Updated Evaluation of the National Health Benefits from the Transition to Zero-Emission Transportation Technologies

American Lung Association

Final Report, March 4, 2022

American Lung Association.

ICF

Table of Contents

Updated Evaluation of National Health Benefits from the Transition to Zero Emission Transportation Technologies

Seth Hartley, Anna Belova, Tyler LaBerge, Paola Massoli, Mike McQueen, Kate Munson, Sam Pournazeri, Ajo Rabemiarisoa, Matt Townley, Fiona Wissell
ICF

4 March 2022

Contact:
Seth Hartley
Senior Air Quality Consultant
+1 (415) 677 7164 main
Seth.Hartley@icf.com

1. Executive Summary

Electric vehicles produce fewer emissions that contribute to climate change and smog than conventionally fueled vehicles.[1] As recently as 2018, transportation was responsible for about 28% of the nation's greenhouse gas emissions.[2] Direct emissions from on-road vehicles alone were responsible for accounting for about 33% of the nation's total nitrogen oxides and about 13% of its emissions of volatile organic species, together the primary contributors to smog, about 39% of the nation's emissions of carbon monoxide, and about 3% of the nation's primary emissions of fine particulate matter.[3] More than 45 million people in the U.S. live within 300 feet of a major transportation facility such as a busy roadway, and thus bear the increased exposure risk from traffic-related air pollution. Such adverse health effects may include asthma, cardiovascular disease, and premature death.[4] Vehicle electrification has the potential to signifcantly reduce air pollutant emissions, improve air quality, slow climate change, and reduce the public health burden associated with exposure to vehicular emissions.

In 2020, ICF conducted a comprehensive analysis for the American Lung Association[5] of the potential health and climate benefits of a scenario for increasing on-road vehicle electrification across the United States. ICF's analysis was the basis for the Lung Association's Road to Clean Air report.[6] The electrification scenario analyzed in that report included both light- and heavy-duty vehicles and both

- *downstream* (tailpipe exhaust, evaporative, brake and tire wear) and

---

1 US Department of Energy, Reducing Pollution with Electric Vehicles (2020). https://www.energy.gov/eere/electricvehicles/reducing-pollution-electric-vehicles.
2 US EPA, Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2018 (2020). https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2018.
3 US EPA, National Annual Emissions Trends: Criteria pollutants National Tier 1 for 1970 – 2019 (2020). https://www.epa.gov/air-emissions-inventories/air-pollutant-emissions-trends-data. All are relative to national totals from all sources excluding wildfires.
4 US EPA, Research on Near Roadway and Other Near Source Air Pollution (2020). https://www.epa.gov/air-research/research-near-roadway-and-other-near-source-air-pollution.
5 https://www.lung.org/getmedia/b9efc73e-aeba-4cd8-b789- 942166c38ca6/ev_technical_documentation.pdf
6 https://www.lung.org/clean-air/electric-vehicle-report

- *upstream* (reduced fuel production, transport, and refining activities for internal combustion vehicles and increased electricity generation for electric vehicles)

emissions components along with two potential Cases for the nation's future electricity production. It presented results for both a short-term (2030) and long-term (2050) projection years including the emissions that could be avoided and resulting public health and climate benefits from these reduced emissions. The Scenario was considered aggressive but realistic in terms of both upstream generation and vehicle adoption. It did not consider cumulative impacts, nor did it address any potential disparities in exposure burden that may be addressed through such a transition.

Since the report's release, electric vehicles (EV) and other zero emission vehicle (ZEV) technology have continued to gain market share in the U.S. For example, in 2021:[7]

- President Biden and major automakers had set a target of 50 percent EV sales by 2030.
- Five states had adopted the California Advanced Clean Truck (ACT) rule – MA, NY, OR, WA, and NJ, while others had begun public proceedings.
- The infrastructure bill became law, allocating more than $30 billion in EV related funding including $7.7 billion in dedicated funding.
- Utilities and automakers continued to invest in EVs. In Q3 utilities proposed $781 million in EV investments, twice the amount of Q1 and Q2 combined. Automakers have announced investments of $108 billion for EVs in the US.
- By 2021 Q3, EVs comprised 5 percent of all light duty sales, more than doubling the sales rate from 2020.
- New EV models continued to come on-line, notably including Ford's F-150 Lightning, the electric version of the most popular new and used vehicle sold in the country last year.

The impacts of air pollution and the potential for EVs to address it are receiving substantial attention, with the disparate impacts of the air pollution burden as a recent focus of EV programs. The Biden Administration's original proposal included grants to electrify 20 percent of all school buses and $20B to transportation projects in underserved communities, while its latest Justice40 Initiative draft guidance specifies that at least 40 percent of the benefits from federal energy and environmental spending reach disadvantaged communities.[8] CA continues to dedicate more than half of the California Climate Investments (CCI) program funded through Cap-and-Trade to underserved communities. CO, NY, and NJ have recently prioritized transportation electrification investment to projects enhancing environmental justice.[9] Reducing electricity generating emissions are another critical component to realizing the benefits of EVs. President Biden's proposal for a clean electricity standard would require utilities to meet goals of 80 percent clean electricity by 2030 and 100% by 2035, where clean is defined as renewable or emissions-free power, including nuclear.[10]

This report documents an updated analysis of the potential benefits of a nationwide EV Scenario. This analysis modernizes the findings from the 2020 study to address current trends and available data. Some of the key changes include:

- More aggressive adoption of EVs, including 100 percent ZEV[11] passenger sales by 2035 and more aggressive ZEV truck sales, roughly in line with the final ACT.
- A simplified vehicle scheme that tracks the impacts of light duty and heavy-duty vehicles separately.

7 Based in part on a summary published January 3, 2022 by EV Hub, "8 Big EV Stories from 2021".
8 E&E News: White House details environmental justice plans, Adam Aton, 07/20/2021.
9 EV Hub, April 5, 2021
10 E&E News: Clean electricity standard carries $1.8T upside — study, Miranda Willson, 07/12/2021.
11 As with the 2020 study, the scope of this analysis was determined to focus exclusively on battery electric vehicles (BEV) as a marker for all ZEVs. This is discussed in Section 3.

- Consideration of a more aggressive transition to renewables on the electric grid, with accelerated retirement of coal and the dramatic push to renewables. The reduced emissions and resulting benefits to human health also apply to the base load on the grid, not only that related to the additional load from new EVs, emphasizing the potential benefits of a cleaner electric grid. The non-combustion electricity case was determined through an optimization modeling approach using ICF's IPM model.
- Modernization of all modeling tools, including the latest version of the COBRA, GREET, and MOVES models. COBRA version 4.0 includes updates to default emissions and sources that account for air quality policymaking through 2018. MOVES3 represents EPA's current estimate and projection of the US vehicle fleet and its emissions. GREET2021 is Argonne National Laboratory's current approach for simulating lifecycle emissions output of vehicle/fuel systems.
- Updated function for avoided mortality estimates are updated to those in the latest version of EPA's BenMAP model, reflecting current understanding of the health impacts of pollution.
- Cumulative health and climate benefits are estimated from the simulated years to illustrate the total impact of changes over the entire period considered (2020-2050).
- Including an analysis of demographic-specific impacts to provide insight into the effects of emissions scenarios on people of color.

Our approach and results are documented in the following sections of this report:

- Section 3 describes the analysis of national-scale, business-as-usual (BAU), on-road vehicle population, engine technology, age distribution, and emissions and our approach to determine the vehicle fleet under our aggressive but achievable vehicle electrification Scenario.
- Section 4 discusses the national level emissions and emission changes resulting from implementation of the vehicle electrification scenario, including both upstream and downstream emissions and two potential Cases for upstream electricity generation associated with the Scenario.
- Section 5 describes the results and approach taken to quantify and monetize the change in adverse health outcomes resulting from air quality changes under the scenario.
- Section 6 summarizes and monetizes the climate benefits anticipated due to reductions in greenhouse gas (GHG) emissions from the vehicle electrification scenario.

Our modeling of the baseline and BAU national vehicle fleet, its related activity, fuel use, population, engine technology, age distribution, and downstream emissions relied on national default values from US EPA's MOVES3 emission model. We simulated emissions of:

- Volatile organic compounds (VOC),
- Oxides of nitrogen (NOx),
- Fine particulate matter less than 2.5 μm in size ($PM_{2.5}$),
- Sulfur dioxide (SO_2),[12]
- Ammonia (NH_3),

These are the criteria pollutants, and precursors for secondary PM, included to capture benefits in health modeling from both directly emitted PM pollution and that formed in the atmosphere. We also modeled emissions of

- GHGs, characterized as CO_2-equivalent (CO_2e).

This study directly models the calendar years:

12 In this analysis, SO_2 and SOx are considered identical.

- 2020,
- 2030,
- 2040, and
- 2050

The US vehicle fleet is grouped into four vehicle categories for analysis:

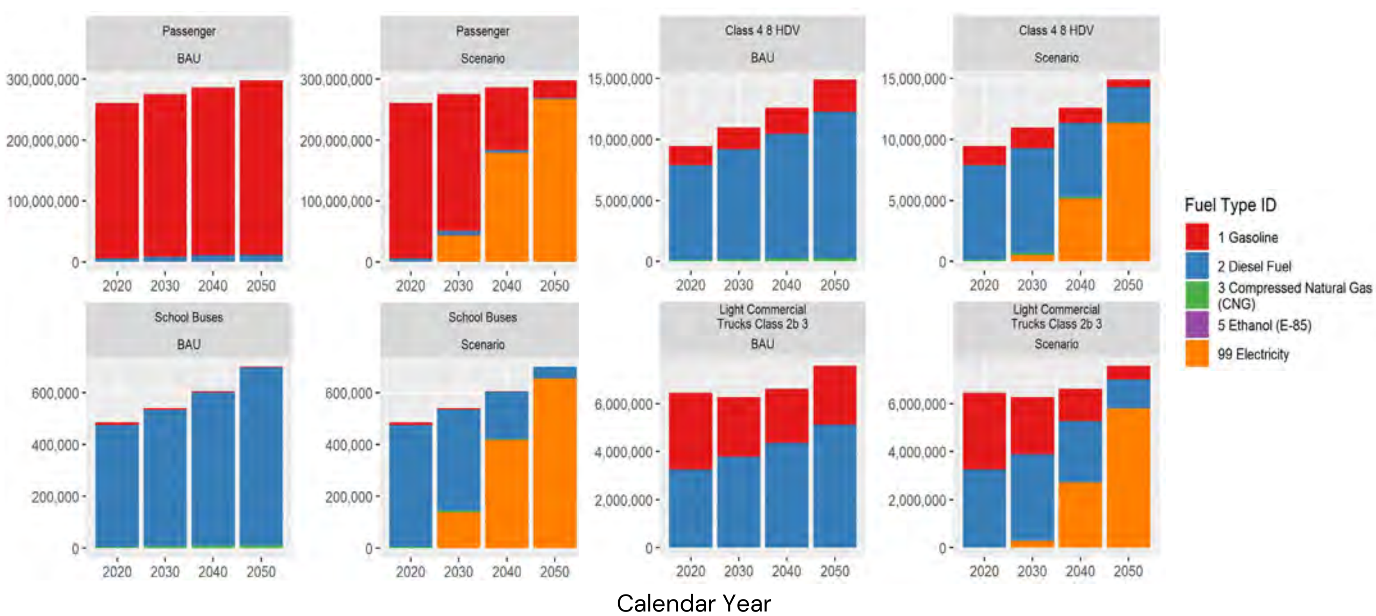
- Passenger vehicles,
- Light heavy-duty trucks,
- Medium-heavy and heavy-trucks, and
- School buses

The aggressive but achievable vehicle electrification Scenario assumes 100 percent sales penetration for EVs by 2029 for school buses, 2035 for passenger vehicles, and 2040 for heavy-duty vehicles. These four categories are tracked through the emissions modeling, but aggregated into two vehicle classes:

- Light duty
- Heavy-duty, and
- Total

for determining the health benefits associated with each Class. Figure ES-1 illustrates how the sales rates listed above determine the population of EVs in the overall fleet. This figure shows the resulting vehicle populations by fuel type and vehicle category under the BAU and vehicle electrification Scenario, for the four modeled calendar years. (Note that sets are paired, with the BAU on the left and scenario on the right. So, the two panels in the top left show passenger vehicles, with the leftmost showing the BAU and the Scenario just to its right.)

Figure ES-1. Modeled vehicle populations in the four vehicle categories and five fuel types under the BAU and vehicle electrification Scenario



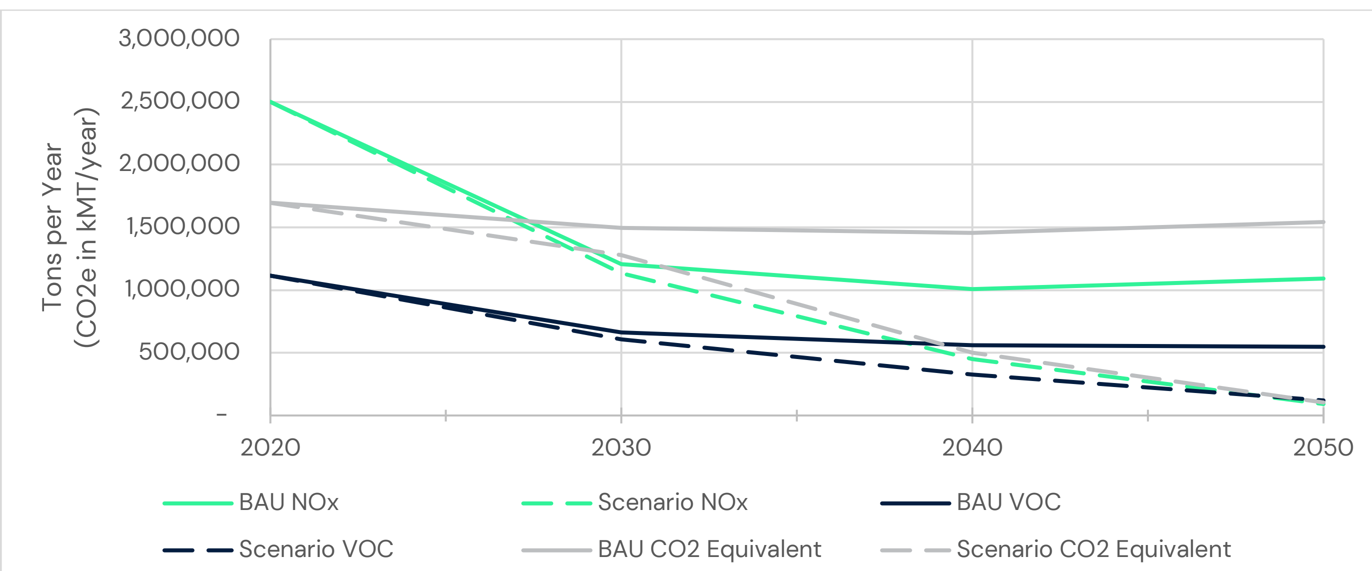
We assessed changes in emissions nationwide resulting from the electrification Scenario considering both downstream and upstream emissions components. Furthermore, we considered the implications of two potential Cases for future electricity production on the upstream emissions to the Scenario.

1. *The Base electricity generation Case*: A more business-as-usual projection for the grid, based on the Bloomberg New Energy Outlook (BNEO) 2019 analysis employed by the 2020 study.
2. *The Non-Combustion electricity generation Case*: A more ambitious renewables projection, with a heavy emphasis on emissions free, renewables, such as from wind and solar.

All analyses reflect national-scale simulations and rely on an average power approach. We do not assume that EV demand causes low carbon intensity electricity growth or implement an incremental approach to future electricity generation that pairs the increased demand with cleaner electricity only. However, the level of emissions associated with baseline and additional power load are coupled with the electric Case. Thus, the health benefits from the Non-Combustion Case also include benefits associated with cleaning the grid regardless of load changes due to EVs.

We calculated the reduction in direct (downstream) emissions of vehicular pollutants nationally for the BAU and vehicle electrification Scenario. Downstream emissions consider both tailpipe emissions and the ongoing contribution of brake and tire wear PM emissions, including for EVs. Comparing these shows national, downstream emissions are significantly lower under the Scenario than the BAU. In 2050, annual downstream emissions of NOx, VOC, and $PM_{2.5}$, and tailpipe GHG emissions (reported as CO_2e) are reduced below the values of a BAU scenario by approximately 1,000,000, 430,000, and 26,000, and 1.6 billion short tons, respectively. These values are 92, 78, 61, and 93 percent below the BAU levels of emissions, respectively. That is, while there is a general trend toward lower downstream criteria pollutant emissions (NOx and VOC) nationally, and a flat-to-increasing trend for and GHGs, under the BAU, the EV Scenario provides dramatic reductions over the modeled period. Figure ES-2 shows these trends for NOx, VOC, and CO_2e.

Figure ES-2. Trends in downstream emission for NOx, VOC, and CO_2e under the BAU and Scenario. All units are short tons per year except CO2e, shown in thousands of metric tons per year.



When combined with the change in upstream emissions, the total net change in emissions (domestic for criteria pollutants; global for GHGs) from combined upstream and downstream under the Non-Combustion

Case electrification show savings of 1,400,000, 830,000, 55,000, and 2.0 billion short tons per year by 2050 relative to the BAU values for NOx, VOC, and $PM_{2.5}$, GHG emissions, respectively.

Figure ES-3 shows the relative contribution of upstream and downstream emissions for the affected sectors modeled here, broadly electricity generation, fuels production, and vehicle use. These are total, national emissions for the sectors under the BAU and the EV Scenario, with the latter coupled to the two different approaches for upstream electrification. Note that the grid assumptions of each Case are applied to both new load from increased EVs and baseline load on the grid. The downstream differs between the BAU and Scenario but is identical between the two electrification Cases implementing the Scenario, so the only difference between the right two columns is the upstream electrification component. No calculation of the total upstream GHG emissions nationwide is made, so only downstream results are shown for CO_2e.

Figure ES-3. Emissions from up- and downstream components for each pollutant (downstream only for GHG) under the Base, Non-Combustion, and Non-Combustion for All Load electrification Case and the national BAU.

