2030	BASIS OF VALUE: WTP OR COI
Premature mortality	Neumann et al. (1994)	$10,400,000	$11,000,000	WTP
Non-fatal heart attacks				
Age 0-24	Cropper and Krupnick (1990)	$106,000	$106,000	COI
Age 25-44		$120,000	$120,000	COI
Age 45-54		$130,000	$130,000	COI
Age 55-64		$217,000	$217,000	COI
Age 65+		$106,000	$106,000	COI
Hospital admission - respiratory	Agency for Healthcare Research and Quality	$39,100	$39,100	COI
Hospital admission - cardiovascular		$45,100	$45,100	COI
Asthma-related emergency department visits	Smith et al. (1999)	$467	$467	COI
Upper respiratory symptoms	Neumann et al. (1994)	$36	$37	WTP
Lower respiratory symptoms	Neumann et al. (1994)	$23	$23	WTP
Asthma exacerbation	Rowe and Chestnut (1986)	$63	$64	WTP
Work loss days	Neumann et al. (1994)	$163	$163	COI
School loss days	U.S. EPA (2015)	$104	$104	COI
Acute Respiratory Symptoms (MRAD)	Tolley et al. (1986)	$74	$75	WTP

HEALTH IMPACT RESULTS

Table 9 presents the substantial health benefits associated with the Clean Air Act Amendments, as derived from the methods outlined above. These benefits range from approximately $2.0 trillion to $3.9 trillion in 2020 and increase to $2.6 trillion to $5.1 trillion in 2030 (all values in year 2015 dollars). The range of values for each year reflects alternative estimates for the mortality impacts associated with exposure to $PM_{2.5}$ and O_3, consistent with EPA practice. The low end is based on the concentration-response coefficients from Krewski et al. (2009) and Smith et al. (2009) for mortality related to $PM_{2.5}$ and O_3, respectively, while the high-end values reflect concentration-response relationships estimated in Lepeule et al. (2012) and Zanobetti and Schwartz (2008). Overall, avoided mortality accounts for the vast majority of benefits, which reflects the high willingness to pay mortality avoidance.

Relative to the benefits estimates presented in the EPA CAAA study,[34] the benefits estimated here are of similar magnitude. Adjusting for inflation, the EPA study estimates $2.2 trillion in benefits in 2020, which is slightly higher than the low end of the range shown in Table 9. Although the present study captures greater emissions reductions in 2020 due to its inclusion of rulemakings not reflected in the EPA CAAA study, the EPA study assumes a stronger relationship between $PM_{2.5}$ exposure and mortality than the low end benefits estimate in Table 9. Specifically, the EPA CAAA study applies a concentration-response coefficient of 1.06 (i.e., 1.06 percent decrease in all-cause mortality per one ug/m^3 change in annual $PM_{2.5}$), while the low-end estimate in Table 9 reflects a coefficient of 0.58 (i.e., a 0.58 percent decrease in all-cause mortality per one ug/m^3 change in annual $PM_{2.5}$).[35]

TABLE 9. SUMMARY OF CLEAN AIR ACT AMENDMENTS BENEFITS (BILLIONS 2015$)

CATEGORY	2020	2030
Total Benefits	$1,962 - $3,879	$2,563 - $5,070
Avoided Mortality	$1,927 - $3,844	$2,521 - $5,028
Avoided Morbidity	$35	$42

Table 10 shows the distribution of benefits across emissions source categories in both 2020 and 2030. Overall, emissions reductions from EGUs account for the greatest share of benefits, representing just less than half of total benefits in 2020 and 44 to 45 percent in 2030. This finding is consistent with the emissions results presented above in Figure 3, which showed that EGUs are the largest contributor to SO_2 reductions and the second largest for NO_x reductions. EGUs do not account for a significant portion of $PM_{2.5}$ or VOC emissions reductions. The overall reductions of $PM_{2.5}$, however, are small relative

[34] See U.S. EPA (2011a).

[35] The beta values presented in Table 6 represent the natural log of these concentration-response relationships.

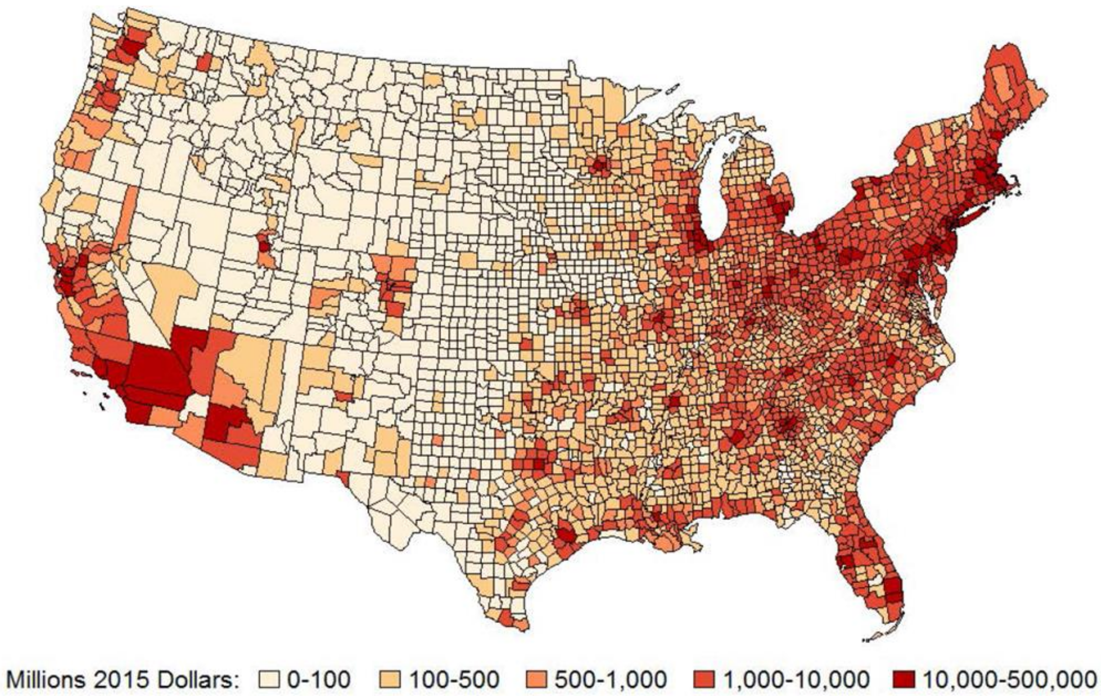
to SO_2 and NO_x reductions, and the benefits per ton of avoided VOCs are on average just 12 percent of the benefits per ton of avoided SO_2. The distribution of benefits across the other source categories is relatively uniform, though benefits associated with reductions from onroad and area sources are slightly greater than benefits related to nonroad and non-EGU point sources.

TABLE 10. ANNUAL BENEFITS OF THE CLEAN AIR ACT AMENDMENTS, BY SECTOR (BILLIONS 2015$)

SECTOR	2020	2030
Onroad	$309 - $597	$408 - $791
Nonroad	$197 - $383	$278 - $541
Non-EGU Point	$226 - $446	$312 - $614
EGU	$925 - $1,854	$1,137 - $2,280
Nonpoint	$305 - $599	$429 - $844
Total	**$1,962 - $3,879**	**$2,563 - $5,070**

For perspective on the spatial distribution of benefits, Figure 6 shows the estimated high-end benefits of the Clean Air Act Amendments in 2030 by county. The benefits shown in the figure reflect the CAAA-related health benefits expected to be realized in a given county, not the benefits associated with the emissions reductions achieved in that county. In other words, the benefits shown for a county reflect the transport of (avoided) air emissions from sources both within the county itself and from other counties. As indicated in the figure, county-level benefits for the eastern U.S. are generally higher than for the western half of the country. This reflects the relatively high population density of the eastern U.S. and the long-range transport of air pollutants from the Midwest to the East Coast. Benefits are also high in major population centers across the U.S., particularly in southern California where the local topography combined with the large number of emissions sources can lead to significant air quality problems in the absence of effective emissions controls.

FIGURE 6. SPATIAL DISTRIBUTION OF BENEFITS – HIGH END BENEFITS IN 2030



Similar to Figure 6, Figures 7, 8, and 9 show benefits at the county level associated with emissions reductions from EGUs, onroad sources, and all other emissions sources (i.e., non-EGU point sources, nonpoint sources, and nonroad engines), respectively. Each figure groups counties into quintiles with respect to their CAAA-related benefits. For example, within Figure 7 the top 20 percent of counties with respect to benefits have benefits ranging from $790 million to $34.38 billion. Comparing across Figures 7 through 9, the spatial distribution of benefits for onroad engines is similar to that for non-EGU point sources, nonpoint sources, and nonroad engines combined. While all three maps show a concentration of benefits in the eastern U.S. and along the west coast, the benefits for EGUs are more heavily concentrated in the Mid-Atlantic and the Northeast. The concentration of EGU-related benefits in these areas may reflect the more significant transport of EGU emissions relative to emissions from other sources, given EGU stack heights relative to other sources and the direction of the prevailing winds.