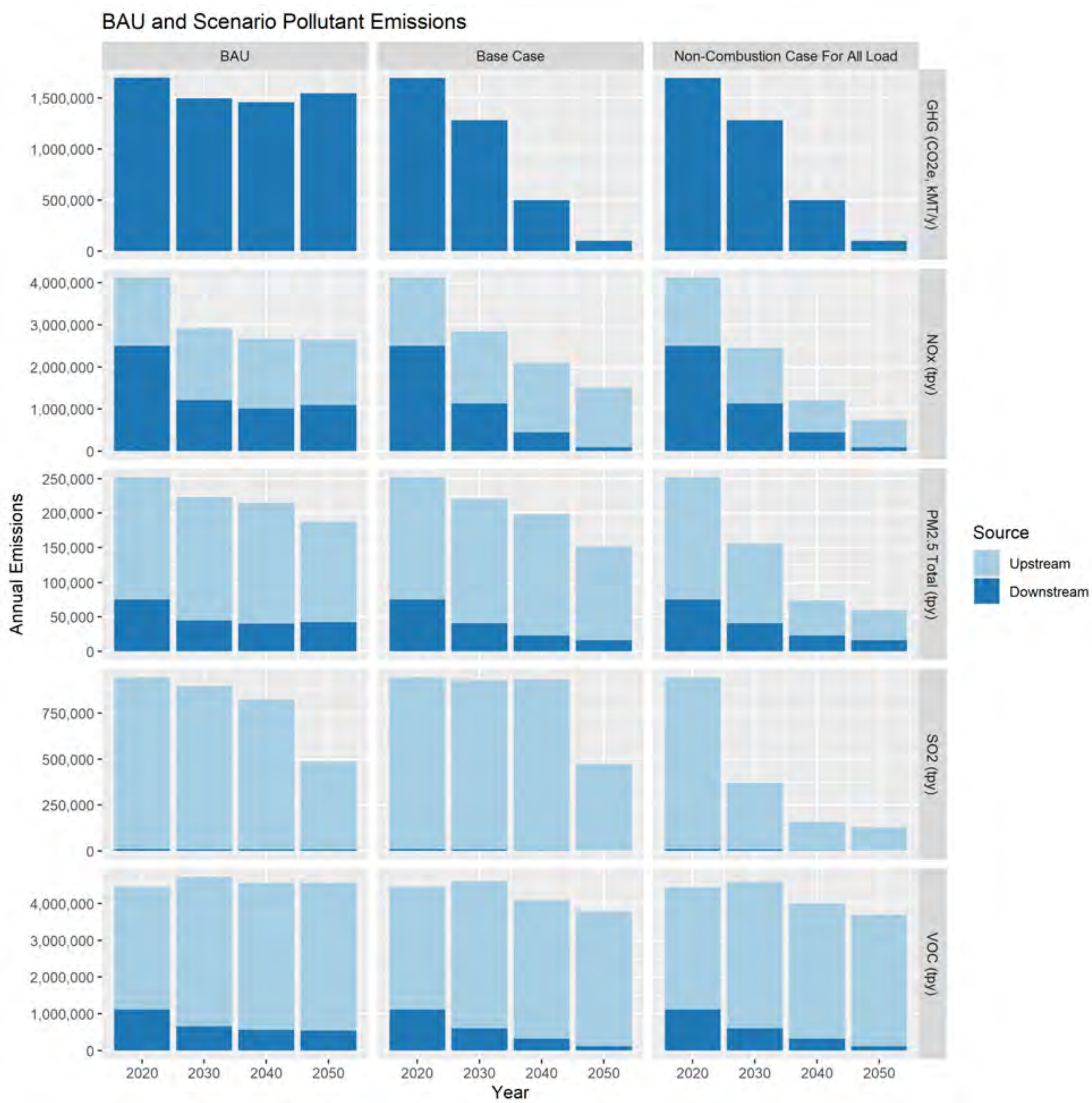
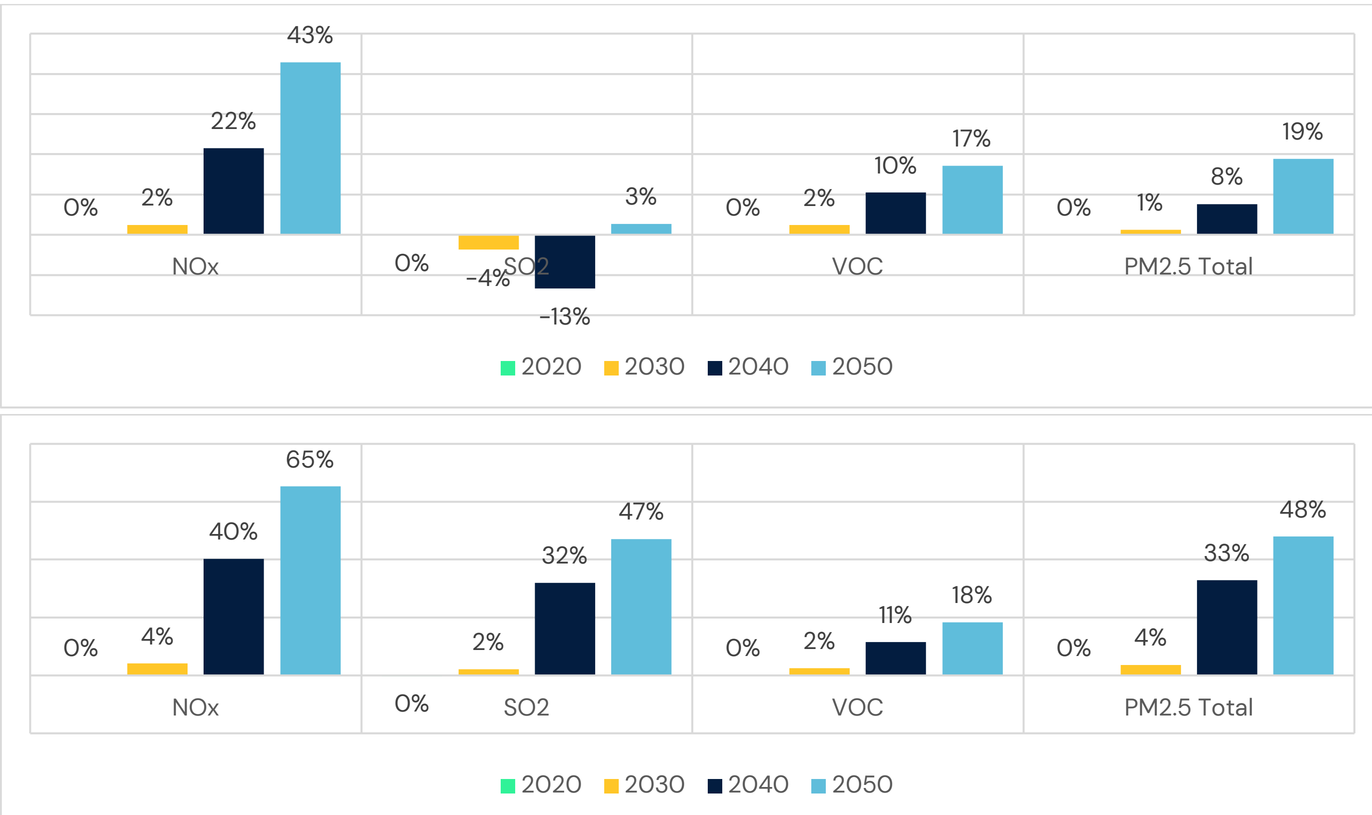


Figure ES-4 illustrates the relative reduction in total (up- and downstream), national emissions of criteria pollutants for the EV Scenario with the Base (top) and Non-Combustion (bottom) Cases. Under the Non-Combustion Case, total, national $PM_{2.5}$ is reduced 48 percent by 2050, or more than twice that of the 19 percent reduction seen in the Base Case. No pollutants show increases in national emissions in any year except SO_2 under the Base Case, which sees increases in emissions due to the new load on the relatively dirtier grid in the mid-term.

Figure ES-4. Relative reduction in emissions by pollutant between the national BAU and the EV Scenario with the Base Case (upper panel) and the Non-Combustion Case (lower panel) Reductions are for combined emissions (up- and downstream). Each set of bars represents different pollutants: NOx, SO_2, VOC, and $PM_{2.5}$. Bars in each set represent the four modeled years.



We then used these national-scale criteria pollutant emissions in EPA's COBRA model to evaluate the potential health benefits of the vehicle electrification Scenario. We quantified and monetized changes in the incidence of adverse health impacts resulting from reduced human exposure to downstream and upstream $PM_{2.5}$ emissions from the Scenario with both electrification Cases. We also determined the contributions to changes from both light- and heavy-duty vehicles and processed each through COBRA separately, as well as the total of all vehicles.

Employing a 3 percent discount, total monetized public health benefits range from approximately $4.5 million in 2020 to $33.1 billion in 2050 under the Base Case considering all vehicle classes. The same approach under the Non-Combustion Case shows benefits ranging from approximately $4.9 million in 2020 to $62.4 billion in 2050. Adult mortality is the main driver of benefits of emissions changes under all electricity generation and vehicle scenarios, with an estimated decrease in the number of premature deaths among adults between 2,650 and 2,830 under the 2050 Base Case and between 5,010 and 5,350 under the 2050 Non-Combustion Case.

We also postprocessed health benefits results from COBRA to show cumulative impacts of the proposed scenarios from 2020 to 2050. At a 3 percent discount, cumulative monetized public health benefits from 2020 to 2050 range from approximately $318 billion to $339 billion in the Base Case and total vehicles scenario. Under the Non-Combustion Case, cumulative benefits from 2020 to 2050 range from approximately $1.1 trillion to $1.2 trillion. Adult mortality is the main driver of monetized benefits from emissions changes under all electricity generation and vehicle scenarios, with an estimated decrease in the number of premature deaths among adults between 28,500 and 30,000 under the Base Case, considering all total vehicles, and between 105,000 and 110,000 under the Non-Combustion Case also considering all vehicles.

Under the Base electricity Case, the cumulative number of avoided adverse health effects is greater for the heavy-duty vehicle scenario compared to the light duty vehicles scenario. For example, estimates indicate between 11,600 and 12,200 avoided mortality cases under the Scenario for light duty vehicles with Base Case electrification and between 16,900 and 17,800 avoided mortality cases from heavy-duty vehicles with Base Case electrification. The difference between light- and heavy-duty avoided adverse health effects shrinks in the Non-Combustion Case, where estimates indicate between 85,400 and 89,300 avoided mortality cases under the light duty Non-Combustion Case scenario and between 83,100 and 86,900 avoided mortality cases under the heavy-duty Non-Combustion Case scenario. However, the light- and heavy-duty vehicles are not directly comparable under the Non-Combustion Case because of the additional benefit from the cleaner grid for the baseline load relative to the BAU, which is independent of vehicle electrification. (That is these additional benefits appear in both the light and heavy vehicle results).

We also calculated the health benefits to populations individually in 25 of the nation's largest metropolitan areas. Total health benefits in these areas under the Base electricity Case in year 2050 range from about $129 million (Portland, OR) to $5.41 billion (Los Angeles, CA). Under the Non-Combustion electricity Case in 2050, total health benefits range from about $152 million (Portland, OR) to $6.81 billion (Los Angeles, CA). Considered cumulatively, from 2020-2050, benefits for these metro areas under the Base electricity Case range from $1.34 billion (St. Louis, MO) to $63.1 billion (Los Angeles, CA). Under the Non-Combustion electricity Case, cumulative benefits are roughly 50% larger, ranging from $2.09 billion (Portland, OR) to $95.5 billion (Los Angeles, CA).

As an indication of, "who would benefit" from the transition described by the scenario, we consolidated the predicted health benefits with county-level demographics. We ranked counties by the percent of the population identifying as people of color (POC). Considering cumulative impacts, 2020-2050, the counties that fall into the top 100 in terms of the proportion of POC are expected to receive $82 billion, or 24 percent, of the national health benefits from the Scenario under the Base electricity Case and $155 billion, 13 percent, under the Non-Combustion electricity Case. These shares of the benefits are notable given that the top 100 counties comprise only 3 percent of all counties in the studied area - 48 contiguous states and the District of Columbia.

Finally, we also evaluated the global climate-change costs that may be avoided due to reductions in GHG emissions for the vehicle electrification Scenario. This considered both the reduction in direct (downstream) emissions from increased vehicle electrification in the country and the associated changes in upstream emissions from reduced fuel production and increased load on the electric grid under both electricity Cases. As not all upstream emissions associated with crude refined for traditional vehicle (internal combustion engine vehicles; ICEVs) fuels is domestic, we include global changes in upstream emissions of these fuels. We then monetized these values using the Social Cost of Carbon (SCC). It is important to note that GHG benefits valued here only consider *changes* in the up- and downstream emissions associated with vehicle electrification. That is, we included the changes in tailpipe, fuels production, and electricity generation emissions directly due to vehicle electrification. As we did not compute a sector-wide BAU curve for GHG emissions, the additional climate benefits of the Non-Combustion case attributable to the baseline load (i.e., that part independent of vehicle electrification) will be significant but are not included here. (These benefits are included in the health-based results.)

The EV Scenario with the Base Case electricity grid shows net avoided climate change-related costs from reductions in 2050 levels of GHG emissions of $116 billion with 1.4 million metric tons of CO_2e emissions avoided. With the Non-Combustion electricity grid, net avoided climate costs are $145 billion from 1.8 million metric tons of CO_2e emissions avoided. We also explored the cumulative avoided costs from GHG reductions from the entire 2020-2050 period. When consolidated over the period, the Scenario with the Base Case electricity grid is expected to reduce GHG emissions by 18.6 billion metric tons for a net avoided cost of $1.36 trillion. With the Non-Combustion electricity grid, 24.2 billion metric tons of CO_2e emissions could be avoided, resulting in $1.76 trillion in avoided climate costs. These values underestimate the true, total benefit due to omitting changes in emissions associated with the base load.

2. Background and Overview

In 2020 ICF prepared an analysis for the American Lung Association on the *Health Benefits of Transition to Zero Emission Transportation Technologies*. That analysis quantified the potential air quality, health, and climate benefits of an ambitious but achievable scenario for on-road vehicle electrificationacross the United States. The purpose of this project is to provide an update to the 2020 study to modernize its methodology and approach and enhance elements of its reporting.

This project was conducted in four tasks. Task 1 focused on developing a detailed business as usual (BAU), and vehicle electrification Scenario fleet model. Task 2 used the fleet profiles of the vehicle electrification Scenario in an emissions modeling exercise to determine the change in both downstream and upstream national emissions under the new Scenario. Upstream emissions were determined for two Cases representing potential pathways for the national electric grid in the future. Task 3 then assessed the potential health and climate impacts associated with the modeled, national emission reductions. The fourth task addresses reporting.

This report consolidates the emissions reductions from Tasks 1 and 2 with the health and climate impacts analysis of Task 3. Section 3 provides a brief discussion and summary of the results from the fleet modeling approach and results. This includes a discussion of the vehicle categories and the BAU and Scenario vehicle fleets. Section 4 documents the resulting changes in emissions associated with the Scenario. It first summarizes the different modeling tools and methodology applied for the downstream and upstream emissions. For upstream emissions, it introduces the two potential Cases for the future national electric grid. It then presents the BAU emissions for both up- and downstream and the change in each expected because of the Scenario. It then summarizes the net change for the BAU and Scenario under both electric Cases. Section 5 summarizes the human health benefits that accrue from the vehicle Scenario. This Section provides a discussion of the methodology and results of the COBRA modeling, resolving impacts from both electrification Cases as well as impacts from light- and heavy-duty vehicles separately from the cumulative impacts. Notably in these results, the baseline grid activities are treated identically to additional grid load from new electric vehicles. This average power approach demonstrates the substantial electricity generation reductions from the cleaner grid under the Non-Combustion Case. Results are shown for the individually modeled years, as well as cumulative impacts over the 2020-2050 period. Finally, to help identify who benefits most from the EV Scenario modeled here, this section summarizes the impacts in 20 of the largest metropolitan areas of the country and reports impacts according to population demographics. Section 4 also provides a summary of deviations in the present analysis from the 2020 study.

A note on terminology in this report: **Scenario** refers to the single vehicle electrification Scenario (EV Scenario), which is compared to a BAU scenario based on the national defaults in the MOVES3 model. **Case** refers to the different electrification Cases describing options for the future national electric grid. When resolving the different impacts from the upstream and downstream emissions according to light- and heavy-vehicles, these vehicle categories are referred to as **Classes**. The mixture of all these different elements, in addition to different possible values of the discount rate, are all presented in output from this analysis.

3. Vehicle Fleet BAU and Scenario Modeling

Task 1 focused on developing the BAU and Scenario models for the national vehicle fleet. These models for the on-road vehicle fleet are the basis for the energy consumption and emissions expected with and without the advancement of EVs[13] considered here. Specifically, this work determines the vehicle categories considered, the sales fractions for EVs under the Scenario for each vehicle category, and the resulting penetration of EVs into the total national vehicle fleet. This is needed for comparison of EV and for establishing baseline emissions by vehicle type, model year, and calendar year and their associated activity (VMT).

3.1. Analysis Years

This study models years:

- 2020
- 2030
- 2040, and
- 2050

Relative to the previous analysis, we have updated the start year 2020 from 2018 to 2020 and maintained the end year at 2050. We added the year 2040 to provide equal increments for use in displaying timeseries and cumulative impacts of the analysis.

3.2. Vehicle Categories

For purposes of this analysis, we consider the entire vehicle fleet to be subject to electrification. We considered the entire vehicle fleet as occurring in one of four vehicle categories.

- Passenger vehicles
- Light heavy-duty trucks
- Medium- and heavy-trucks, and
- School buses

Table 1 provides the definitions used for these categories. These vehicle categories are based on definitions in EPA's MOVES3 vehicle emissions model.[14] Accordingly, Table 2 defines the vehicle types ("sourceTypeID") and regulatory classification ("RegClassID") mapping used in the MOVES3 model.

13 Note that the scope of this analysis was determined to focus exclusively on battery electric vehicles (BEV), excluding traditional hybrid, plug in hybrid (PHEV), and other zero emission vehicle (ZEV) technologies such as hydrogen fuel cell vehicles (FCEV). This strategy was selected to be simpler and cleaner for messaging and presentation of results. For example, this approach avoids complications of both down- and upstream emissions from hybrids and characterization of upstream emissions for H2 fuel, which varies widely depending on feedstock, and highlights the benefits of BEVs over PHEVs which are likely to become disfavored under pushes for increasing decarbonization.

14 https://www.epa.gov/moves/latest-version-motor-vehicle-emission-simulator-moves

Table 1. Scenario Vehicle Category Definitions.

Vehicle Type ID	Description	Notes
1	Passenger Vehicles	Defined as MOVES vehicle types (sourceTypeID) 11, 21, 31, and the part of 32 that are not Class 2b or 3. Note that there are some Class 2b3 passenger trucks (veh type 31). These vehicles are included in Type 1.
2	Light Heavy Trucks Class 2b-3 that are not school buses or passenger trucks	Defined as all vehicles in MOVES' new regulatory class 41 (RegClassID=41) that are not school buses (MOVES sourceTypeID=43) or Passenger Trucks (sourceTypeID=31)
3	Medium-Heavy and Heavy-Heavy Trucks and Buses, Class 4-8 that are not school buses.	Defined as all MOVES RegClassID=42-49 that are not sourceTypeID=43.
4	School Buses (all)	Defined as all school buses of any size (MOVES vehicle type 43; all regClassIDs)

Table 2. MOVES3 Source Type Definitions.[15]

		Source Use Types												
		Motorcycles	Passenger Cars	Passenger Trucks	Light Commercial Trucks	Other Buses	Transit Buses	School Buses	Refuse Trucks	Short-Haul Single Unit Trucks	Long-Haul Single Unit Trucks	Motor Homes	Short-Haul Combination Trucks	Long-Haul Combination Trucks
Regulatory Classes		11	21	31	32	41	42	43	51	52	53	54	61	62
MC	10	X												
LDV	20		X											
LDT	30			X	X									
LHD2b3	41			X	X			X	X	X	X	X		
LHD45	42					X	X	X	X	X	X	X		
MHD67	46					X	X	X	X	X	X	X	X	X
HHD8	47					X	X	X	X	X	X	X	X	X
Urban Bus	48						X							
Gliders	49													X

3.3. BAU Fleet Modeling

All national fleet and activity data for the baseline and BAU scenario is based on data in US EPA's MOVES3 model. MOVES3 is now the official version of MOVES, posted to the Federal Register and approved for official use in January 2021.