FIGURE 7. DISTRIBUTION OF BENEFITS ASSOCIATED WITH EGU EMISSIONS REDUCTIONS - HIGH END BENEFITS IN 2030

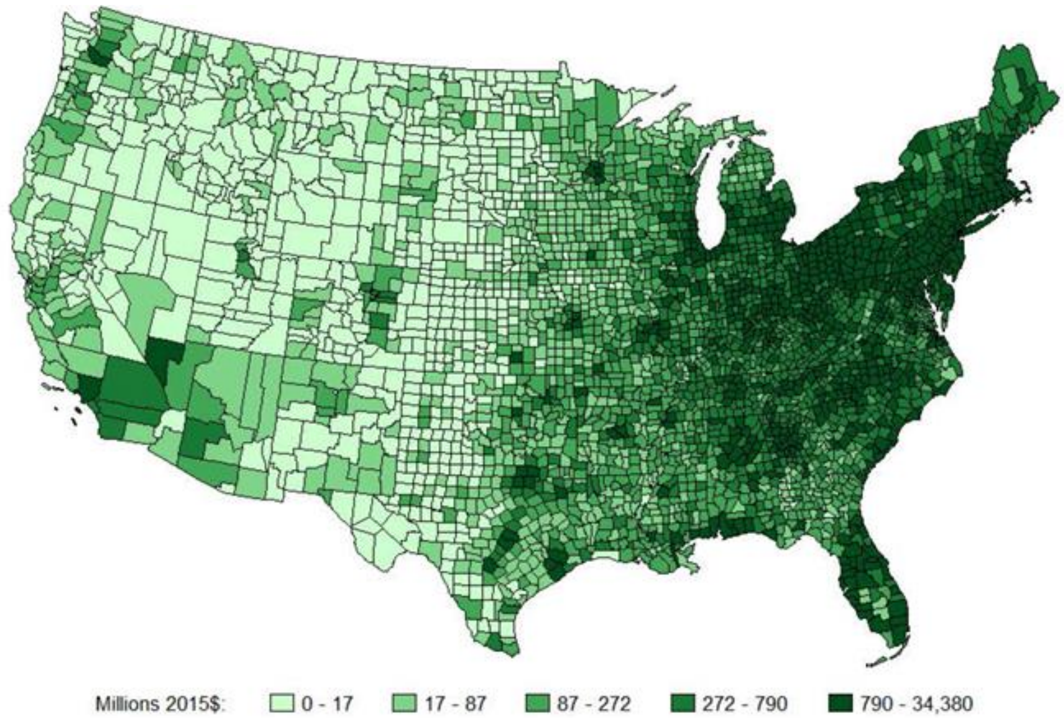


FIGURE 8. DISTRIBUTION OF BENEFITS ASSOCIATED WITH ONROAD SECTOR EMISSIONS REDUCTIONS - HIGH END BENEFITS IN 2030

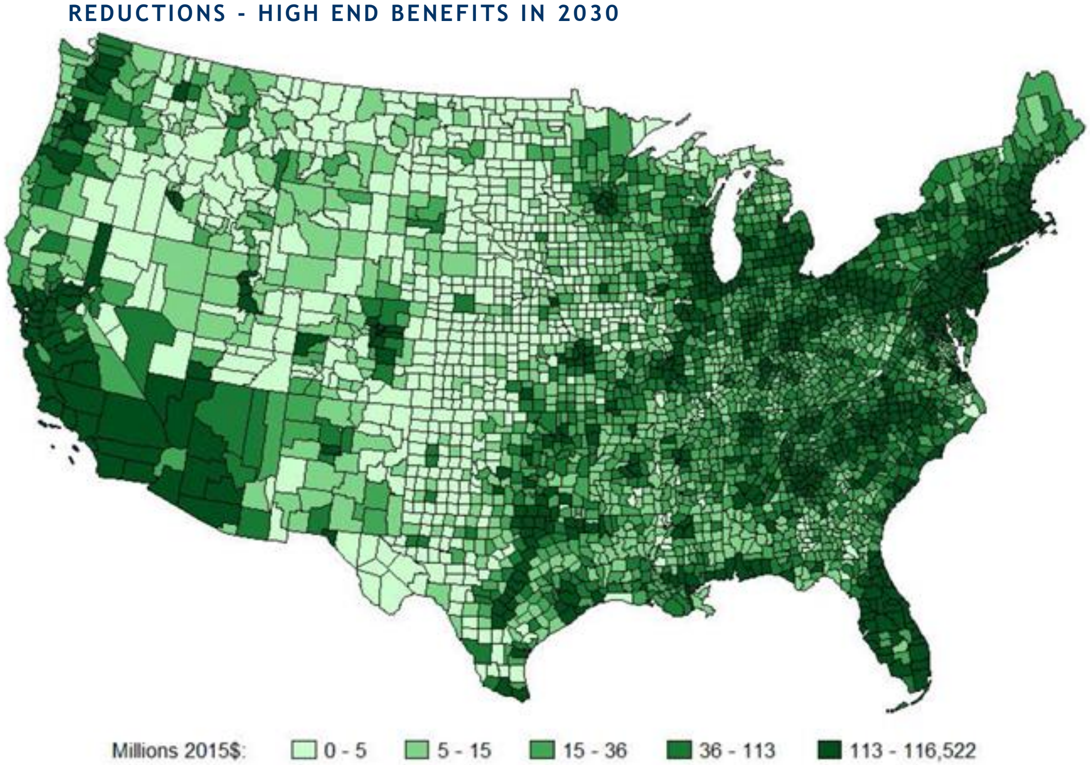
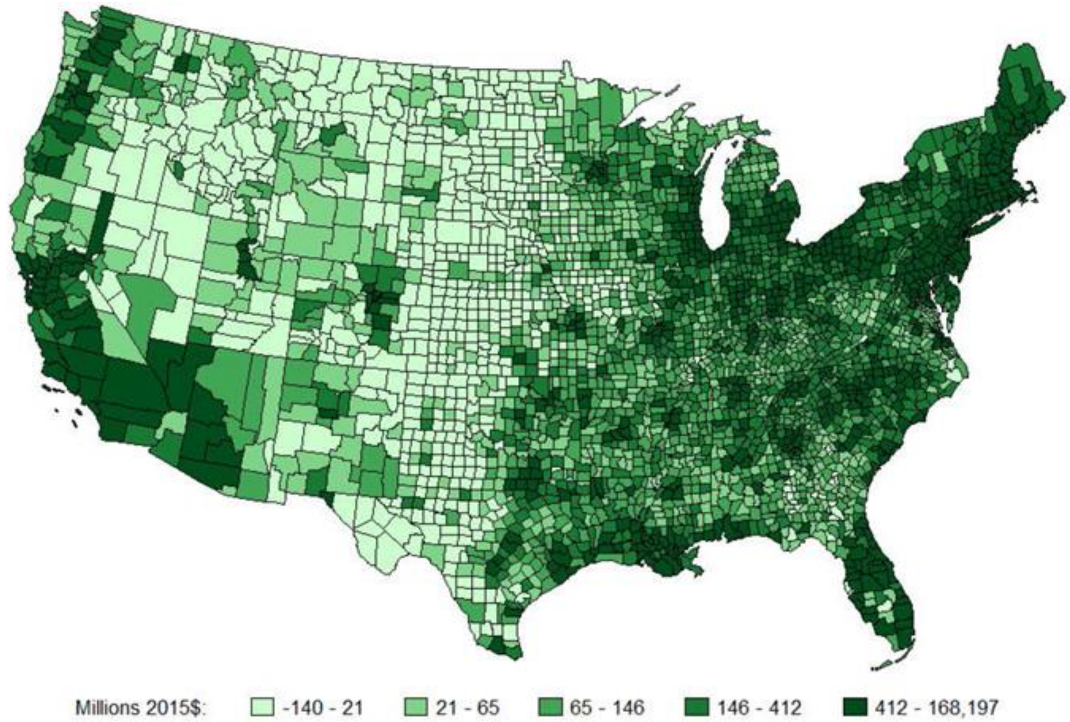


FIGURE 9. DISTRIBUTION OF BENEFITS ASSOCIATED WITH EMISSIONS REDUCTIONS FROM NON-EGU POINT SOURCES, NONPOINT SOURCES, AND NONROAD ENGINES - HIGH END BENEFITS IN 2030



Figures 10 and 11 display the spatial distribution of benefits separately for benefits related to avoided premature mortality and benefits associated with avoided morbidity, respectively. Overall, the distribution of these benefits mirrors the distribution of total benefits shown in Figure 6.