15 These definitions and tables are provided in, "Population and Activity of Onroad Vehicles in MOVES3", EPA-420-R-20-023, November 2020. See Table 2-7. Available at: https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P1011TF8.pdf

Notable changes to MOVES3 relative to MOVES2014b include updates to vehicle miles travelled (VMT) and vehicle population inputs with newer historical data from FHWA and updated forecasts from DOE.[16] Multiple pollutant emission rates from different vehicle and fuel types have been updated, as has fuel supply information. Some differences in vehicle types and classification scheme are included. Notably, MOVES3 incorporates changes resulting from the Heavy-Duty Greenhouse Gas Phase 2 rule and the Safer Affordable Fuel-Efficient (SAFE) Vehicles Rule. (The SAFE rule was repealed December 20, 2021.[17]) MOVES3 also continues to model all-electric passenger cars as having zero penetration nationally. EPA states this is due to EV penetration varying geographically with MOVES unable to capture this variation at the national scale.[18]

This study includes a single, national vehicle fleet for the BAU and another for the Scenario. The BAU is based on modeling with MOVES3. The default MOVES3 fleet is modeled for the 48 contiguous U.S. states plus the District of Columbia, with results at a national scale.[19] The BAU fleet uses MOVES' default values of VMT, vehicle age distribution, and population by MOVES vehicle types, which are combined into the four Scenario vehicle types, as described in Section 3.2.

We also used the same MOVES simulation to determine the BAU levels on on-road (downstream) emissions for all vehicles across the US. In this case, downstream includes criteria and GHG emissions from both exhaust and evaporative processes. It also includes fugitive $PM_{2.5}$ emissions from brake and tire wear. This is discussed in Section 4.1.

Table 3. BAU Vehicle Populations.

Vehicle Type ID	Year			
	2020	2030	2040	2050
1	260,470,263	275,236,460	286,075,820	298,109,711
2	6,447,695	6,269,072	6,609,708	7,575,780
3	9,480,537	10,981,869	12,604,199	14,916,760
4	484,750	538,782	604,119	700,740
Grand Total	276,883,245	293,026,184	305,893,846	321,302,991

3.4. Scenario Fleet Modeling

3.4.1. Zero Emission Sales Trajectories for Light, Medium, and Heavy-Duty Vehicles

Relative to the previous analysis, this study uses different vehicle categories (Section 3.2) and BAU fleet and activity assumptions from MOVES3 (Section 3.3) It also includes a more aggressive approach to vehicle electrification. The objective is to hit 100% ZEV sales by 2035 for passenger vehicles (less than 8,500 lbs. GVWR) and by 2040 for the rest of the fleet (i.e., above 8,500 lbs. GVWR). This study continues to use Battery Electric Vehicles (BEVs) as a marker for zero emission technologies, as we anticipate the market for most ZEVs will be addressed through EVs. Also, for simplicity as before it substitutes EVsfor traditional vehicles (internal combustion engine vehicles; ICEVs) one-to- one, excluding any replacement of existing EVs.

This section discusses the EV sales targets used in the remainder of the study.

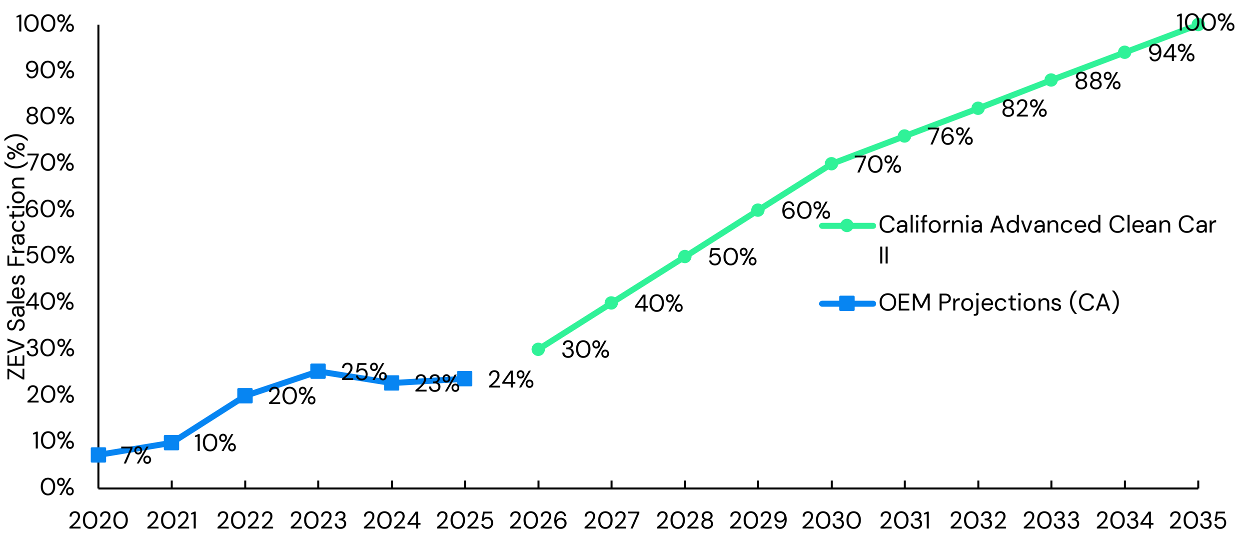
16 EPA-420-F-20-050, November 2020. Available at: https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P1010M06.pdf.
17 https://www.epa.gov/regulations-emissions-vehicles-and-engines/final-rule-revise-existing-national-ghg-emissions
18 EPA-420-R-21-012. Available at: https://www.epa.gov/sites/production/files/2021-04/documents/420r21012.pdf
19 Throughout this analysis, the focus is on the 48 contiguous U.S. states (excluding Hawaii and Alaska) plus DC. This is because the EPA's COBRA model, used to estimate public health impacts, does not include impacts in Alaska, Hawaii, or the U.S. territories.

Light Duty Vehicles

According to latest data from Alliance for Automotive Innovation, the national sales of light duty ZEVs have been increasing rapidly over the past two years. More than 168,000 zero emission vehicles (battery, plug-in hybrid, and fuel cell electric vehicles, BEV, PHEV, and FCEV) were sold in the second quarter of 2021, a 33 percent increase over the first quarter and 122,000 units more than the same period in 2020. For the months of April – June 2021, ZEVs represented 3.8 percent of the overall market, the highest for any quarter to date. The data reveals a ZEV market share of approximately 3.5% in 2021 as compared to 2.5% in 2020[20].

In the meantime, California is proposing the Advanced Clean Cars 2 regulation which will set a ZEV sales target of 100% by 2035. In doing so, California Air Resources Board (CARB) have analyzed sales projection from various manufacturers for model years 2021 through 2025 and conducted a cost analysis to determine their initial ZEV sales stringencies for 2026 and subsequent model years as shown in Figure 1 below.[21]

Figure 1 Proposed ZEV stringencies under California Advanced Clean Cars 2



Considering that the market share of ZEVs is much lower at national level (e.g., 2.5% in 2020), we developed a separate curve that starts at lower levels than California in earlier years and eventually meet 100% ZEV sales target by 2035. As illustrated in Figure 2, we started with historical national ZEV market share in 2020/2021 and employed a logit function that join a California's ZEV sales target of 70% by 2030[22] and ultimately reaches 100% target by 2035. The use of logit function is in line with the diffusion of innovations' theory. Under this theory, the transition to a new technology can be characterized by an early emergent phase in which growth appears small, but then it gathers momentum as the technology become established and enter a phase of widespread diffusion characterized by exponential rates of growth. This is followed by a culmination phase when the pace of diffusion slows as the new technology stabilizes and its deployment begins to saturate. In the case of zero emissions vehicles, it is expected that majority of the market to transition to ZEV in the next 10 years at a rapid rate. However, it is expected that high mileage vehicles (e.g., long-distance commuters) in

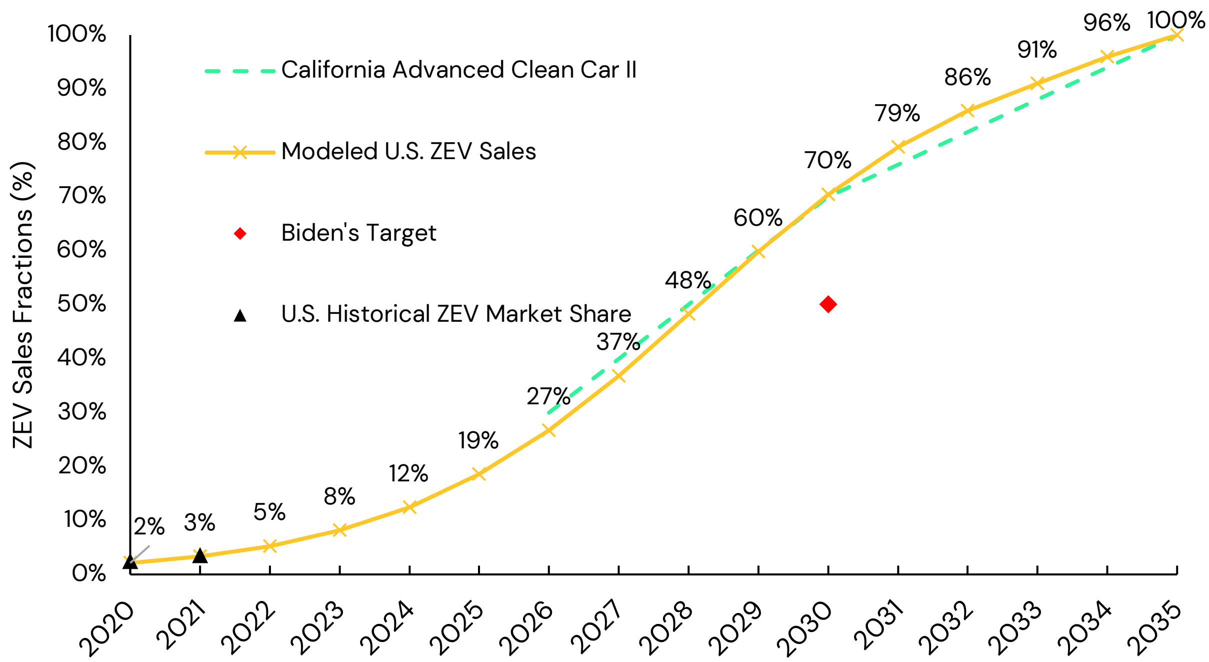
20 https://www.autosinnovate.org/posts/papers-reports/Get%20Connected%20Electric%20Vehicle%20Quarterly%20Report%20Q2%202021.pdf

21 We note that CARB's initial proposal is not as ambitious as its own modeling suggests is needed, and far behind the cost parity estimates of Bloomberg and others.

22 While Biden's administration has set a target of 50% electric vehicle sales share in 2030, hitting the 100% ZEV target by 2035 would require higher market share in 2030.

regions with lack of sufficient infrastructure availability or other factors to slow down the rate of penetration in the last couple of years before the 100% of sales transition to ZEV.

Figure 2 Light Duty Zero Emission Vehicle Sales Trajectories



Medium and Heavy-Duty Vehicles

In 2020, California adopted the Advanced Clean Truck (ACT) regulation[23] which sets the first in the nation ZEV sales requirements for MD/HD vehicle manufacturers. Washington, Oregon, Massachusetts, New York, New Jersey have now adopted the California ACT rule.

As shown in Table 4, the ACT sales requirements starts with 2024 model year medium and heavy-duty vehicles, and the stringency increases through 2035 model year vehicles. These sales requirements were developed based on the operational characteristics of various truck vocations, the cost and availability of zero emission MD/HD trucks, as well as the timeline for infrastructure buildout (e.g., line haul trucks need state/national network of infrastructure, whereas for return to base trucks – e.g., delivery trucks – the charging infrastructure might be limited to truck depots). Upon the adoption of the ACT regulation in California, 15 states and the District of Columbia announced a joint memorandum of understanding (MOU)[24], committing to work collaboratively to advance and accelerate the market for electric medium- and heavy-duty vehicles, with the goal of reaching 100 percent of all new medium- and heavy-duty vehicle sales to be zero emission vehicles by 2050 with an interim target of 30 percent zero-emission vehicle sales by 2030.

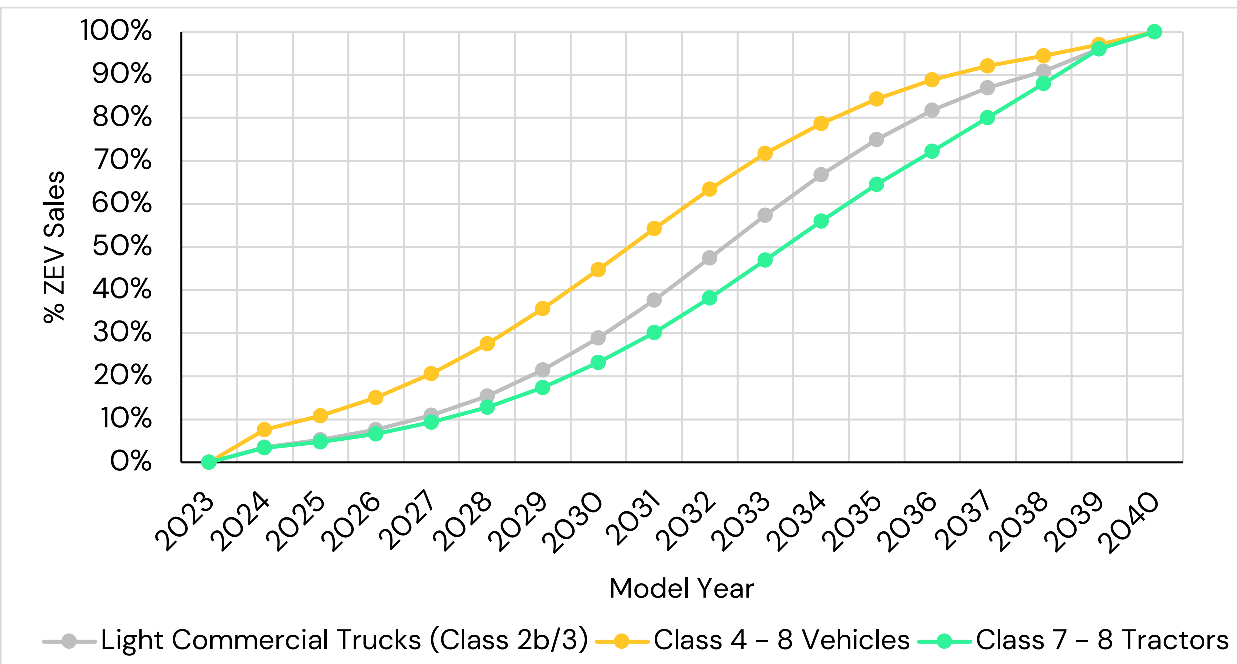
23 https://ww2.arb.ca.gov/our-work/programs/advanced-clean-trucks
24 https://ww2.arb.ca.gov/sites/default/files/2020-07/Multistate-Truck-ZEV-Governors-MOU-20200714.pdf

Table 4 ACT manufacturers ZEV sales requirement.

Model Year	Class 7-8 Tractor	Class 4-8 Vocational	Pickup/Vans
2024	5%	9%	5%
2025	7%	11%	7%
2026	10%	13%	10%
2027	15%	20%	15%
2028	20%	30%	20%
2029	25%	40%	25%
2030	30%	50%	30%
2031	35%	55%	35%
2032	40%	60%	40%
2033	40%	65%	45%
2034	40%	70%	50%
2035	40%	75%	55%

To project the ZEV market share for medium- and heavy-duty vehicles with the goal of achieving 100 percent ZEV sales by 2040, we started with the ACT ZEV sales requirements and utilized a logit function to develop trajectories for sales of various MD/HD vehicles classes as illustrated in Figure 3.

Figure 3 MD/HD Sales Trajectories



As shown in Figure 3, the sales trajectory of zero emission light commercial, single unit and combination trucks, starts in 2024, follows an S-shaped curve, and reaches 100 percent by 2040. Between 2024 and 2030, the ZEV sales percentage for these three categories are similar to California's ACT requirements, and they diverge between 2030 and 2040 as the new curves reach for 100% ZEV sales by 2040, while California's requirements plateau in 2035 at 40-75 percent. While California's ACT requires 55% of Class 2b-3 vehicle sales to be ZEV by 2035, the diffusion curves illustrated in Figure 3 calls for 75% of sales to be zero emission by that time. This is also consistent with the California's proposed advanced Clean Fleet (ACF) regulation[25] which proposes to increase the sales of medium and heavy-duty ZEVs beyond the ACT requirements.

School Buses

For school buses California's Innovative Clean Transit (ICT) regulation[26] requires large transit agencies to have 25 percent, 50 percent, and 100 percent of their new purchases to be zero emission starting from 2023, 2026, and 2029, respectively. These categories are "beachheads" for zero emission technology adoption in the MD/HD space and while the proposed sales percentages seem to be very ambitious, these trajectories are consistent with and in certain cases even less stringent than the Truck and Engine Manufacturer Association (EMA) proposal.[27]

These values are consistent with the previous analysis for target years but use a gradual increase rather than the step functions assumed previously.

Summary

Table 5 below provides detailed ZEV sales percentages for each vehicle category and calendar/model year.[28]

25 https://ww2.arb.ca.gov/our-work/programs/advanced-clean-fleets
26 https://ww2.arb.ca.gov/sites/default/files/barcu/regact/2018/ict2018/ictfro.pdf
27 Those are: 100 percent of new school buses and municipal step vans to be zero emission by 2023; 100 percent of new public utility vehicles and yard tractors to be zero emission by 2024; 100 percent of non-airport shuttle buses and new step vans to be zero emission by 2025; and 100 percent of new refuse haulers to be zero emission by 2026. https://www.arb.ca.gov/lists/com-attach/142-act2019-WjAAY1A1AAwEbwdm.pdf
28 Because this considers new vehicle sales only, model year and calendar year sales targets are identical.

Table 5 ZEV Sales percentage by model year

Vehicle Type ID	1	2	3	4
Description	Passenger	Light Commercial Trucks (Class 2b/3)	Class 4-8 HDV	School Buses
Year				
2020	2%	0%	0%	0%
2021	3%	0%	0%	3%
2022	5%	0%	0%	10%
2023	8%	0%	0%	25%
2024	12%	4%	4%	30%
2025	19%	5%	5%	40%
2026	27%	8%	8%	50%
2027	37%	11%	11%	63%
2028	48%	15%	15%	76%
2029	60%	21%	20%	100%
2030	70%	29%	28%	100%
2031	79%	38%	36%	100%
2032	86%	48%	46%	100%
2033	91%	57%	55%	100%
2034	96%	67%	65%	100%
2035	100%	75%	73%	100%
2036	100%	82%	80%	100%
2037	100%	87%	86%	100%
2038	100%	91%	90%	100%
2039	100%	96%	96%	100%
2040	100%	100%	100%	100%
2041	100%	100%	100%	100%
2042	100%	100%	100%	100%
2043	100%	100%	100%	100%
2044	100%	100%	100%	100%
2045	100%	100%	100%	100%
2046	100%	100%	100%	100%
2047	100%	100%	100%	100%
2048	100%	100%	100%	100%
2049	100%	100%	100%	100%
2050	100%	100%	100%	100%

3.4.2. EV Penetration Modeling

We then used a fleet modeling approach to determine the penetration of electric vehicles into the national vehicle fleet. This estimates the share of EVs in the national fleet following their introduction via new vehicle sales.

EV fleet penetration for each of the four vehicle categories was calculated using the ZEV sales fractions and the national BAU vehicle population by vehicle category, fuel type, and model year in each of the four simulated years (2020, 2030, 2040, and 2050). EVs were assumed to have the same scrappage schedule as non-EV vehicles. Additionally, EVs were assumed to replace non-EV fuel type vehicles proportional to the makeup of non-EV fuel type vehicles. For example, if the BAU fleet of model year 2026 vehicles consisted of 75% gasoline and 25% diesel vehicles, and the sales fraction of EVs is 27%, the Scenario fleet of model year 2026 vehicles could consist of 27% EVs, with the EVs replacing 27% × 75% gasoline vehicles and 27% × 25% diesel vehicles. These fuel distinctions are then propagated through the calculations since the Energy Efficiency Ratio (Section EER) is dependent on the fuel and also incorporates the vehicle's in-use duty cycle.

Fleet aggregation calculations were performed for the four analysis years. The appropriate sales ratio was assigned to each row of this inventory by model year and vehicle type grouping. The total number of EVs was then calculated by multiplying the appropriate sales ratio by the population for each sub-group and summing. In the Scenario fleet, the number of non-EV vehicles were decremented by the number of EVs that replaced them.

3.5. Results

Figure 4 shows the makeup of the overall fleet, under the BAU and EV Scenario. Figure 5 shows the same data, but with additional stratification by vehicle type.

Figure 4: BAU Fleet and Modified Fleet

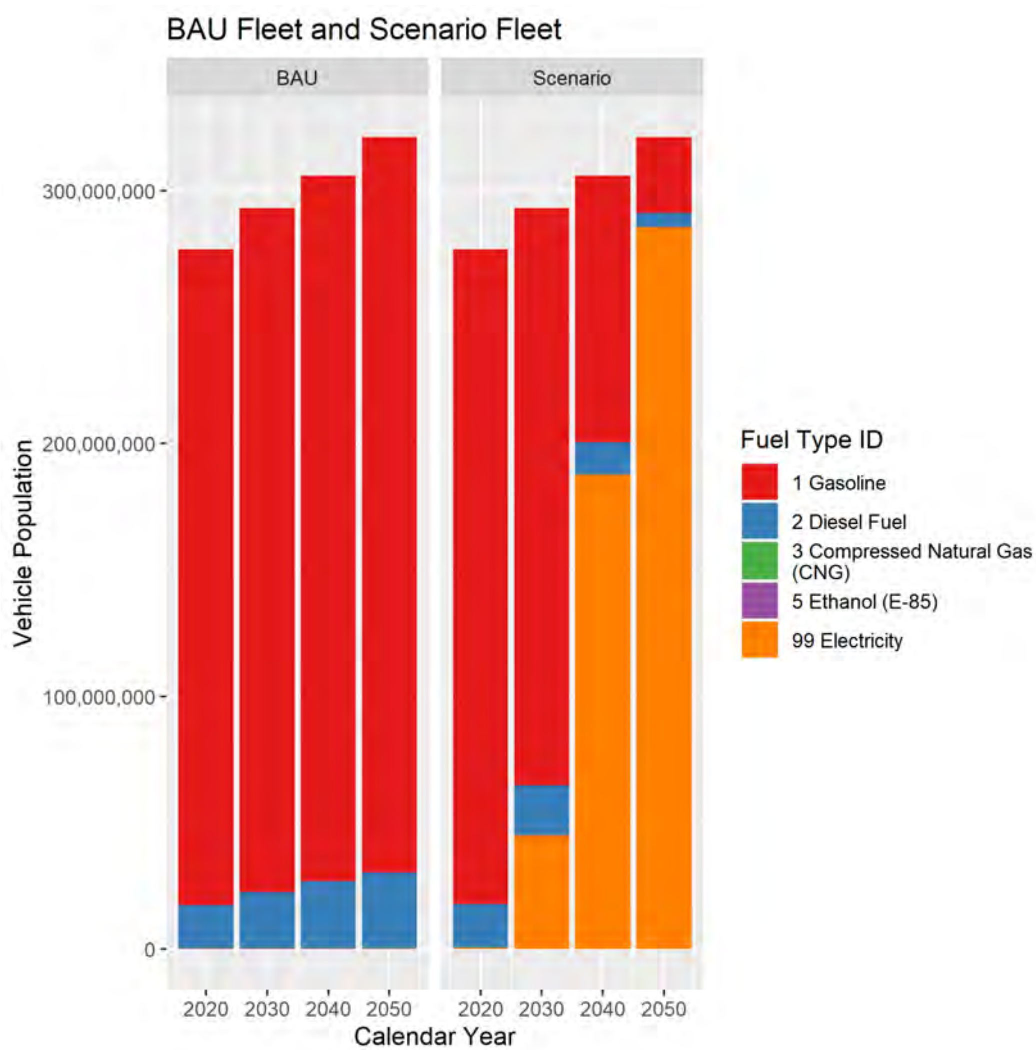
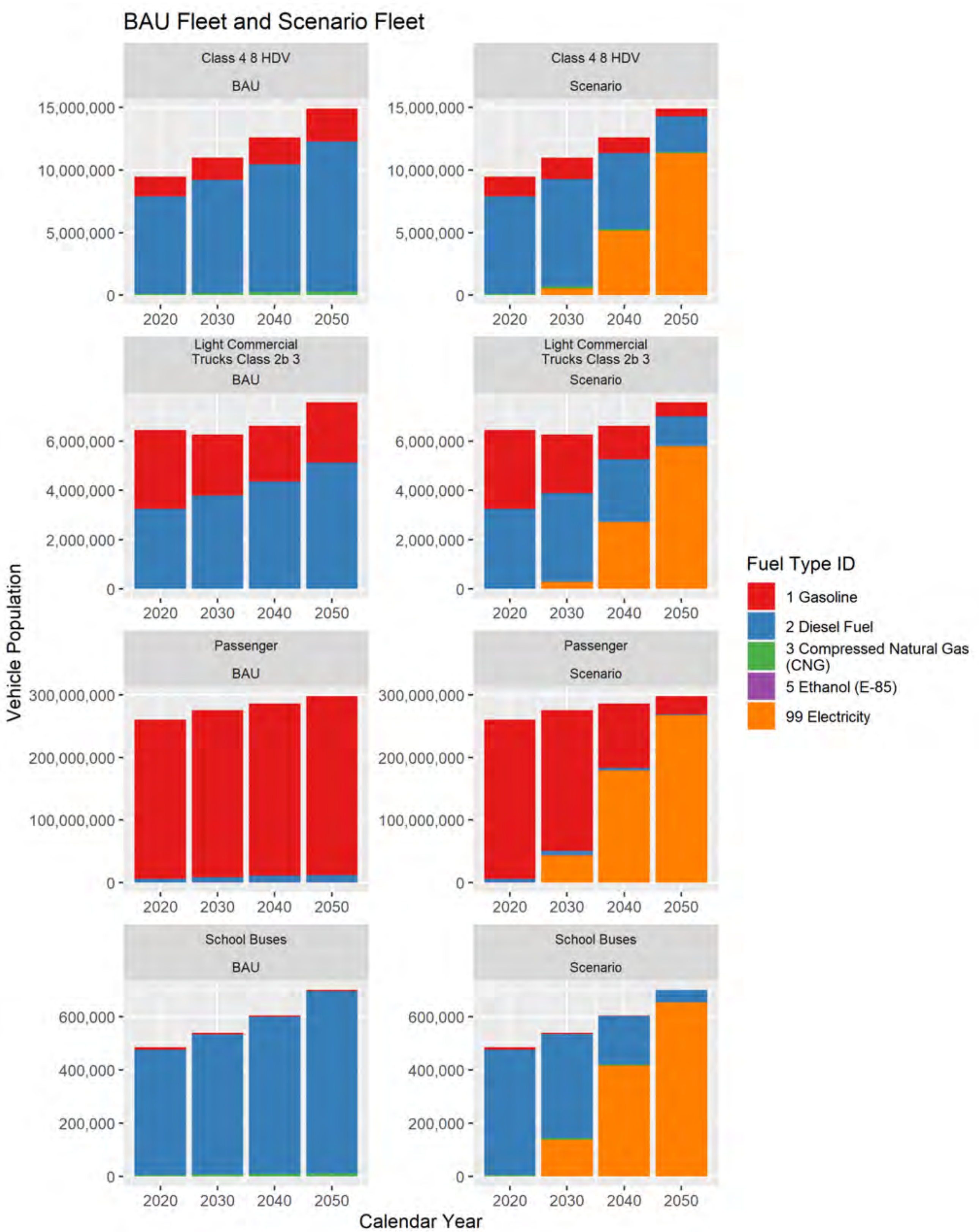


Figure 5: BAU Fleet and Modified Fleet, Stratified by Vehicle Type Group



4. BAU and Scenario Emissions Modeling

ICF modeled emissions nationally under both the BAU and Scenario. The modeled emissions included direct PM from:

- $PM_{2.5}$ exhaust
- $PM_{2.5}$ brake wear (BW)
- $PM_{2.5}$ tire wear (BW)

PM is the focus as it is the basis for health modeling to be conducted under Task 3. In addition, we computed emissions of:

- nitrogen oxides (NOx)
- ammonia (NH_3)
- sulfur oxides (SO_2), and
- volatile organic compounds (VOC).

And greenhouse gases (GHGs) as:

- CO_2e

determined from:

- carbon dioxide (CO_2)
- methane (CH_4), and
- nitrous oxide (N_2O).

combined using the global warming potential values currently in MOVES3, which are those from IPCC's AR4.[29]

This modeling included both downstream processes – pollutants released directly from the vehicle fleet- and upstream emissions. The downstream emissions include exhaust, evaporative, and fugitive emissions processes, such as brake and tire wear. Notably, while EVs release no tailpipe emissions, they continue to produce fugitive emissions. Downstream emissions are determined with the MOVES3 model.

Upstream emissions include emissions associated with conventional ICEV fuel extraction, transport, refining, and related emissions and emissions associated with both the feedstock and fuels used in electricity generation (via electric generating units; EGUs). For this analysis, we modeled *changes* in upstream emissions associated with changes in activity (reduced ICEV fuel consumption; increased electricity demand to power additional EVs) driven by the Scenario. Upstream emissions are determined from a combination of models, including emission factors derived from the Argonne National Laboratory's latest Greenhouse gases, Regulated Emissions, and Energy use in Technologies Model (GREET2021[30]). Upstream electricity production is strongly associated with the power production "grid mix". This analysis considers two potential "cases" for the future electric grid:

1. *The Base electricity generation Case*: A more business-as-usual projection for the grid, based on the Bloomberg New Energy Outlook (BNEO) 2019 analysis employed by the 2020 study.
2. *The Non-Combustion electricity generation Case*: A more ambitious renewables projection, with a heavy emphasis on emissions free, renewables, such as from wind and solar.

The IPM model was employed to determine the grid mix to meet the Non-Combustion Case.

There will be both upstream and downstream emissions even after 100 percent ZEV sales have been reached due to the lag in time between new EV sales and the turnover of the overall fleet population, and the fugitive emissions that emanate from ZEVs. Furthermore, some emissions associated with crude oil sourced outside of

29 E.g., https://www.ghgprotocol.org/sites/default/files/ghgp/Global-Warming-Potential-Values%20%28Feb%2016%202016%29_1.pdf.
30 https://greet.es.anl.gov/

the U.S. are emitted outside the boundaries of the continental US. We consider changes in domestic criteria emissions, but present both domestic and global emissions of GHGs.[31]

There are also emissions from the refining and electricity generation sectors that are independent of those used for vehicles but appear in the BAU for these sectors. This study also estimates a national BAU estimate of the relevant upstream emission components. Resulting net emissions are determined by combining the changes in upstream emissions resulting from the Scenario with the BAU estimate of emissions from the sectors. Not all the upstream emissions are related to the on-road fleet. This analysis is not intended to simulate a marginal grid mix that would differ by sources. Thus the "BAU" emissions curve under the Non-Combustion Case should also be reduced below that of the Base Case due to the cleaner grid, regardless of any additional load from EVs. This assumes that the entire grid is becoming cleaner under the Non-Combustion Case. To demonstrate this difference, we show the Non-Combustion Case results two ways. The first maintains the Base Case level of emissions independent of any new EV load, then adds emissions from new EV load assuming the power for these is met with the Non-Combustion grid. This demonstrates impact of new EV load with a very clean grid, but only applies the change to the new load, roughly consistent with the approach used in the 2020 study. The second uses the Non-Combustion Case electric grid emission factors for the baseline load and the additional load from new EVs. This has the effect of dramatically reducing both the emissions from the base load on the grid and emissions associated with new load from EVs and is consistent with using an "average grid" approach but show impacts to the grid not directly attributed to EVs.

4.1. Downstream Emissions Modeling

4.1.1. MOVES BAU Modeling

To model the BAU downstream emissions, ICF used data from EPA's current mobile source emissions model, MOVES3. This modeling is the same as that used to determine the BAU fleet and described in Section 3.3. We split national total emissions and energy consumption into the four vehicle categories and four fuel types. All emission processes were considered for each pollutant. That is, running, starting, evaporative, extended idle, and APU were all modeled for the relevant vehicle types and pollutants. These were aggregated into total emissions per year for each decade from 2020 to 2050.

All exhaust processes were computed with a single, national MOVES3 simulation. This used the national scale approach, with the 48 states plus DC combined in the analysis and used annual preaggregation for all four modeled years. The simulations for evaporative emissions were similar, but due to the very long run times for these simulations, only January and July were simulated for each of the modeled years. The annual emissions were then computed by assuming these two summer and wintertime emissions each applied for half the year.

4.1.2. Scenario Fleet Modeling

To compute the emissions under the national Scenario, we used the BAU vehicle populations and emissions to determine per-vehicle, annual emissions and energy consumption. Emissions are tracked by pollutant, fuel type, vehicle type, decade, and model year.

For pollutants excluding brake wear and tire wear, electric vehicles produce no downstream emissions. Thus, to compute the emissions under the Scenario, we began with the outputs of the Scenario fleet modeling (Section 3.4) to determine the population by vehicle and fuel type under the Scenario (including EVs). For the ICEVs remaining in the fleet, we calculated the product of the Scenario fleet populations and the BAU annual

31 Only crude/feedstock emissions are assumed to occur outside of the US. All other upstream components (refining and transport for traditional fuels and electricity production) are assumed to occur domestically and within the bounds of this study. .

emissions, essentially zeroing out all emissions for internal combustion engine vehicles (ICEVs) that were displaced by EVs.

We then added back in the fugitive emissions associated with $PM_{2.5}$ brake and tire wear emissions from these new EVs. Following the approach implemented by the CARB, we assumed that EV brake wear emissions are half that of the ICEVs they replace, and that there are no changes to the tire wear emission rates.[32] We determined ICEV brake and tire wear annual emissions as above for exhaust emissions, applied these CARB-based scaling factors, and added these to the Scenario downstream emission totals.

4.1.3. Resulting Downstream Emission Changes

Table 6 and Table 7 show the changes in national-level, on-road, downstream emissions from the implementation of the Scenario. Note in Table 7 that all values are reductions, and thus not shown here as negative values. Figure 6 shows these same changes graphically for three pollutants. Please note that the scale for each of the three pollutants differs.

Table 6. Total Downstream Emission Reduction Nationwide, tons per year

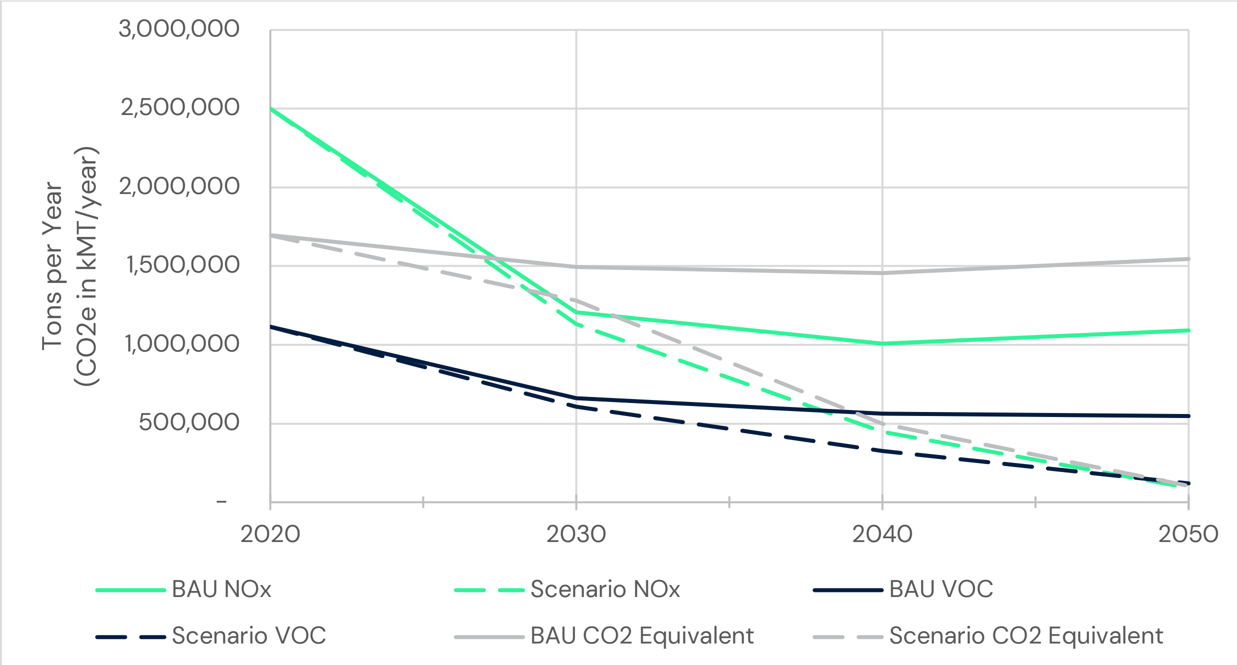
Year	NOx	SO_2	VOC	$PM_{2.5}$ Total	CO_2 Equivalent	NH_3
2020	284	10	473	24	1,653,148	101
2030	74,398	1,309	53,395	3,547	234,692,666	14,480
2040	559,853	5,529	236,899	17,106	1,054,670,878	65,233
2050	998,808	8,134	427,469	25,851	1,587,872,845	100,265

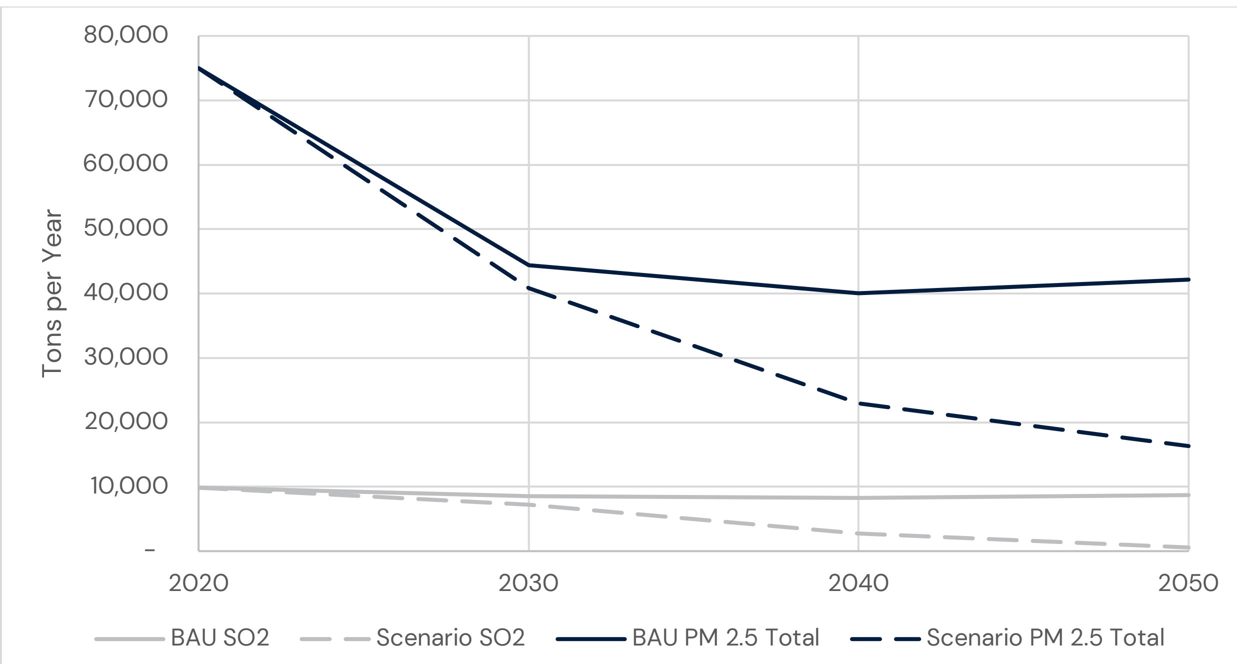
Table 7. Total Downstream Emission Reduction Nationwide, percent

Year	NOx	SO_2	VOC	$PM_{2.5}$ Total	CO_2 Equivalent	NH_3
2020	0	0	0	0	0	0
2030	6	15	8	8	14	15
2040	56	67	42	43	66	65
2050	92	93	78	61	93	93

32 https://ww2.arb.ca.gov/sites/default/files/2021-03/emfac2021_volume_3_technical_document.pdf. Also confirmed in email from CARB, "Currently, we're planning to follow a similar approach to what we modeled in ACT regarding brake and tire wear PM emissions, where a ZEV will see 50% reduced brake wear PM and equivalent tire wear PM to their combustion-powered counterparts. This is due to the impact of regenerative braking decreasing the usage of the friction brakes. We do not have any plans to update these assumptions at the moment as we have not seen any data beyond what we cited in ACT." From William Barrett to Seth Hartley, December 20, 2021.