FIGURE 10. DISTRIBUTION OF BENEFITS RELATED TO AVOIDED PREMATURE MORTALITY - HIGH END BENEFITS 2030

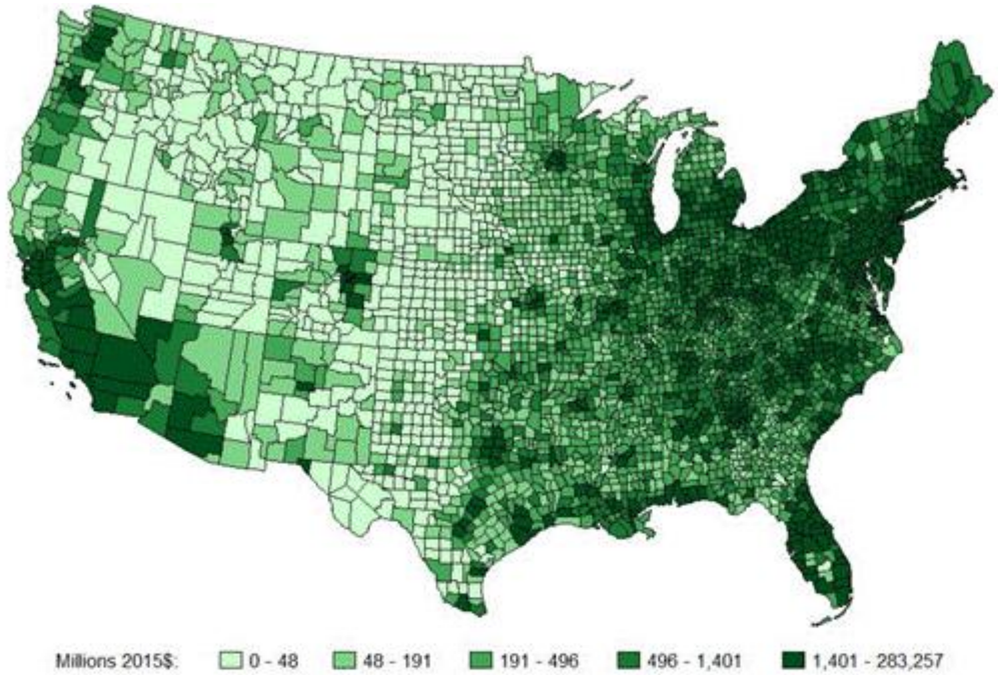
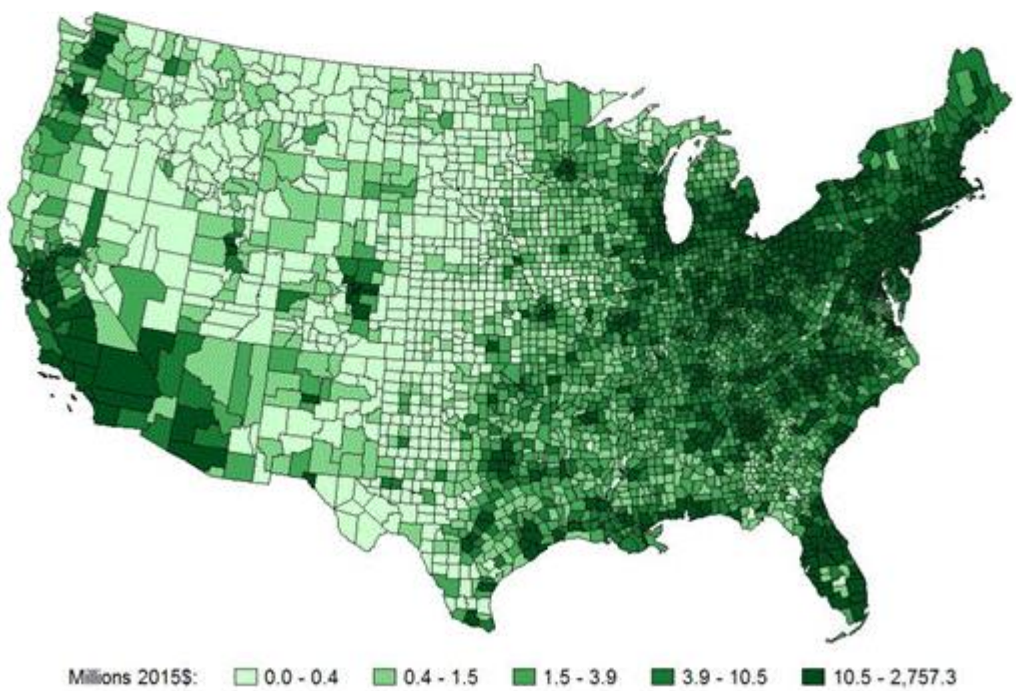