Figure 6. Downstream emission trends for the modeled years, BAU and Scenario (all units are short tons per year except CO2e, shown in thousands of metric tons per year)





In addition to the emissions reductions, the EV scenario would result in dramatic reductions in the amount of fossil energy consumed. Table 8 shows the reductions in fuel consumed by on-road vehicles (only). This excludes any change in energy that occurs upstream, such as to produce these fuels. Units are in millions of gallons, or millions of SCF for CNG.

Table 8. Total National reductions in energy consumed by vehicles (Downstream energy consumption only), millions of gallons (millions of SCF for CNG)

Year	Gasoline (Mgal)	Diesel Fuel (Mgal)	CNG (Mscf)	E-85 (Mgal)
2020	162	7	0	0
2030	19,610	3,809	8,403	46
2040	74,880	28,281	74,566	195
2050	105,696	48,468	134,250	271

4.2. Upstream Emissions Modeling

The changes in upstream (well-to-tank) life cycle emissions due to reduced consumption of transportation fuels due to the Scenario were based on calculations using a series of models. We determined upstream emission factors from refining for VOC, NO_x, PM_{10}, $PM_{2.5}$, SO_x, and GHG. Inputs included the GREET model, custom analysis of grid mix using the IPM model, the energy consumption of conventional ICEVs from MOVES, and for EVs based on their BAU counterparts with information from CARB. The next sections discuss these.

4.2.1. EER

We used energy efficiency ratios from CARB along with energy consumption rates from MOVES3 to estimate the amount of additional energy required by the electric grid to fuel EVs.

Along with the BAU emissions and fleet information, we extracted from MOVES total energy consumption, in J, again for the BAU fleet subject to electrification. As with emissions, this value is normalized to the vehicle population to produce the BAU energy consumption rate by vehicle, age, and fuel type. The additional electricity consumed was calculated according to the energy consumption of the type of vehicle the EV replaced. That is, if a gasoline passenger vehicle is replaced with an EV, the energy consumption of the EV was assumed to equal that of the gasoline vehicle.

To account for the energy efficiency differences from ICEVs and EVs, we included the increased efficiency of electric engines over internal combustion – such as the energy lost to heat and never converted to mechanical energy in ICEVs – via Energy Efficiency Ratios (EER) for each vehicle and fuel type. For this study, we used the CARB's EERs,[33] which were assigned to the four vehicle types considered here. We also accounted for a 10% difference in the EER of diesel engines relative to gasoline and CNG. Table 9 shows these factors.

Table 9. Selected EER Values by vehicle category, for electricity with respect to the base fuel

Vehicle type ID	Diesel	CNG/ Gasoline/ E85
1	3.1	3.4
2	5.0	5.6
3	5.0	5.6
4	5.0	5.6

33 As included in the leftmost column of Table 5 of CARB's LCFS regulation (page 73), available at: https://ww2.arb.ca.gov/sites/default/files/2020-07/2020_lcfs_fro_oal-approved_unofficial_06302020.pdf.

4.2.2. GREET

The Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET2021) model, developed by Argonne National Laboratory[34] is an analytical tool that simulates the fuel lifecycle, also known as well-to-wheels (WTW), energy use and emissions output of vehicle/fuel systems. GREET model is widely recognized as a reliable tool for life cycle analysis (LCA) of transportation fuels and has been used by several regulatory agencies (e.g., US Environmental Protection Agency for the Renewable Fuel Standard (RFS) and California Air Resource Board for the Low-Carbon Fuels standard (LCFS)) for evaluation of various fuels. We used GREET only for the upstream (well-to-tank) emissions, which do not include the tailpipe emissions generated from burning the fuels.

The upstream emissions of liquid fuels (i.e., gasoline, diesel, E85) include crude extraction and recovery, feedstock, refining, transportation, and distribution of the final product. The gasoline in the U.S. contains 10% ethanol, thus the upstream emissions of corn ethanol production in the U.S. were included in the calculations as well. For E85, we assumed a gasoline-ethanol blend with 83% ethanol[35]. Finally, for CNG, the upstream emissions include the extraction and recovery of fossil natural gas, gas processing, transportation and compression.

The upstream emissions factors representing electricity generation from the utility grid associated with powering EVs were also included and also based on GREET. The original GREET emission factors were based on EPA's Emissions and Generation Resource Integrated Database (eGRID) and allocated according to the average resource mix used in the U.S. grids. For this analysis, we have created two new grid mix Cases (described in Section 4.2.3). We developed emission factors in GREET corresponding to these mixes. Table 11. National, upstream electricity emission factors determined with GREET Table 11 summarizes these factors. This analysis does not model marginal power mixes.

Table 10 and Table 11 show the upstream fuel and electricity emission factors. Upstream fuel includes emissions from extraction, refining, transport, and distribution. Upstream electricity generation emission factors include contributions from both feedstock and fuels. Because of this, emission factors can be non-zero even when the electricity mix represents only non-combustion fuel mix.

Table 10. Total upstream refining emission factors from GREET, in g/gal or g/MJ (for CNG)

Pollutant	Diesel				Gasoline			
Year	2020	2030	2040	2050	2020	2030	2040	2050
VOC	0.946	0.944	0.942	0.945	3.296	3.287	3.285	3.287
NOx	2.294	2.277	2.258	2.330	2.840	2.759	2.734	2.801
PM_{10}	0.168	0.165	0.162	0.166	0.319	0.312	0.307	0.312
$PM_{2.5}$	0.142	0.141	0.139	0.144	0.214	0.209	0.207	0.212
SO_2	0.611	0.600	0.578	0.605	0.803	0.776	0.742	0.778
CO_2e	2097.5	2031.5	2005.7	2031.1	2593.6	2512.2	2477.6	2507.8
	E-85				CNG			
VOC	4.363	4.307	4.303	4.300	0.010	0.010	0.010	0.010
NOx	6.105	5.561	5.536	5.503	0.039	0.038	0.038	0.038
PM_{10}	1.075	1.034	1.029	1.018	0.001	0.001	0.000	0.000
$PM_{2.5}$	0.421	0.387	0.385	0.381	0.001	0.000	0.000	0.000
SO_2	1.719	1.572	1.544	1.466	0.012	0.012	0.011	0.011

34 https://greet.es.anl.gov/
35 https://afdc.energy.gov/fuels/ethanol_e85_specs.html

CO_2e	4121.2	3909.1	3872.9	3811.5	16.3	15.9	15.1	15.1

Table 11. National, upstream electricity emission factors determined with GREET, in g/kWh, for the two upstream electricity cases

Pollutant	Case 1: Base Case					Case 2: Non-Combustion Case			
Year	2020	2023	2030	2040	2050	2020	2030	2040	2050
VOC	0.048	0.046	0.040	0.038	0.034	0.048	0.025	0.000	0.000
NOx	0.300	0.292	0.246	0.220	0.158	0.291	0.113	0.001	0.001
PM_{10}	0.044	0.045	0.036	0.031	0.015	0.043	0.010	0.000	0.000
$PM_{2.5}$	0.025	0.025	0.021	0.019	0.012	0.025	0.009	0.000	0.000
SO_2	0.251	0.260	0.204	0.172	0.064	0.246	0.040	0.000	0.000
CO_2e	433.7	423.2	363.4	330.0	252.7	432.5	189.0	0.293	0.273

Note that Emission Factors of fuel combustion for Stationary Applications are the same between GREET2019 and GREET2021. However, there is a decrease in the Power Plant Energy Conversion Efficiency assumption between GREET2019 and GREET2021 that leads to a difference in emission factors for some pollutants relative to the 2020 analysis, even when the Case definitions are identical.

4.2.3. Electric Grid Cases and IPM

This analysis explored the potential impacts on upstream electrification of two potential future Cases for the electric grid. These 2 scenarios for upstream electrification were defined at the beginning of Section 4.

The Base Case was defined based on the "ALA Case" in the previous 2020 analysis. For this, we used the U.S. Energy Information Administration's 2021 Annual Energy Outlook projections (in BkWh) for the years 2020, 2030, and 2040, and converting these values into percentages of grid generation mix for GREET2021 input. The 2050 BkWh projections were taken from the Bloomberg 2020 New Energy Outlook.

The Non-Combustion Case was crafted uniquely for this analysis, based on the potential for a highly renewable grid being considered by several states and the Federal government. President Biden had stated a proposal of sourcing all electricity from carbon-free sources by 2035 (100% by 2035), in a goal to hit economywide net zero by 2050.[36] In California, SB100 set goals of 60% renewable, zero-carbon grid by 2030 and 100% by 2045.[37] New York State's Clean Energy Standard mandates 70% renewable electricity by 2030 and 100% by 2040.[38] We based the Non-Combustion Case on these standards to set goals of 70% clean by 2030 and 100% clean grid by 2035. The definition of "clean" was specified to mean non-combustion-based generating sources only. As such, biomass, RNG, CCS and other such options were not allowed.

To model the feasibility and resulting grid mix of the Non-Combustion Case, we used ICF's proprietary Integrated Planning Model[39] to create national annual projections of generation and emissions in the U.S. IPM is a least-cost optimization capacity expansion model of the North American electric power sector. The model used default assumptions (ISO/RTO/NERC energy and peak demand forecasts, NREL ATB renewable and storage costs, static transmission, all mandatory RPS/CES state-level policies, etc.) We added a constraint forcing a 100% clean grid by 2035 and an interim target of 70% clean by 2030. By 2040, IPM meets demand

36 https://www.bloomberg.com/news/features/2021-02-22/after-texas-blackouts-biden-s-climate- agenda-focuses-on-power-grid.
37 https://ww2.arb.ca.gov/sites/default/files/2021-11/CEC-sp22-electricity-ws-11-02-21.pdf
38 https://www.nyserda.ny.gov/All-Programs/Clean-Energy-Standard
39 https://www.icf.com/technology/ipm

without combustion through a capacity mix of about 60% renewables (mostly solar and wind) and 30% battery storage capacity, with the rest being mostly hydro & nuclear. By 2040, the generation mix is 80% wind and solar, with the remaining 20% coming from mostly nuclear and hydro. The first of these is capacity mix, and the second is generation. Capacity mix includes storage which is not counted in the generation mix. Once the generation mix was specified, it was utilized in GREET2021 as percentages of the national grid mix to specify grid emission factors.[40] Importantly, IPM also specifies emission factors for a portion of the pollutants included here. The factors from IPM and GREET were compared and seen to agree well, however IPM is not a lifecycle model and only considers emissions from the "stack" where full lifecycle (fuel plus feedstock) emissions from GREET are used here. Table 12 shows the grid mix resulting from both Cases, corresponding to the emission factors shown by Table 11.

Table 12. Electricity grid mix corresponding to upstream electricity Case 1, the Base Case, in percent

Year	Residual Oil	Natural Gas	Coal	Nuclear	Biomass	Hydro-electric	Geo-thermal	Wind	Solar	Other
2020	0	40	19	19	0	8	0	9	2	1
2030	0	35	16	14	0	7	1	16	10	2
2040	0	35	13	12	0	7	1	16	15	1
2050	0	43	2	12	0	6	1	22	13	1

Table 13. Electricity grid mix corresponding to upstream electricity Case 2, the Non-Combustion Case, in percent

Year	Oil	Natural Gas	Coal	Nuclear	Biomass	Hydro-electric	Geo-thermal	Wind	Solar	Other
2020	0	41	19	19	1	7	0	9	2	1
2030	0	33	1	16	0	6	1	18	24	1
2040	0	0	0	14	0	6	0	28	51	0
2050	0	0	0	13	0	6	0	27	54	0

4.2.4. Business-As-Usual Levels of Upstream Emissions

BAU emissions for the upstream emission sectors of fuel production and electricity generation are used to place the calculated change in these values in context. This was not included in the previous (2020) analysis, where changes in upstream emissions were presented then compared only to the downstream emissions under the BAU scenario. However, the projected BAU values for criteria pollutants are needed for the health impact modeling. Here we estimate a BAU level of emissions for the same upstream sectors affected by vehicle electrification – ICEV fuel production and electricity generation – and for the same analysis years. Furthermore, the Non-Combustion Case of electrification would modify the entire grid, not just the portion powering EVs. Thus, we also calculate upstream emissions for the entire grid, under this Case. These upstream components against which these changes may be compared and later be incorporated consistently in the health impact modeling.

GREET reports three elements for upstream fuels production:

- Fuels refining

40 Note that this IPM run does not answer the question of whether there is enough capacity on the grid to handle the shift to EVs envisioned by the Scenario. That is, the IPM simulation did not include a load shaping exercise. This work considered only the generation mix and thus the grid's emission factors under the given constraints and the average power assumption that the generation mix for EVs would be the same as the rest of the grid. Thus, the predicted emissions are addressed here, while the question of available infrastructure required to support this increased load due to increased vehicle (and building) electrification is considered beyond this study's scope.

- Fuels transport
- Crude and other feedstock

and two for electricity production:

- Fuel consumption
- Feedstock

To estimate the BAU upstream national inventory in a manner consistent with later health modeling, we began with emissions data within the COBRA model for year 2023. The 2023 COBRA emissions are based on EPA's 2016v1 Air Emissions Modeling Platform, which is a product from the National Emissions Inventory (NEI).[41] ICF scaled these emissions to the analysis years by estimating relative changes in the emissions intensity of the upstream processes based on GREET emission factors and in the relative change in activity based on projections from different resources. US AEO 2021[42, 43] was used to help scale the change in Crude, Refining, and Transport activities for the transportation fuels and for the baseline electricity case scenario for EGUs. The ICF IPM run was the source to quantify the net electric power sector generation activities for the Non-Combustion Case. The product of these two ratios across years – one for activity and one for emissions, both pollutant specific – multiplied by the COBRA-based 2023 emissions provided the BAU national inventory for the years 2020, 2030, 2040, and 2050. Note that as COBRA does not include GHG emissions, we did not determine a national, BAU upstream inventory for GHGs for these sectors. Similarly, as GREET does not produce NH_3 emissions, upstream BAU NH_3 emissions were grown based solely on changes in activity for the ICEV fuels. For electricity generating emissions NH_3 was grown as for other pollutants, but the ratio of NOx emissions factors was used as NOx-generating applications are closely correlated to NH_3 use in stationary EGUs applications.[44]

The emission inventory in COBRA is based on the NEI, reported in a series of Tiers. EPA provided a crosswalk between these Tiers and the Source Classification Codes.[45] ICF then determined a list of Tiers that best match the upstream emission sectors simulated by GREET. The sum of emissions in the selected Tiers are those that were scaled to the upstream sectors by year. We rely on emissions as reported in COBRA for consistency with the health analysis.

For electricity production, we include additive emissions from both upstream categories to the BAU upstream inventory. For upstream ICEV fuels where emissions are reduced, the matching is more critical to ensure that more emissions are not removed with our MOVES- and GREET-based approach than is in the BAU upstream sectors based on the NEI. Emissions reduction from all three upstream categories were combined and removed from the upstream BAU inventory, based on the list of Tiers best matching the petroleum sector and emissions

41 These baseline emissions estimates account for federal and state regulations as of May 2018. More details about the development of the 2023 baseline emissions case are available in the supporting information for the 2016v1 Emissions Modeling Platform, available at: https://www.epa.gov/airemissions-modeling/2016v1-platform.
42 Electricity Electric Power Sector Net Available to the Grid (Case Reference case) for electricity generation, available at: https://www.eia.gov/outlooks/aeo/data/browser/#/?id=8-AEO2021&region=0-0&cases=ref2021&start=2019&end=2050&f=A&linechart=~ref2021-d113020a.24-8-AEO2021&ctype=linechart&sid=ref2020-d112119a.5-11-AEO2020&sourcekey=0. Liquid Fuels (Case Reference case) for ICEV fuels activity, available at: https://www.eia.gov/outlooks/aeo/data/browser/#/?id=11-AEO2021&region=0-0&cases=ref2021&start=2019&end=2050&f=A&linechart=~ref2021-d113020a.42-11-AEO2021~ref2021-d113020a.10-11-AEO2021&ctype=linechart&sid=ref2020-d112119a.5-11-AEO2020&sourcekey=0.
43 Sources: 2020: U.S. Energy Information Administration (EIA), Short-Term Energy Outlook, October 2020 and EIA, National Energy Modeling System run ref2021.d113020a. Projections: EIA, AEO2021 National Energy Modeling System run ref2021.d113020a. Table 11. Petroleum and Other Liquids Supply and Disposition – Liquid Fuels: Crude Oil: Total Crude Supply.
44 For example, see, "Estimating Ammonia Emissions from Stationary Power Plants", Electric Power Research Institute, April 2009. Available at: https://www.epri.com/research/products/000000000001017985.
45 Email from Emma Zinsmeister to Kate Munson, January 12, 2022 5:23 PM.

from ethanol and biodiesel production. This COBRA-based BAU provided sufficient margin for the MOVES- and GREET-based predicted emission reductions. This agreement lends confidence to the national, upstream BAU values determined here. In Task 3, the health impact modeling will be based on the net upstream emissions consistent with all five upstream sectors modeled here. Appendix B lists all the Tiers from the default COBRA inventory included in developing the upstream BAU inventory shown here.