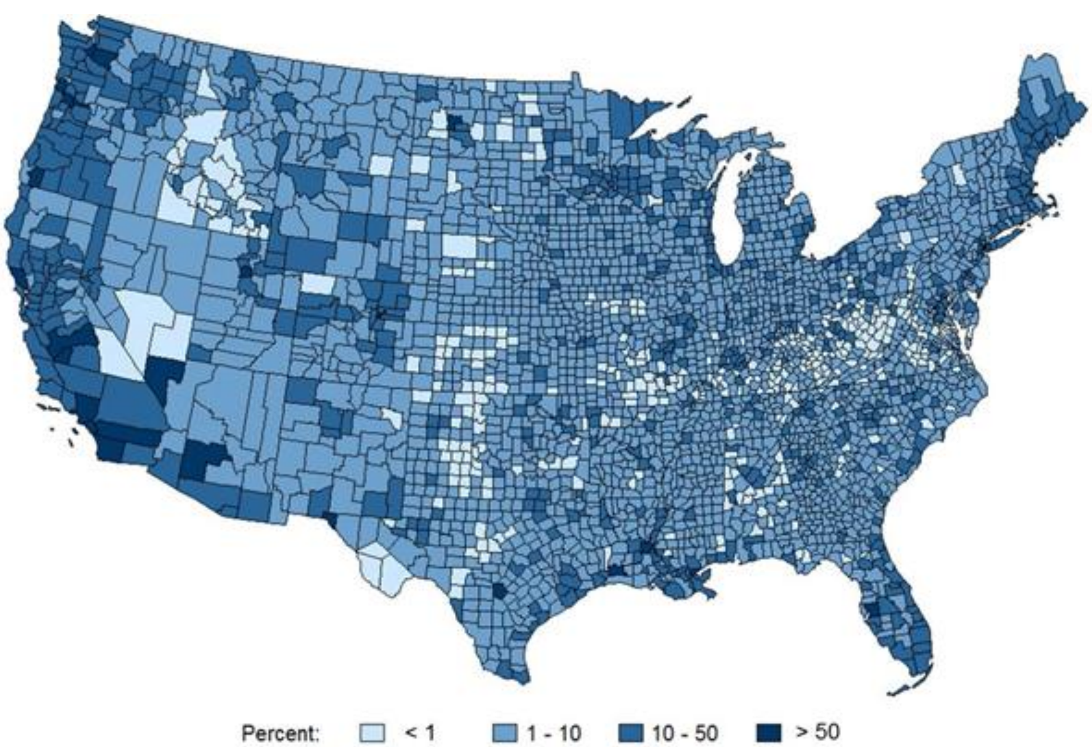
FIGURE 11. DISTRIBUTION OF BENEFITS RELATED TO AVOIDED MORBIDITY - HIGH END BENEFITS 2030



To provide insights into the importance of pollutant transport for a given county's benefits, Figure 12 shows the percentage of each county's high-end benefits in 2030 attributable to emissions reductions achieved within that county itself. As shown in the figure, within-county emissions reductions account for less than 10 percent of benefits in most counties across the contiguous U.S. Thus, the vast majority of the benefits realized in most counties are due to reductions in pollutant transport. This highlights the importance of controlling emissions not just in major population centers but also upwind from these areas. The results in Figure 12 also illustrate that the transport of air pollutants is not constrained by county or state boundaries and that the national policies implemented under the Clean Air Act Amendments are critical to maintaining or achieving clean air in any given local area.

Figure 12 also indicates that within-county emissions reductions make up a relatively large portion of benefits on the west coast and the Florida peninsula (i.e., Florida excluding the panhandle). Because of their location and the direction of the prevailing winds, neither the west coast nor the Florida peninsula are located downwind from significant sources of emissions. With prevailing winds coming from the west, both areas are typically downwind from the open sea. In addition, with the California coastal ranges and the Cascades hindering the transport of local air pollution eastward, a larger portion of emissions released on the west coast remain in the local area.

FIGURE 12. PERCENTAGE OF COUNTY-LEVEL BENEFITS ATTRIBUTABLE TO WITHIN-COUNTY EMISSIONS REDUCTIONS – HIGH END ANNUAL BENEFITS IN 2030



The monetized benefits presented above reflect significant improvements in human health associated with reduced air pollutant exposure. As air quality improves due to Clean Air Act policies, the incidence of several adverse pollution-related health effects will decline. Table 11 presents the policy-related reduction in incidence of these effects for the years 2020 and 2030. As shown in the table, we estimate that policies implemented pursuant to the Clean Air Act Amendments will prevent 185,000 to 370,000 premature deaths in 2020 and 229,000 to 457,000 premature deaths in 2030. The low end of these ranges reflects the PM-mortality and ozone-mortality relationships estimated in Krewski et al. (2009) and Smith et al. (2009), respectively, while the high end reflects the corresponding relationships estimated by Lepeule et al. (2012) for $PM_{2.5}$ and Zanobetti and Schwartz (2008) for ozone. The estimated number of avoided deaths in 2020 is approximately 12 to 24 percent of the total mortality from the top four causes of non-accidental death in the U.S. in 2015: heart disease (more than 633,000), cancer (more than 595,000), chronic lower respiratory disease (more than 155,000), and stroke (more than 140,000).[36]