Finally, the Non-Combustion Case results in an emissions profile that drops dramatically and quickly. This is demonstrated by the emission factors in Table 11. Emissions are based on year 2023 values in COBRA but the Non-Combustion Case is much cleaner by 2023 than envisioned there. When this approach is used to estimate year 2020 estimates under the Non-Combustion Case for the entire grid it results in 2020 emissions much higher than in COBRA or the Base Case. To accommodate this, we scaled down the Non-Combustion Case emissions, when applied to the entire grid's load, so that the Base Case and Non-Combustion Case agree for year 2020.

Table 14 shows the resulting estimates of national, total upstream emissions for the relevant sectors. As discussed in Section 4 and above, we show two different values for the BAU EGU emissions, according to the two different paths for the future electric grid.

Table 14. National total upstream BAU emissions inventory for the relevant sectors, tons per year

Year	NOx	VOC	$PM_{2.5}$	SO_2	GHG (CO_2e)	NH_3
BAU Upstream Emissions from Crude, Feedstock, Refining & Transport, Domestic						
2020	850,275	3,291,868	59,550	199,282	N/A	8,988
2030	1,018,118	4,023,830	71,528	236,889	N/A	11,016
2040	1,000,679	3,964,229	70,144	225,161	N/A	10,926
2050	1,023,491	3,976,403	71,755	234,962	N/A	10,885
BAU Upstream Emissions from EGUs with Baseline Load attributed to the Base Case Electric Grid, Domestic						
2020	777,070	38,047	117,826	735,976	N/A	38,552
2030	693,679	34,516	107,747	651,186	N/A	34,415
2040	667,268	35,270	104,856	590,550	N/A	33,104
2050	530,525	34,936	73,315	243,265	N/A	26,320
BAU Upstream Emissions from EGUs with Baseline Load attributed to the Non-Combustion Case Electric Grid, Domestic						
2020	777,070	38,047	117,826	735,976	N/A	38,552
2030	334,382	22,297	45,751	133,923	N/A	16,589
2040	3,947	346	234	113	N/A	196
2050	3,965	348	235	115	N/A	197
Total BAU Upstream Emissions, Base Case Electric Grid, Domestic						
2020	1,627,345	3,329,915	177,376	935,258	N/A	47,540
2030	1,711,797	4,058,346	179,275	888,074	N/A	45,431
2040	1,667,947	3,999,499	175,000	815,711	N/A	44,030
2050	1,554,016	4,011,338	145,070	478,227	N/A	37,206
Total BAU Upstream Emissions, Non-Combustion Case Electric Grid, Domestic						
2020	1,627,345	3,329,915	177,376	935,258	N/A	47,540
2030	1,352,499	4,046,127	117,279	370,812	N/A	27,605
2040	1,004,626	3,964,576	70,378	225,274	N/A	11,121
2050	1,027,456	3,976,751	71,990	235,077	N/A	11,082

4.2.5. Changes in Upstream Emissions due to Vehicle Electrification

We calculated changes in upstream emissions associated with increased vehicle electrification under the Scenario as follows.

1. Calculate the total downstream fuel consumption values in gallons (or scf for CNG) for the BAU vehicle fleet. This is determined from the same MOVES outputs discussed in Section 3.3. As MOVES does not report fuel use in volume units, this was determined by dividing CO_2 emissions by fuel-specific emission factors (g CO_2 per gallon).[46]
2. Calculate fuel-consumption-per-year-and-per-vehicle emission factors by dividing the calculated values above by the BAU vehicle population.
3. Multiply the factors from in Step 2 by the ICEV population under the Scenario to obtain the Scenario-specific fuel consumption and resulting avoided fuel consumption in gallons (or scf for CNG).
4. Multiply the Avoided fuel consumption values with the GREET2021 fuel-and year-specific emission factors to obtain values for total avoided NOx, VOCs, SO_2, $PM_{2.5}$, and GHGs upstream emissions from the Scenario implementation.
5. Similarly, calculate the additional emissions resulting from the additional load to the grid from the EVs in the fleet Scenario
    a. Calculate energy factors in Joules per vehicle category and year, by dividing the BAU total energy use (in Joules) numbers by the BAU Vehicle Population
    b. Multiply these energy factors by the year and vehicle category-specific EV population breakdown resulting from the Scenario modeling and divide with their respective energy efficiency ratios (EER) to obtain the additional grid load resulting from these additional EVs.
    c. Multiply the grid load values obtained in step 6b with the GREET2021 EGU emission factors to obtain the additional electricity emissions under the Base and Non-Combustion Cases.

Note that GREET simulates global emissions from upstream activities. To account for the domestic portion of the crude and feedstock emissions, we applied a factor of 74% based on the GREET estimate of crude that is domestic. Note also that all grid emissions are assumed to be domestic.

Table 15 shows the global changes in total upstream emissions associated with the Scenario under the Base Case grid mix. Table 16 shows the same information but for domestic emissions. Note that the Additional Upstream Emissions due to Additional Grid Load line is not repeated in Table 16 since it is the same both domestically and globally under this EV Scenario. Table 17 shows the same global change in total upstream emissions resulting from the Scenario, but under the Non-Combustion Case grid mix. Similarly, Table 18 shows the same information as Table 16, but for the Non-Combustion Case grid mix.

46 Source: EPA 2021 Emission Factors for GHG Inventories. Available at: https://www.epa.gov/sites/default/files/2021-04/documents/emission-factors_apr2021.pdf

Table 15. Global changes total upstream emissions for the relevant sectors, Base Case electrification, tons per year

year	NOx	VOC	$PM_{2.5}$	SO_2	GHG (CO2e)	NH_3
Upstream Feedstock, Crude, Refining, and Transportation Emissions Reductions (Global)						
2020	-526	-596	-39	-149	-479,894	N/A
2030	-69,843	-75,336	-5,138	-19,476	-63,178,128	N/A
2040	-300,331	-302,279	-21,535	-80,509	-269,111,064	N/A
2050	-458,082	-436,290	-32,569	-124,962	-404,082,264	N/A
Additional Upstream Emissions due to Additional Grid Load						
2020	564	90	48	472	814,384	N/A
2030	62,208	10,209	5,271	51,557	91,735,747	N/A
2040	236,890	40,357	19,902	184,649	354,537,666	N/A
2050	250,195	53,207	19,526	101,807	400,155,528	N/A
Global Net Changes from Avoided Crude, Feedstock, Refining and Transport, and Additional EGUs						
2020	38	-506	8	324	334,490	N/A
2030	-7,635	-65,128	133	32,081	28,557,620	N/A
2040	-63,441	-261,922	-1,633	104,140	85,426,602	N/A
2050	-207,887	-383,083	-13,043	-23,154	-3,926,737	N/A

Table 16. Domestic changes total upstream emissions for the relevant sectors, Base Case electrification, tons per year

year	NOx	VOC	$PM_{2.5}$	SO_2	GHG (CO2e)	NH_3
Upstream Feedstock, Crude, Refining, and Transportation Emissions Reductions, Domestic						
2020	-444	-559	-35	-128	-423,762	N/A
2030	-58,969	-70,405	-4,592	-16,772	-55,843,321	N/A
2040	-253,090	-281,490	-19,250	-69,370	-237,717,792	N/A
2050	-384,751	-405,604	-28,989	-106,847	-355,975,180	N/A
Net Upstream Emissions Change: Avoided Crude, Feedstock, Refining and Transport Emissions, and Additional EGUs, Base Case, Domestic						
2020	120	-469	12	344	390,621	N/A
2030	3,239	-60,196	679	34,786	35,892,426	N/A
2040	-16,199	-241,133	652	115,279	116,819,874	N/A
2050	-134,556	-352,398	-9,463	-5,040	44,180,347	N/A
Percent Net Change in Emissions from BAU, Base Case Electrification, Domestic						
2020	0%	0%	0%	0%	N/A	N/A
2030	0%	-1%	0%	4%	N/A	N/A
2040	-1%	-6%	0%	14%	N/A	N/A
2050	-9%	-9%	-7%	-1%	N/A	N/A

Table 17. Global changes total upstream emissions for the relevant sectors, Non-Combustion Case electrification, tons per year

year	NOx	VOC	$PM_{2.5}$	SO_2	GHG (CO2e)	NH_3
Feedstock, Crude, Refining, and Transportation Emissions Reductions (Global)						
2020	-526	-596	-39	-149	-479,894	N/A
2030	-69,843	-75,336	-5,138	-19,476	-63,178,128	N/A
2040	-300,331	-302,279	-21,535	-80,509	-269,111,064	N/A
2050	-458,082	-436,290	-32,569	-124,962	-404,082,264	N/A
Additional Emissions due to Additional Grid Load						
2020	546	90	47	462	812,076	N/A
2030	28,484	6,418	2,208	10,188	47,719,961	N/A
2040	1,314	389	44	34	315,064	N/A
2050	1,799	533	61	47	431,504	N/A
Global Net Changes from Avoided Crude, Feedstock, Refining and Transport, and Additional EGUs						
2020	20	-506	7	314	332,183	N/A
2030	-41,359	-68,918	-2,930	-9,288	-15,458,166	N/A
2040	-299,017	-301,889	-21,491	-80,476	-268,796,000	N/A
2050	-456,283	-435,757	-32,509	-124,915	-403,650,761	N/A

Table 18. Domestic changes total upstream emissions for the relevant sectors, Non-Combustion Case electrification, tons per year

year	NOx	VOC	$PM_{2.5}$	SO_2	GHG (CO2e)	NH_3
Feedstock, Crude, Refining, and Transportation Emissions Reductions, Domestic						
2020	-444	-559	-35	-128	-423,762	N/A
2030	-58,969	-70,405	-4,592	-16,772	-55,843,321	N/A
2040	-253,090	-281,490	-19,250	-69,370	-237,717,792	N/A
2050	-384,751	-405,604	-28,989	-106,847	-355,975,180	N/A
Net Upstream Emissions Change: Avoided Crude, Feedstock, Refining and Transport Emissions, and Additional EGUs, Non-Combustion Case, Domestic						
2020	102	-469	12	334	388,314	N/A
2030	-30,485	-63,987	-2,384	-6,583	-8,123,360	N/A
2040	-251,776	-281,101	-19,206	-69,336	-237,402,729	N/A
2050	-382,952	-405,071	-28,928	-106,800	-355,543,677	N/A
Percent Net Change in Upstream Emissions from Upstream BAU, National Scenario, with Baseline Load attributed to the Non-Combustion Case Electric Grid, Domestic						
2020	0%	0%	0%	0%	N/A	N/A
2030	-2%	-2%	-2%	-1%	N/A	N/A
2040	-25%	-7%	-27%	-31%	N/A	N/A
2050	-37%	-10%	-40%	-45%	N/A	N/A

Figure 7. Net domestic upstream criteria pollution emissions changes from electrification scenario, with the Base Case

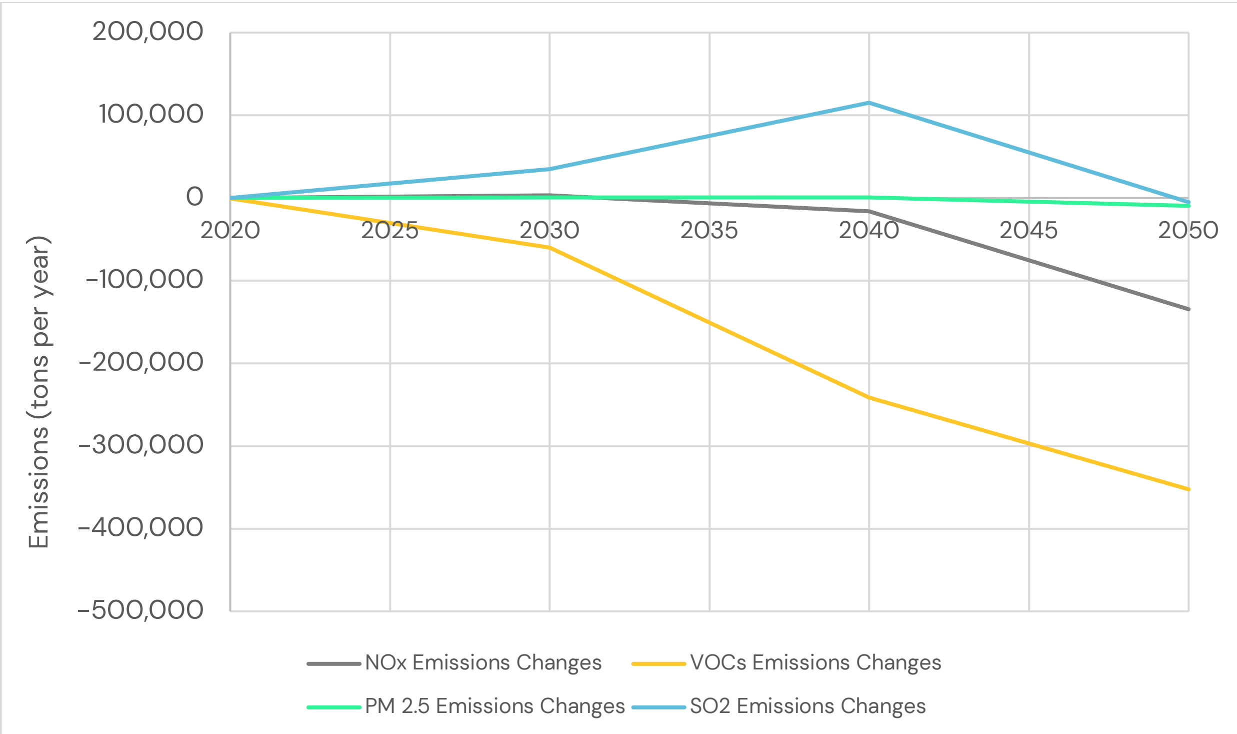


Figure 8. Global change in upstream GHG emissions with the Base Case and total number of electric vehicles under the Scenario

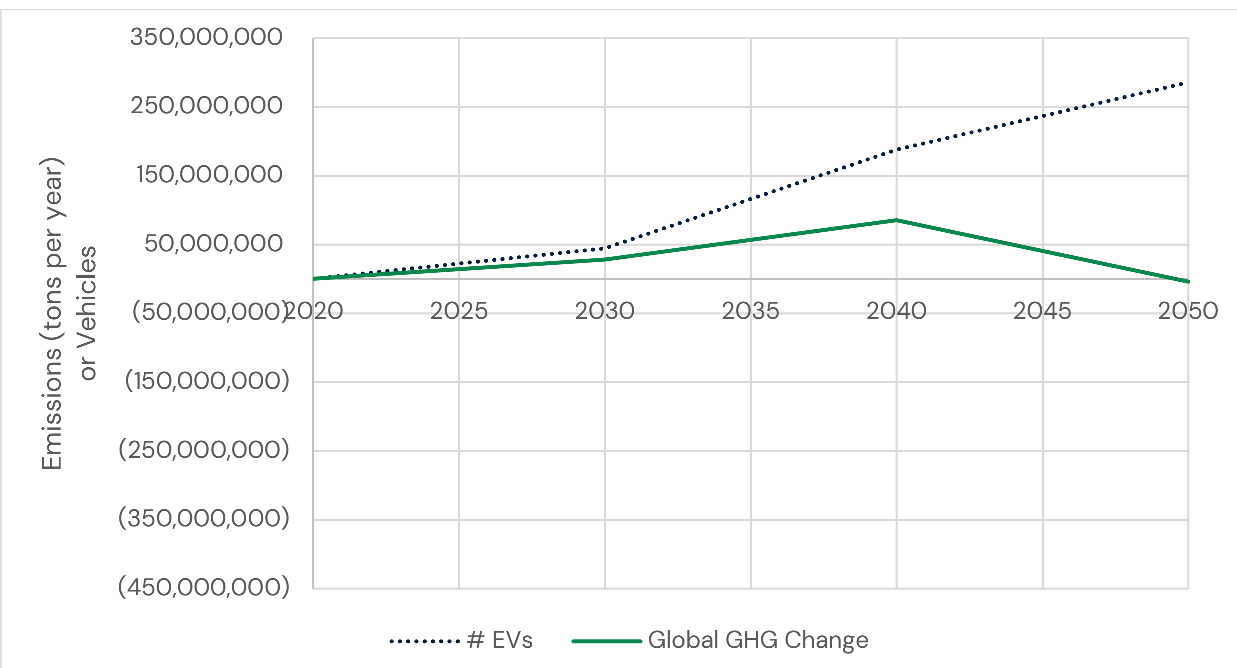


Figure 9. Net domestic upstream criteria pollution emissions changes from electrification scenario, with the Non-Combustion Case