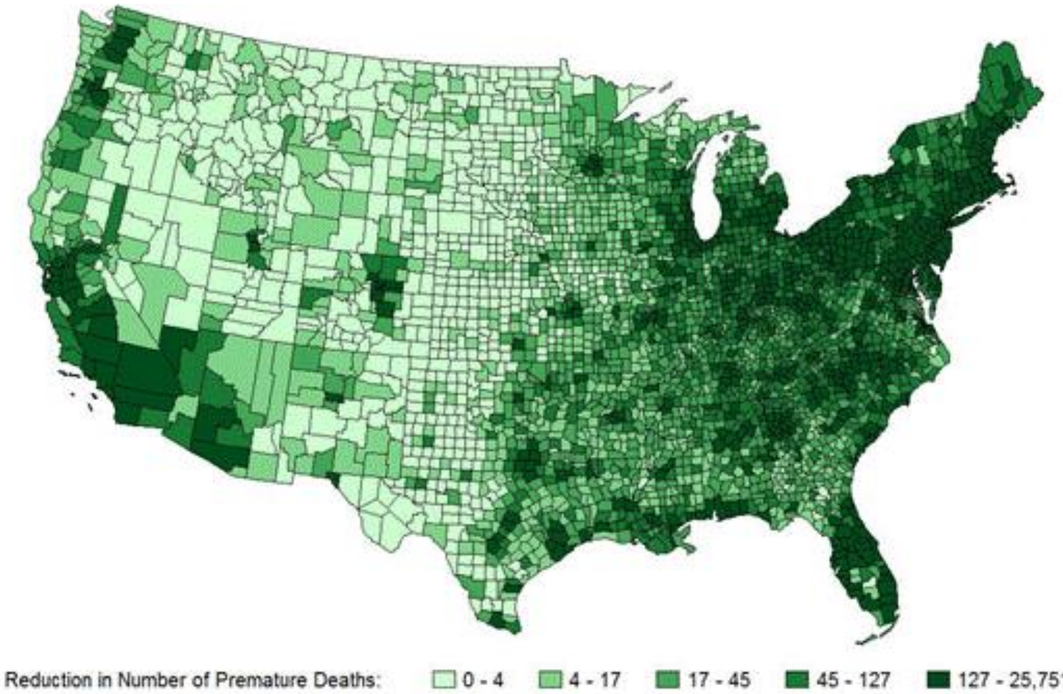
TABLE 11. REDUCED INCIDENCE OF ADVERSE HEALTH EFFECTS REALIZED IN 2020 AND 2030

HEALTH EFFECT	2020	2030
Premature Mortality - Low	185,000	229,000
Premature Mortality - High	370,000	457,000
Non-fatal Heart Attacks	46,300	54,600
Hospital Admissions - Cardiac	151,000	177,000
Hospital Admissions - Respiratory	38,300	45,200
Acute Respiratory Symptoms	147,000,000	175,000,000
Upper Respiratory Symptoms	2,630,000	3,130,000
Lower Respiratory Symptoms	2,480,000	2,950,000
Asthma Exacerbations	55,800,000	67,100,000
ER Visits Asthma	119,000	141,000
Work Loss Days	21,900,000	26,000,000
School Loss Days	8,290,000	10,100,000
All values rounded to three significant figures.		

Figure 13 shows the reduced incidence of premature mortality by county in 2030 under the high-end assumptions specified above. Similar to the figures above, the counties in Figure 13 are grouped into quintiles, based on the reduction in premature mortality in each county. As indicated in the figure, county-level reductions in premature mortality are generally higher in the eastern U.S. and in California than in other parts of the U.S.

[36] For 2015 mortality data, see Murphy et al. (2017).

FIGURE 13. AVOIDED PREMATURE MORTALITY BY COUNTY - HIGH END BENEFITS 2030



Sensitivity Analysis - Value of a Statistical Life

The health benefits presented above largely reflect avoided cases of premature mortality associated with exposure to $PM_{2.5}$ and ozone. To value avoided mortality, this analysis applies the value of a statistical life (VSL), consistent with the practice of EPA and other federal agencies. The VSL estimate that we use is the same as that applied by EPA in its regulatory impact analyses, adjusting for inflation and changes in income over time. Because the benefits estimates presented above are highly dependent on the choice of VSL, we also conducted a sensitivity analysis in which we applied alternative VSL estimates. More specifically, drawing on the VSL range reported in the review of the VSL literature in Robinson and Hammitt (2015), We estimated year 2020 benefits using alternative VSL estimates of $4.5 million and $14.7 million and year 2030 benefits based on VSL estimates of $4.8 million and $15.5 million. The range of values reported in Robinson and Hammitt (2015) reflects their selection of studies meeting a variety of quality criteria.

Table 12 presents the health benefits of the Amendments based on these alterative VSL estimates and for reference also shows the primary benefits estimates presented above. For both 2020 and 2030, the benefits estimates based on the low VSL value are approximately 56 percent less than our primary estimates, while the values based on the high VSL estimates are 40 percent greater than the primary estimates.

TABLE 12. HEALTH BENEFITS UNDER ALTERNTAIVE VSL ASSUMPTIONS

VSL SCENARIO	2020		2030	
	VSL (MN 2015$)	HEALTH BENEFITS (BN 2015$)	VSL (MN 2015$)	HEALTH BENEFITS (BN 2015$)
Low	*$4.5*	*$869 - $1,698*	*$4.8*	*$1,142 - $2,236*
Primary Estimate	**$10.4**	**$1,962 - $3,879**	**$11**	**$2,563 - $5,070**
High	*$14.7*	*$2,759 - $5,468*	*$15.5*	*$3,594 - $7,127*

BENEFITS OF REDUCED GHG EMISSIONS

In addition to the health benefits described above related to reduced criteria pollutant emissions, policies implemented under the Clean Air Act Amendments will lead to benefits associated with reduced GHG emissions. Due to their radiative properties, reductions in both CO_2 and CH_4 emissions will mitigate the adverse impacts of climate change, such as sea level rise, increased storm intensity, longer and more severe droughts, etc. In addition, the oxidation of CH_4 in the atmosphere contributes to the formation of tropospheric ozone, which (as described above) leads to a variety of adverse health impacts.

To estimate the benefits of reduced GHG emissions, we rely on published estimates of the social cost of CO_2 (SCC), the social cost of CH_4 (excluding ozone impacts), and the ozone impacts of CH_4. For the SCC, we apply the Interagency Working Group on the Social Cost of Greenhouse Gases' (2016) central SCC estimates, which are roughly $47 per metric ton of CO_2 in 2020 and $57 per metric ton in 2030.[37] For the social cost of CH_4 (excluding ozone impacts), we rely on findings from Marten et al. (2015) and apply a social cost of $1,356 per metric ton of CH_4 for both 2020 and 2030.[38] To monetize the ozone impacts of CH_4 emissions, we apply results from Sarofim et al. (2015), who estimated an impact of $841 per metric ton of methane (adjusted for inflation) in 2020.

Table 13 presents the estimated benefits associated with the GHG reductions achieved in 2020 and 2030. Reductions in CO_2 emissions account for most of these benefits in both years. In addition, we note that the GHG benefits presented in Table 13 are underestimates of the actual GHG benefits associated with the 1990 Clean Air Act Amendments, as GHG reduction data were not available for many of the rulemakings developed in the 1990s and early 2000s.

[37] The estimates published by the Interagency Working Group on the Social Cost of Greenhouse Gases (2016) reflect the results of three highly respected Integrated Assessment Models: the Dynamic Integrated Climate-Economy Model (DICE), the Climate Framework for Uncertainty, Negotiation and Distribution (FUND), and the Policy Analysis of the Greenhouse Effect (PAGE) model. Based on these models, the Interagency Working Group published mean estimates of the cost per metric ton of CO2 based on discount rates of 2.5 percent, 3 percent, and 5 percent.