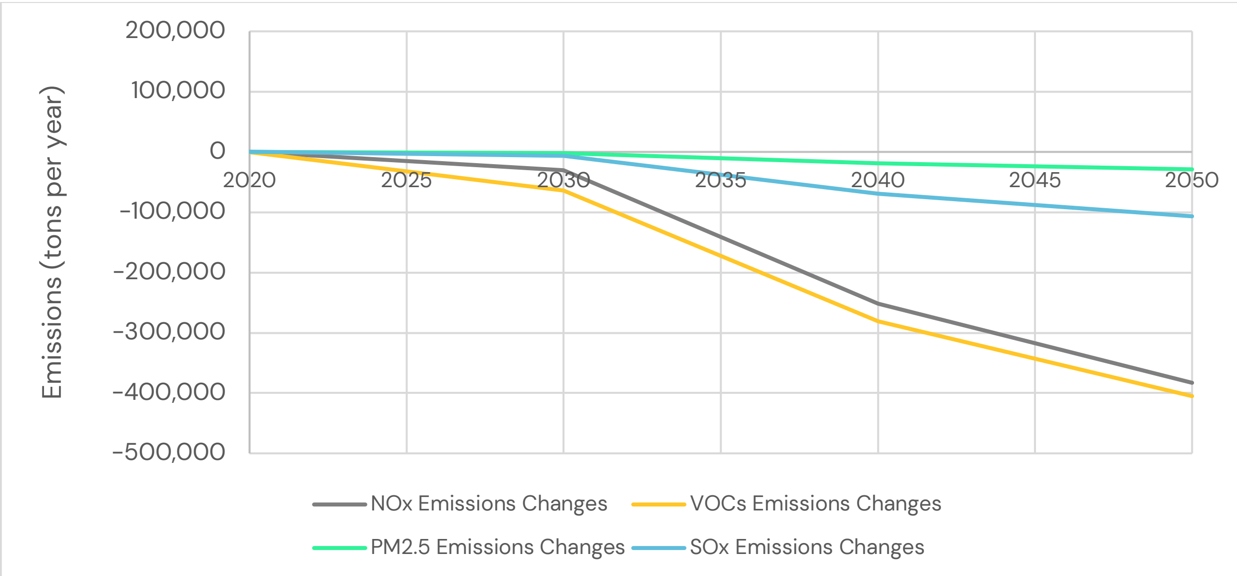
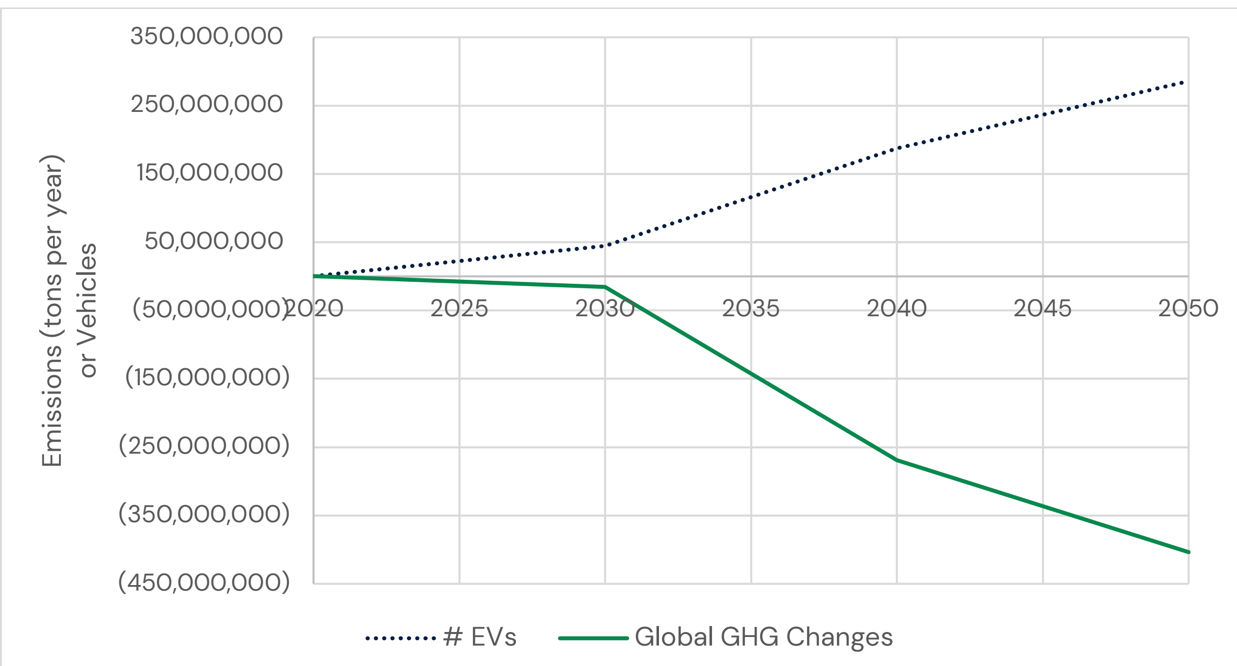


Figure 10. Global change in upstream GHG emissions with the Non-Combustion Case and total number of electric vehicles under the Scenario



4.3. Net Emissions

Finally, we calculated the net emissions nationally by combining the overall upstream BAU emissions and the overall downstream BAU emissions into a total BAU set of emissions. We combined the overall change in the upstream and in downstream emissions into an overall change in emissions under the Scenario, with each electrification Case. The upstream values are associated with the changes in refining, transportation, and crude/feedstock emissions from ICEV fuels and the emissions associated with EGUs (Section 4.2.4). The downstream changes are the changes tailpipe and fugitive emissions from the vehicles.
For this comparison, only domestic values are considered except for GHGs, where global values are presented. As discussed in Section 4.2.4, no upstream estimates of BAU GHGs are computed. Similarly, GREET does not produce NH_3 emissions, so no calculations of upstream changes in NH_3 emissions are included.

Table 19, and Table 20 show summaries of the national, total emissions under the Scenario, and the relative change in emissions. These include both the upstream and downstream activities. The two tables correspond to the two different potential approaches to representing upstream emissions, discussed at the beginning of Section 4 and in Section 4.2.4. Table 19 shows the total change in up and downstream emissions using the Base Case electrification. Table 20 is based on the Non-Combustion Case electrification, using the Non-Combustion Case electric grid emission factors for the baseline load and the additional load from new EVs.

Appendix A provides tables with additional details supporting this summary. Figure 11 and Figure 12 show the same net reduction in national, criteria pollutant emissions from the EV Scenario with the two electrification Cases. As with Table 19, and Table 20, the first figure shows net reductions as percent reductions relative to the national BAU value determined with the Base Case electrification. The second shows the reductions relative to a BAU curve based on the Non-Combustion Case for both new and existing loads on the electric grid. All are combined up- and down-stream emissions. Note that values here are reductions, such that positive values show decreasing emissions.

Figure 13 shows the upstream and downstream components of the national total emissions separately, for the two electrification Cases and the BAU. As above, the two rightmost columns represent the two different approaches to the upstream electrification Cases, with the rightmost illustrating the Non-Combustion Case applied to both new and baseline load. This demonstrates the relative magnitude of the up- and downstream components to the total and allows direct comparison between the two electrification scenarios. Note that both electrification Cases share the same EV Scenario, thus only the upstream electrification component differs. Also note that for GHGs (top row), no upstream emissions are shown. This is because there is no national, BAU predicted here for GHG emissions, as there is for the other pollutants (only the change in upstream emissions due to vehicle electrification).

Table 19. Total net change in emissions (domestic for criteria pollutants; global for GHGs) from combined upstream and downstream and corresponding total BAU emissions for the relevant sectors, with Base Case electrification, tons per year

Year	NOx	SO_2	VOC	$PM_{2.5}$ Total	CO_2 Equivalent	NH_3
Net Emissions Change, Nationally						
2020	-165	334	-942	-12	-1,318,658	N/A
2030	-71,159	33,476	-113,592	-2,868	-206,135,046	N/A
2040	-576,052	109,751	-478,032	-16,455	-969,244,276	N/A
2050	-1,133,364	-13,174	-779,867	-35,314	-1,591,799,582	N/A
National BAU (Upstream BAU Emissions from Fuels Production, Electricity Generation, and Downstream Vehicles)						
2020	4,127,515	945,119	4,444,636	252,367	N/A	148,576
2030	2,918,601	896,634	4,718,699	223,682	N/A	149,107
2040	2,675,300	823,977	4,561,125	215,044	N/A	154,626
2050	2,644,017	486,934	4,558,861	187,239	N/A	167,424
Percent Net Change in Emissions from BAU, National Scenario, Domestic						
2020	0%	0%	0%	0%	N/A	N/A
2030	-2%	4%	-2%	-1%	N/A	N/A
2040	-22%	13%	-10%	-8%	N/A	N/A
2050	-43%	-3%	-17%	-19%	N/A	N/A

Table 20. Total net change in emissions (domestic for criteria pollutants; global for GHGs) from combined upstream and downstream and corresponding total BAU emissions for the relevant sectors, with Non-Combustion Case electrification applied to both new and baseline load, tons per year

Year	NOx	SO_2	VOC	$PM_{2.5}$ Total	CO_2 Equivalent	NH_3
Net Emissions Change, Nationally						
2020	-182	324	-941	-13	-1,320,965	N/A
2030	-104,883	-7,892	-117,382	-5,931	-250,150,832	N/A
2040	-811,629	-74,865	-517,999	-36,313	-1,323,466,879	N/A
2050	-1,381,760	-114,935	-832,540	-54,779	-1,991,523,606	N/A
National BAU						
2020	4,127,515	945,119	4,444,636	252,367	N/A	149,604
2030	2,559,304	379,372	4,706,480	161,686	N/A	124,846
2040	2,011,979	233,540	4,526,202	110,422	N/A	110,883
2050	2,117,457	243,784	4,524,273	114,159	N/A	118,978
Percent Net Change in Emissions from BAU, National Scenario, Domestic						
2020	0%	0%	0%	0%	N/A	N/A
2030	-4%	-2%	-2%	-4%	N/A	N/A
2040	-40%	-32%	-11%	-33%	N/A	N/A
2050	-65%	-47%	-18%	-48%	N/A	N/A

Figure 11. Relative reduction in total (up- and downstream), national emissions of criteria pollutants for the EV Scenario with the Base Case and the national BAU.

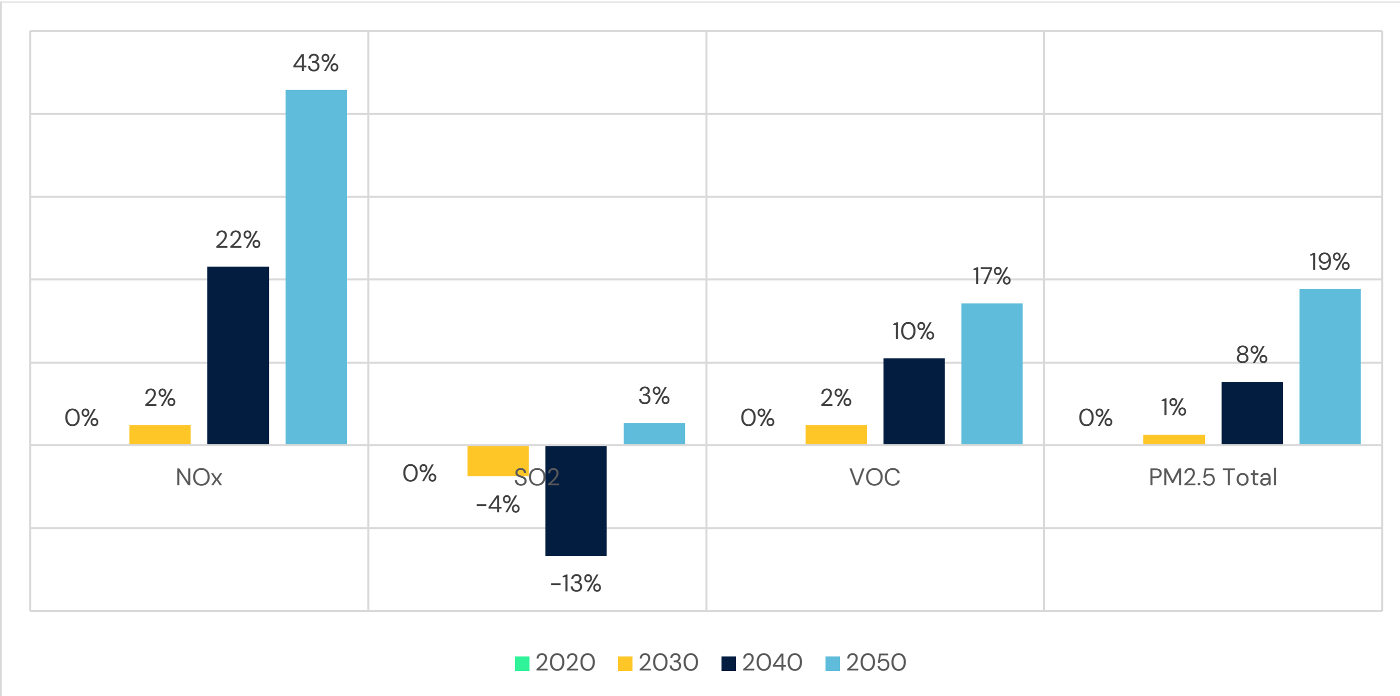


Figure 12. Relative reduction in total (up- and downstream), national emissions of criteria pollutants for the EV Scenario with the Non-Combustion Case and the national BAU (using the Non-Combustion Case electrification for both baseline and new load).

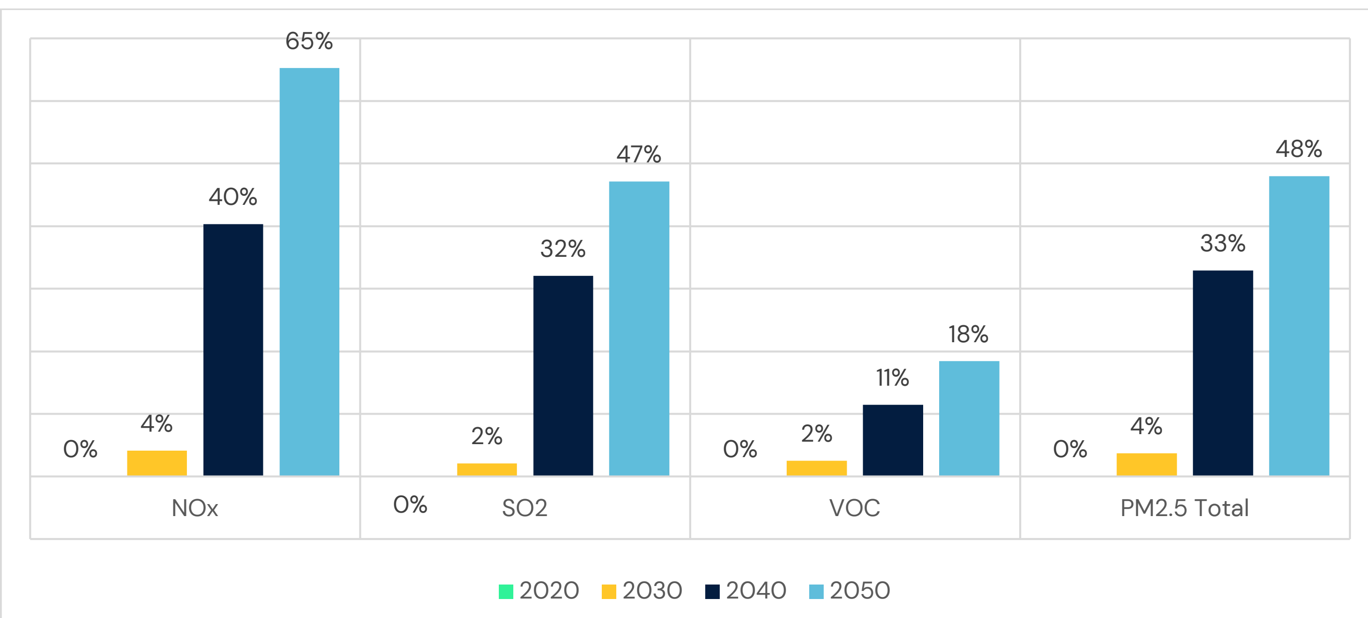
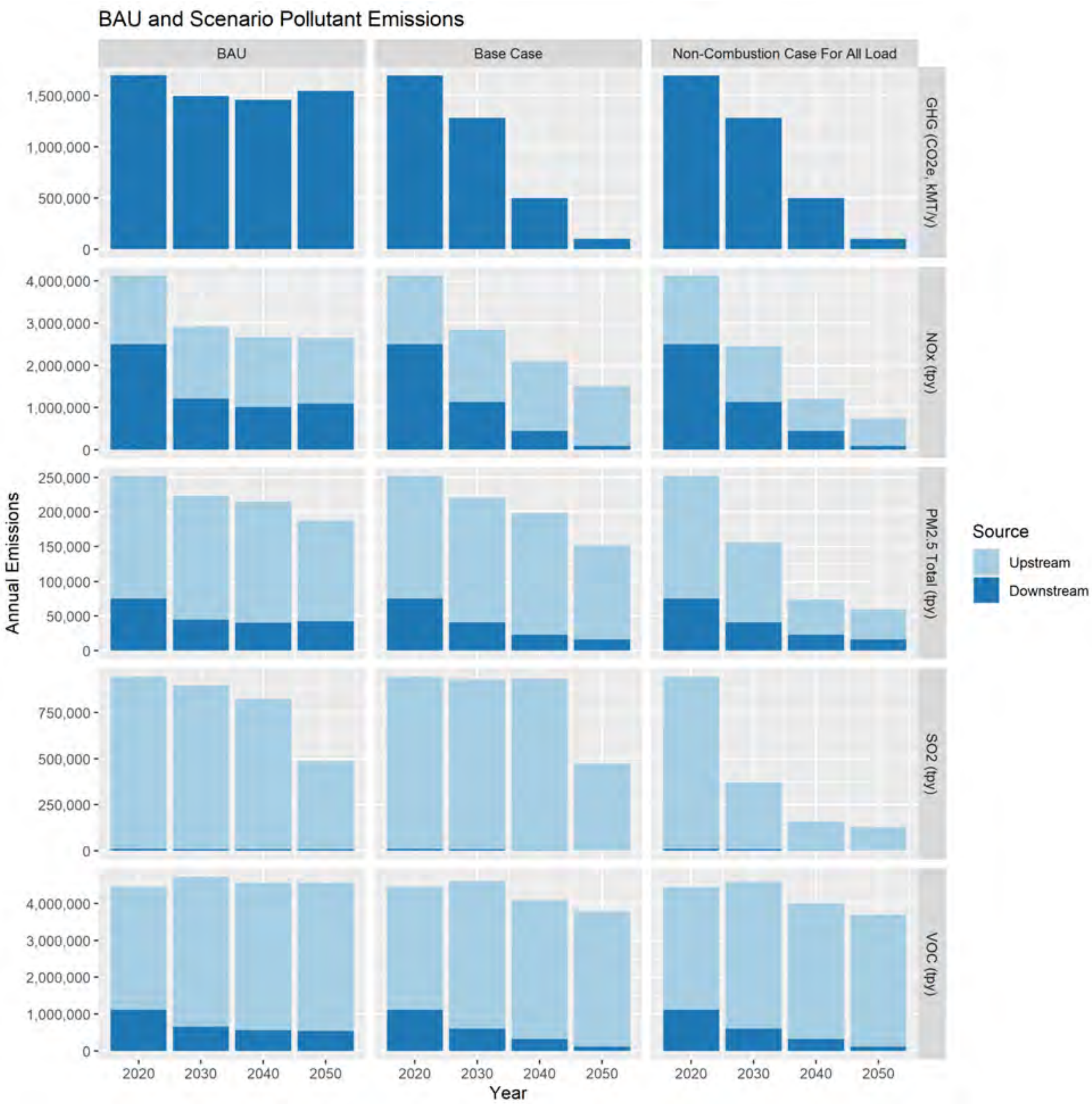


Figure 13. Emissions from up- and downstream components for each pollutant (downstream only for GHG) under the Base, Non-Combustion, and Non-Combustion for All Load electrification Case and the national BAU.



5. Human Health Benefits

5.1. COBRA Health Effects Modeling

We used the U.S. EPA Co-Benefits Risk Assessment (COBRA Version 4.1) model[47,48] to quantify and monetize changes in the incidence of adverse health impacts resulting from changes in human exposure to $PM_{2.5}$ following the transition to zero emission transportation technologies. COBRA is a screening-level air quality health benefits model that provides estimates of the impact of air pollution emissions changes on ambient $PM_{2.5}$ concentrations, associated health effect impacts, and the monetary value of avoidable health impacts.[49]

COBRA uses a source-receptor (S-R) matrix to translate changes in emissions of air pollutants into changes in ambient $PM_{2.5}$ concentrations. The S-R matrix consists of fixed transfer coefficients that relate annual average $PM_{2.5}$ concentrations at a single receptor in each county and the contribution of $PM_{2.5}$ precursors to this concentration from each emission source. The S-R matrix is based on the Climatological Regional Dispersion Model (CRDM), which includes summary data collected in 1990 from meteorological sites throughout North America.[50] The CRDM relies on simple dispersion-transport functions and chemical conversions at the receptor location.