[38] Marten et al. (2015) adapted the social cost of CO_2 framework to estimate the social cost of CH_4 and N_2O. Based on the study's results, we apply a social cost of $1,356 per metric ton of CH_4, assuming a discount rate of 3 percent and adjusting for inflation. This value reflects Marten et al.'s published estimate for 2020, which we use for both 2020 and 2030.

TABLE 13. BENEFITS OF REDUCED GREENHOUSE GAS EMISSIONS (BILLIONS OF $2015)

GREENHOUS GAS	2020	2030
CO2	$18.2	$58.4
CH4 - climate impacts	$1.6	$3.0
CH4 - ozone impacts	$1.0	$1.8
Total	**$20.8**	**$63.2**

ESTIMATION OF COSTS

Similar to our assessment of the emissions reductions associated with Clean Air Act regulations, we estimated the costs of these regulations separately for the rules included in the EPA CAAA study and the additional rules identified in Table 1. In both cases, we estimated costs for the years 2020 and 2030. For the regulations included in the EPA CAAA study, we used the year 2020 costs as reported in the study and adjusted for inflation using the GPD implicit price deflator. To estimate the costs of these rules in 2030, we applied growth factors to the year 2020 costs for each source category, similar to the growth factors used to project emissions. Our specification of these growth factors, by source category, is as follows:

- ***Electricity Generating Units:*** We assume that costs between 2020 and 2030 grow in proportion to electricity demand, as projected in the AEO 2016.
- ***Onroad Vehicles and Fuels:*** For onroad fuel standards, we assume that costs change in proportion to motor vehicle fuel consumption. To project costs related to vehicle standards, we assume that costs between 2020 and 2030 grow in proportion to motor vehicle sales. Finally, for costs related to inspection and maintenance programs, we assume that costs grow in proportion to the size of the vehicle stock. Changes in fuel consumption, vehicle sales, and the vehicle stock were obtained from AEO 2016.
- ***Non-EGU Point Sources, Nonpoint Sources, and Nonroad Engines:*** For these three source categories, we assume that costs between 2020 and 2030 grow at the same rate as emissions reductions. As described above, however, growth in the emissions reductions for each of these source categories varies by pollutant. To avoid the underestimation of costs, we used the highest growth rate for each source category. For example, using the approach described above, we project that emissions reductions from nonpoint sources grow by 18 percent (VOCs) to 24 percent (NO_x) between 2020 and 2030 (see Table 3). To estimate the costs of nonpoint source controls in 2030, we assume that costs in 2030 are 24 percent higher than in 2020.
- ***Local Controls for NAAQS Compliance:*** As described above, we hold emissions reductions related to local controls adopted to achieve further progress toward compliance with the 8-hour ozone NAAQS and $PM_{2.5}$ NAAQS, and CAVR constant between 2020 and 2030. Consistent with this assumption, we assume that costs related to local controls in 2030 are the same as in 2020.

To estimate the costs of the rules finalized after development of the EPA CAAA study (i.e., the rules listed in Table 1), we relied on the cost information included in the RIA for each rule. The RIAs for each of the EGU and motor vehicle rules present costs for both 2020 and 2030. After adjusting for inflation, we used these estimates directly in our analysis. For the other rulemakings, we project costs to 2020 and 2030 using the same growth indicators that we used to project emissions. More specifically, our approach for these rulemakings was as follows:

- ***Oil and Natural Gas Industry Rules:*** For both the 2012 and 2016 rules, we project costs through 2030 based on the growth in the number of affected sources, as reported in the rule RIAs.
- ***Petroleum Refinery Rule***: Consistent with our approach for projecting the emissions reductions associated with the rule, we project the rule's costs to 2020 and 2030 by assuming that annual costs grow at the same rate as U.S. refinery throughput, as projected in AEO 2016.
- ***Industrial, Commercial, and Institutional Boiler Rule***: Consistent with our assumption that the annual emissions reductions associated with this rule remain constant from 2015 through 2030, we assume that the annual costs of the rule also remain flat during this period.

Based on the approach above, the estimated costs of regulations issued under the 1990 Clean Air Act Amendments were approximately $122 billion in 2020 and $162 billion in 2030, as shown in Table 14. As shown in the table, onroad vehicles account for the largest share of costs for both years, making up more than 50 percent of costs in 2020 and more than 60 percent in 2030. EGUs and local controls each represent between 15 and 20 percent of costs in both years.

TABLE 14. ESTIMATED COSTS OF CLEAN AIR ACT AMENDMENTS (MILLION 2015$)

SOURCE CATEGORY	2020	2030
EGUs	$24,017	$27,909
Non-EGU Point Sources	$7,696	$8,743
Onroad Vehicles	$64,447	$98,494
Nonroad Engines	$1,334	$1,652
Nonpoint Sources	$1,532	$2,165
Local Controls	$22,869	$22,869
TOTAL	**$121,895**	**$161,831**

For additional perspective on the costs of the Amendments, Table 15 shows the distribution of costs between the rulemakings reflected in the EPA CAAA study and the additional rules considered in this analysis incremental to those in the EPA study (as summarized above in Table 1). As shown in the table, the rules reflected in the EPA CAAA study are projected to account for more than 60 percent of CAAA compliance costs in 2020. In 2030, however, the additional rules that this analysis examines incremental to those reflected in the EPA CAAA study are projected to make up more than 50 percent of compliance costs, while the rules included in the EPA study are projected to account for slightly less than half of compliance costs. This increase in the share of costs associated with rulemakings not reflected in the EPA CAAA study largely reflects the costs of rules affecting onroad vehicles, in particular the light-duty vehicle CAFE standards for model years 2017-2025.

TABLE 15. DISTRIBUTION OF CAAA COSTS BETWEEN RULES REFLECTED IN EPA CAAA STUDY AND ADDITIONAL RULEMAKINGS (MILLION 2015$)

	2020	2030
Rules Reflected in EPA CAAA Study	$75,971	$77,936
Rules Incremental to EPA CAAA Study	$45,924	$83,895
TOTAL	**$121,895**	**$161,831**

In addition to the costs shown in Tables 14 and 15, many Clean Air Act rulemakings finalized after the development of EPA's benefit-cost analysis of the Amendments are expected to result in costs savings associated with avoided fuel consumption or, in the case of oil and gas sector rules, product recovery. To avoid the appearance of under-estimating costs, we do not include these impacts in our primary cost estimates; however, we do note that these savings amount to an estimated $59.4 billion in 2020 and $231.0 billion in 2030.. In 2030, these savings would more than offset the estimated costs of the Clean Air Act Amendments as presented above in Table 14.

COMPARISON OF BENEFITS AND COSTS

Drawing on the results presented in previous sections, Table 16 presents the estimated benefits, costs, and net benefits (benefits minus costs) associated with policies implemented under the 1990 Clean Air Act Amendments. Overall, the table shows that the Amendments yield significant net benefits to society, ranging from $1.9 trillion to $3.8 trillion in 2020 and $2.5 trillion to $5.0 trillion in 2030, excluding avoided costs associated with fuel savings and natural gas recovery. The differences between the low end and high end of each range reflect the alternative assumptions regarding the mortality impacts of $PM_{2.5}$ and ozone, as described above. In proportional terms, the benefits of the Amendments exceed the costs by a factor of 16 under the low benefits assumptions and by a factor of 32 when applying high benefits assumptions.

TABLE 16. BENEFITS, COSTS, AND NET BENEFITS OF CLEAN AIR ACT POLICIES (BILLIONS $2015)

	2020		2030	
	LOW	HIGH	LOW	HIGH
Benefits	**$1,983.0**	**$3,899.6**	**$2,626.0**	**$5,133.1**
Criteria Pollutants - Avoided Mortality	$1,927.4	$3,844.0	$2,521.3	$5,028.3
Criteria Pollutants - Avoided Morbidity	$34.9	$34.9	$41.6	$41.6
Greenhouse Gases - Avoided Impacts	$20.8	$20.8	$63.2	$63.2
Costs	**$121.9**	**$121.9**	**$161.8**	**$161.8**
EGUs	$24.0	$24.0	$27.9	$27.9
Non-EGU Point Sources	$7.7	$7.7	$8.7	$8.7
Onroad Vehicles	$64.4	$64.4	$98.5	$98.5
Nonroad Engines	$1.3	$1.3	$1.7	$1.7
Nonpoint Sources	$1.5	$1.5	$2.2	$2.2
Local Controls	$22.9	$22.9	$22.9	$22.9
Net Benefits	**$1,861.1**	**$3,777.7**	**$2,464.2**	**$4,971.3**
Fuel Savings & Natural Gas Recovery	$59.4	$59.4	$231.0	$231.0
Net Benefits (with fuel savings & natural gas recovery)	**$1,920.5**	**$3,837.1**	**$2,695.2**	**$5,202.3**

KEY LIMITATIONS AND UNCERTAINTIES

While this study provides robust evidence of the net benefits associated with the 1990 Clean Air Act Amendments, we note the following uncertainties and their implications for the estimation of net benefits:

- ***Exclusion of some rulemakings:*** As described in the Scenario Definition section above, this analysis reflects all rulemakings included in EPA's 2011 benefit-cost analysis of the Clean Air Act Amendments plus most major air rules finalized after the cutoff data for inclusion in the study. Therefore, a number of rules, most of which are relatively minor, are not reflected in this analysis. This would suggest that this analysis underestimates both the costs and benefits of the CAAA.
- ***Multiple categories of criteria pollutant benefits not estimated:*** Focusing on human health benefits, this analysis does not capture a variety of benefits associated with reduced criteria pollutant emissions, including improved productivity for agricultural crops and commercial timber, visibility improvements in recreational and residential areas, avoided degradation of buildings constructed with acid-sensitive materials, and reduced acid deposition.

- **No treatment of potential health benefits related to reductions in organic aerosols:** A recent paper by Heald et al. (2018) in the Proceedings of the National Academy of Sciences estimates that policies implemented under the 1990 Clean Air Act Amendments averted 180,000 premature deaths between 1990 and 2012 due to reduced atmospheric concentrations of organic aerosols. This effect is not reflected in this analysis or in prior analyses conducted by EPA. To the extent that this finding related to the Amendments' impact on organic aerosols is robust, this analysis underestimates the benefits of the Amendments.
- ***No assessment of benefits related to reduced air toxics emissions:*** The assessment of health benefits included in this analysis reflects reduced emissions of SO_2, NO_x, $PM_{2.5}$, and VOCs. However, pursuant to Title III of the Amendments, EPA has also established multiple regulations to limit air toxics emissions. While the costs of many of these rules (i.e., those included in the EPA CAAA study) are reflected in the cost estimates presented above, we did not quantify or monetize the benefits of reduced air toxics emissions. All else equal, this would suggest that we underestimate the benefits of the CAAA.
- ***Incomplete treatment of GHG benefits:*** Because GHG emissions data was available only for a portion of the rules included in this analysis, the GHG-related benefits presented above are likely under-estimates of such benefits.
- ***Treatment of fuel cost savings and product recovery:*** To avoid the potential underestimation of costs, the net benefits estimates presented above do not reflect the avoided costs resulting from several rules developed in recent years. These avoided costs reflect reductions in fuel consumption due to motor vehicle fuel efficiency improvements and the product recovery cost savings associated with emissions controls in the oil and gas sector (e.g., recovered methane). By excluding these cost savings from the analysis, we likely underestimate net benefits.
- ***No changes in emissions reductions or costs associated with local controls for NAAQS compliance post-2020:*** As described above, this analysis holds both the emissions reductions and costs associated with local controls implemented for NAAQS compliance constant at 2020 levels through 2030, due to uncertainty regarding local controls required after 2020. This assumption likely leads to underestimation of both costs and benefits, as many local areas would likely be required to implement further controls post-2020 pursuant to the Clean Air Act's Reasonable Further Progress (RFP) requirements.

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