The COBRA model contains detailed county- and source type-specific emissions estimates for the year 2023 in discrete categories. These estimates account for federal and state regulations as of May 2018.[51]

The COBRA health effects modeling analysis is similar to the 2020 "ALA Case" analysis but differs based on the following:

- **COBRA model version.** The COBRA model has been updated since the 2020 analysis, which relied on COBRA version 3.2. COBRA version 4.0 includes updates to default emissions data that accounts for air quality policymaking through 2018.
- **Updated function for avoided mortality estimates.** ICF implements a health impact function from a more recent study of the impact of changes in emissions levels on adult mortality incidence (Di et al., 2017).[52] Section 5.2.5 below discusses this change.
- **Investigating the potential impacts of electrification in different vehicle categories.** The updated analysis estimates the human health benefits from light duty (passenger) and heavy-duty (trucks) vehicles separately to tease out effects by vehicle class.
- **Pushing the grid to 100 percent renewables.** The updated analysis considers the extent to which the accelerated retirement of coal and the dramatic push to renewables make a difference in human health benefits. This Non-Combustion Case considers health benefits from all emissions reductions on the

47 https://www.epa.gov/cobra

48 A later version of COBRA, Version 4.1, was released November 2021, after this project was in progress. An EPA contact confirmed that none of the underlying COBRA data sources changed between version 4.0 and 4.1. The only changes are improved connectivity with the AVERT tool, which enables users to estimate the impacts of different energy efficiency and/or renewable energy programs based on temporal energy savings and hourly generation profiles. Therefore, we do not expect the COBRA release version to have material impacts on the results presented here.

49 COBRA relies on a suite of health impact functions and valuation functions that closely approximate what EPA used in developing the Final 2006 National Ambient Air Quality Standards (NAAQS) for PM.

50 The CRDM does not fully account for all chemical interactions that take place in the secondary formation of PM2.5.

51 Projected EGU emissions comply with the Cross-State Air Pollution Rule Update (CSAPR Update) finalized December 27, 2016, the Mercury and Air Toxics Rule (MATS), and the Standards of Performance for Greenhouse Gas Emissions from New, Modified, and Reconstructed Stationary Sources.

52 Di, Q., Wang, Y., Zanobetti, A., Wang, Y., Koutrakis, P., Choirat, C., Dominici, F. and Schwartz, J.D. 2017. Air pollution and mortality in the Medicare population. New Engl J Med 376(26): 2513-2522.

grid, meaning that both incremental load from new EVs and the base load on the grid are subject to the same grid mix, and the effects of both cleaner incremental and base loads are compared against the BAU electricity generation emissions for health effects. The implication is that health benefits from the Non-Combustion Case include benefits not related to EVs.[53]

- **New emissions modeling.** As discussed above, the latest versions of the MOVES and GREET models were implemented, resulting in changes to the baseline vehicle fleet and its associated emissions, along with that from the upstream activities.
- **New upstream emissions changes approach.** This updated analysis uses the full mass upstream emissions data calculated above for health impacts in COBRA for both the control and scenario emissions. National-level emissions by category are scaled to the county and COBRA emission tiers using the distribution of county- and tier-specific default 2023 COBRA emissions. The previous analysis did not include this level of consistency. Instead, it relied on an adjustment factor approach to determine future year BAU emissions.[54]
- **Reporting cumulative impacts and different analysis years.** The COBRA model assesses annual changes in cases of adverse health effects and the monetary benefits or disbenefits associated with those changes for years 2020, 2030, 2040, and 2050. The previous analysis considered 2018, 2030, and 2050. We also used a linear interpolation method to assess the cumulative impacts of proposed emissions scenarios over the entire period 2020 to 2050.
- **Including an analysis of demographic-specific impacts.** The updated analysis provides insight into the effects of emissions scenarios on people of color.

In addition to the health outputs, we also report the population-weighted change in annual average $PM_{2.5}$ concentrations under the scenario calculated based on COBRA's estimates of county-level changes in $PM_{2.5}$ and the total population in each county. This metric is useful as an approximation of the overall affect the Scenario will have on regional air quality.

5.2. Modeling Inputs and Approach

5.2.1. Emissions Changes

ICF adjusted emissions for the categories of emissions sources related to the emissions changes driven by two electricity generation Cases, three vehicle classes (light duty, heavy-duty, and total), and four analysis years (2020, 2030, 2040, and 2050). The emission sources adjusted for the BAU and scenarios include three main categories:

1. Downstream exhaust, fugitive, and evaporative emissions from highway vehicles;

53 This makes the sum of light- and heavy-vehicle results under the Non-Combustion Case much greater than the total-vehicle class since the benefits of the cleaner grid for baseline load appear in both. This does not happen for the Base Case because the BAU and Base Case use the same grid emission factors (See Table 11).
54 Default COBRA data in version 3.2 was for the year 2025, while the updated COBRA model version 4.0 default data reflect emissions in the year 2023. We scaled default 2025 COBRA emissions to future years, based on pollutant-specific adjustment factors and developed based on BAU emissions modeling in 2025 and future years (2030 and 2050 for the previous analysis). Reduced upstream emissions in the previous analysis were based on mass emissions and the distribution of upstream emissions in the 2025 default COBRA dataset for the EGU emissions category, similar to that done here for all upstream emissions. However, to accommodate discrepancy in calculated differences in upstream reductions and default BAU inventory, ICF reduced emissions in the refining category using a single percentage reduction for each modeled scenario in the previous analysis. The present study resolved these issues. See Section 4.2.4.

2. Upstream emissions from electric utilities; and
3. Upstream emissions from crude/feedstock production, fuel refining, and fuel transport.[55]

ICF did not adjust emissions for the remaining categories in the default COBRA emissions dataset.

ICF mapped the MOVES simulations used to determine the BAU downstream exhaust, fugitive, and evaporative emissions to highway vehicle emission source categories in COBRA. For the upstream emissions categories, ICF estimated BAU emissions based on factors derived from GREET modeling and total net electric power sector generation estimates (electric utilities) or total crude supply estimates (crude/feedstock production, fuel refining, and fuel transport) for the years 2020, 2023 (the year of COBRA default emissions data), 2030, 2040, and 2050 from the U.S. Energy Information Administration Annual Energy Outlook (AEO) for 2021.[56,57,58]

To develop base case and scenario emissions for the two electricity generation cases and three vehicle electrification scenarios, we distributed modeled mass emissions (described in detail in Section 4) for each relevant emission source category to county-level base case and scenario emissions proportional to the magnitude of county-level emissions in the default 2023 COBRA emissions. Base case and scenario emissions for the natural gas extraction and asphalt manufacturing sub-categories of petroleum production are unchanged here. For the highway vehicle emission source category, modeled mass emissions changes varied by vehicle type sub-category, to capture the COBRA model's encapsulation of the different S-R matrix values by different vehicle types. Modeled mass emission changes for the electric utilities and crude/feedstock production, fuel refining, and fuel transport emission source categories did not vary by emission source sub-category. The emissions in COBRA are organized around different sectors and subsectors and calculated with different models than employed here.

5.2.2. Vehicle Classes for Outcome Reporting

ICF evaluated the impacts of changes in emissions on human health separately for the following three vehicle classes:

1. **Total**: evaluation of emissions changes among both light duty and heavy-duty vehicles together;
2. **Light duty**: evaluation of both up and downstream emissions changes related to light duty vehicles only; and
3. **Heavy-duty**: evaluation of emissions changes related heavy-duty vehicles only.

As with the 2020 study, the three different vehicle categories modeled for emissions were allocated to the two vehicle (light and heavy-duty) and fuel type categories in COBRA. Section 3.2 summarized the vehicle categories considered for electrification in this study. For cross-referencing purposes, those four categories are numbered as:

1. Passenger vehicles

---

55 In COBRA, these upstream emissions categories correspond to categories (described as "tiers") for industrial fuel combustion, petroleum and related industries, storage & transport, and other industrial processes (specifically miscellaneous ethanol production). ICF did not adjust emissions for the subcategory of petroleum and related industries that relates to asphalt or natural gas manufacturing.

56 U.S. Energy Information Administration (U.S. EIA). 2021. Annual Energy Outlook 2021. Table 8: https://www.eia.gov/outlooks/aeo/pdf/AEO_Narrative_2021.pdf

57 U.S. Energy Information Administration (U.S. EIA). 2021. Annual Energy Outlook 2021. Table 11: https://www.eia.gov/outlooks/aeo/pdf/AEO_Narrative_2021.pdf

58 Note that COBRA operates on annual emissions and does not include seasonality that may be present in pollution sources, including evaporative emissions. As described in Section IV, all emissions calculated and used here represent annual totals.

2. Light heavy-duty trucks
3. Medium- and heavy-trucks, and
4. School buses

The first two columns of Table 21 list the vehicle-fuel categories in version 4.0 of the COBRA model. The third lists the two vehicle classes into which benefits are aggregated. The fourth column provides a cross-walk between vehicle categories. This mapping applies to the six vehicle classes modeled in COBRA.

Table 21. COBRA and Scenario vehicle-fuel combinations used in this study

COBRA Tier 1	Fuel	COBRA Vehicle Class	Corresponding EV Scenario Vehicle Categories
Highway Vehicles	Compressed Natural Gas (CNG)	Heavy-Duty	(3) Medium- and heavy-trucks and (4) School buses
Highway Vehicles	Diesel Fuel	Heavy-Duty	(2) Light heavy-duty trucks, (3) Medium- and heavy-trucks, and (4) School buses
Highway Vehicles	Diesel Fuel	Light Duty	(1) Passenger vehicles
Highway Vehicles	Ethanol (E-85)	Light Duty	(1) Passenger vehicles
Highway Vehicles	Gasoline	Heavy-Duty	(2) Light heavy-duty trucks, (3) Medium- and heavy-trucks, and (4) School buses
Highway Vehicles	Gasoline	Light Duty	(1) Passenger vehicles

5.2.3. Vehicle Emissions

Section 4 provided the emissions changes under the vehicle scenario, with both electricity Cases. To allocate vehicle emissions changes to the two vehicle classes amongst which benefits were attributed, we first split the up- and downstream emissions changes into the same two classes. These are the emission values used in COBRA for each simulation segregating impacts by vehicle class. Table 22 summarizes the emissions changes. Note that GHGs are not relevant for COBRA and thus are not reported here. Note also that upstream emissions are not calculated for ammonia as it is not included in the GREET model.

Table 22. Summary of changes In up- and downstream emissions allocated to light and heavy vehicle classes.

Year	NOx (tpy)	VOC (tpy)	$PM_{2.5}$ (tpy)	SO_2 (tpy)	NH_3 (tpy)	NOx (tpy)	VOC (tpy)	$PM_{2.5}$ (tpy)	SO_2 (tpy)	NH_3 (tpy)
Net Upstream Emissions Change: Avoided Crude, Feedstock, Refining and Transport Emissions, and Additional EGUs, Base Case, Domestic										
Base Case										
	Light Duty Vehicles					Heavy-Duty Vehicles				
2020	120	-469	12	344	N/A	0	0	0	0	N/A
2030	3,677	-57,359	579	31,110	N/A	-438	-2,837	100	3,675	N/A
2040	-6,449	-215,133	323	90,484	N/A	-9,750	-26,000	329	24,794	N/A
2050	-87,239	-303,536	-7,158	-1,829	N/A	-47,317	-48,862	-2,305	-3,212	N/A
Non-Combustion Case										
	Light Duty Vehicles					Heavy-Duty Vehicles				
2020	102	-469	12	334	N/A	0	0	0	0	N/A
2030	-26,338	-60,733	-2,147	-5,710	N/A	-4,147	-3,254	-237	-874	N/A
2040	-189,008	-246,106	-15,066	-52,583	N/A	-62,768	-34,995	-4,140	-16,755	N/A
2050	-268,323	-341,935	-21,349	-76,015	N/A	-114,628	-63,136	-7,580	-30,788	N/A
Downstream Emissions Changes										
	Light Duty Vehicles					Heavy-Duty Vehicles				
2020	-284	-473	-24	-10	-101	0	0	0	0	0
2030	-23,123	-49,079	-2,903	-1,176	-13,305	-51,275	-4,316	-644	-133	-1,175
2040	-80,974	-195,520	-11,369	-4,360	-54,801	-478,879	-41,379	-5,737	-1,169	-10,432
2050	-111,168	-347,094	-16,170	-6,050	-81,460	-887,640	-80,375	-9,681	-2,085	-18,805

5.2.4. Impacts from a Cleaner Grid

In addition to differences in health impacts among the three vehicle classes, we also simulated differences in health impacts among two grid electrification Cases summarized in Section 4:

- The **Base Case**: A more business as usual projection for the grid, based on the BNEO analysis from the 2020 study; and
- The **Non-Combustion Case**: A more ambitious renewables projection, with a heavy emphasis on non-emissions free power, such as from wind and solar.

As noted in Section 5.1, the BAU and Base Case have different loads due to the new EVs, but use the same grid mix, and thus the same emission factors. The Non-Combustion Case uses different grid emission factors. (See Table 11.) this study uses an average grid approach, which applies the same emission rate (g/kWh) to both existing/baseline and new loads. Thus, the emissions and health benefits of the Non-Combustion Case include load changes from new EVs and emission changes from the baseline load which has the same level of activity, but lower emissions than the BAU, due to the cleaner grid mix. Thus, the health benefits from the Non-Combustion Case compared against the BAU include benefits not related to EVs.

5.2.5. Health incidence and impact functions

COBRA relies on baseline incidence rates for each health endpoint and pre-loaded health impact functions to estimate the absolute change in annual incidence of mortality. We obtained age-, health endpoint-, and county-specific incidence rates in the United States projected for years 2020, 2030, 2040, and 2050 from the U.S. EPA Environmental Benefits Mapping and Analysis Program (BenMAP[59]) model database.

COBRA includes several pre-loaded health impact functions that estimate the change in adverse health effects from changes in air pollutant concentrations based on epidemiological studies. Each function was developed based on data from cohort studies performed in various locations throughout the U.S. and uses different formulas and coefficients. The applicable ages for each health impact function reflect the age groups examined in the cohort studies. COBRA employs these health impact functions to assess the impact of $PM_{2.5}$ reductions on mortality incidence (for both infants and adults), nonfatal heart attacks, hospital admissions for respiratory and cardiovascular events, acute bronchitis, upper and lower respiratory symptoms, emergency room visits, minor restricted activity days, work loss days, and asthma exacerbation. (Note that COBRA does not determine health outcomes related to changes in ambient ozone.) For certain health endpoints, such as adult mortality and nonfatal heart attacks, COBRA employs multiple functions to obtain a lower bound and an upper bound estimate of potential health impacts. This is consistent with methods EPA employed when analyzing proposed National Ambient Air Quality Standards.[60]

BenMAP, EPA's comprehensive model for estimating health impacts from air pollution, was updated in May 2021 to include more recent studies of the relationship between mortality:

- Di et al. (2017), based on an analysis of Medicare beneficiaries in the U.S. from 2000-2012 (applies to ages 65 to 99); and

---

59 Environmental Benefits and Mapping Program-Community Edition (BenMAP-CE). BenMAP is US EPA's detailed model for estimating the health impacts from air pollution. Unlike COBRA, it relies on detailed input on air pollutant concentration changes, then applies concentration-response (C-R) health impact functions. See https://www.epa.gov/benmap For more information.

60 U.S. EPA. (2006). Final Regulatory Impact Analysis: PM2.5 NAAQS. Research Triangle Park, NC: Office of Air and Radiation, Office of Air Quality Planning and Standards; U.S. EPA. (2009). Proposed NO2 NAAQS Regulatory Impact Analysis (RIA). Research Triangle Park, NC.: Office of Air and Radiation, Office of Air Quality Planning and Standards

- Turner et al. (2016),[61] based on analysis of participants in the American Cancer Society (ACS) Cancer Prevention Study II from 1982-2004 (applies to ages 30-99).

To remain consistent with the most recent research on particulate matter and mortality, ICF used the health impact function from Di et al. (2017) in place of the older study from Lepeule et al. (2012)[62] from the COBRA default health impact function dataset. However, the Turner et al. (2016) health impact function is based on estimated $PM_{2.5}$ levels measured during the warm season (April-September) and is therefore not applicable to annual average $PM_{2.5}$ estimates produced by COBRA. Therefore, ICF retained the Krewski et al. (2009) analysis of the ACS data as the basis for the mortality impact calculations.

As in the 2020 study, we classify mortality impacts as, "high" and "low". However, these classifications are not directly comparable to the previous study. Like Lepeule et al. (2012), the relative risk value per 10 $\mu g/m^3$ increase in $PM_{2.5}$ from Di et al. (2017) (1.07) is higher than the relative risk value per 10 $\mu g/m^3$ increase in $PM_{2.5}$ from Krewski et al. (2009)[63] (1.03) indicating that, in most cases, Di et al. (2017) will produce a higher estimate of avoided mortality cases than Krewski et al. (2009). However, the relative risk value per 10 $\mu g/m^3$ increase in $PM_{2.5}$ from Di et al. (2017) is smaller than the relative risk value from Lepeule et al. (2012) (1.14) and the health impact function based on Di et al. (2017) applies to a smaller subset of the population (those aged 65 to 99). Still, the health impact function based on Di et al. (2017) will more often generate a larger estimate of avoided mortality cases compared to Krewski et al. (2009), even though Krewski et al. (2009) applies to a larger subset of the population (those aged 30 to 99) because the Di et al. (2017) relative risk value is much larger and because baseline mortality incidence among the elderly is high. We would especially expect larger estimates of avoided mortality cases from Di et al. (2017), compared to Krewski et al. (2009), in future years, when estimates of the proportion of the total population that is aged 65 to 99 is expected to grow due to medical advancements leading to increased lifespan and reduced mortality incidence.

Appendix C summarizes the health impact functions and their applicable age ranges used here.

5.2.6. Population

The exposed population is the number of people affected by the reduction in $PM_{2.5}$ levels resulting from the transition to zero emission transportation technologies. ICF obtained county- and age-specific population estimates for the 2020, 2030, 2040, and 2050 scenario years from the BenMAP model database. These are based on the 2010 U.S. Census[64] with annual population growth rates developed by Woods and Poole (2015).[65]

5.2.7. Valuation

The final step in the health benefits analysis is to estimate the economic value of avoided health impacts. COBRA includes several pre-loaded valuation functions for health endpoints associated with $PM_{2.5}$ concentrations. Depending on the health endpoint being considered, valuation methods may involve estimates

61 Turner, M.C., Jerrett, M., Pope, A., III, Krewski, D., Gapstur, S.M., Diver, W.R., Beckerman, B.S., Marshall, J.D., Su, J., Crouse, D.L. and Burnett, R.T. 2016. Long-term ozone exposure and mortality in a large prospective study. Am J Respir Crit Care Med 193(10): 1134-1142.

62 Lepeule J, Laden F, Dockery D, Schwartz J. Chronic exposure to fine particles and mortality: an extended follow-up of the Harvard Six Cities study from 1974 to 2009. Environ Health Perspect, 120(7), 965-970.

63 Krewski, D., M. Jerrett, R. Burnett, R. Ma, E. Hughes, Y. Shi, M. C. Turner, C. A. I. Pope, G. Thurston, E. Calle and M. J. Thun. 2009. Extended follow-up and spatial analysis of the American Cancer Society study linking particulate air pollution and mortality. HEI Research Report, 140, Health Effects Institute, Boston, MA.

64 Because county-level data is based on the 2010 Census, FIPS county codes may be outdated. ICF did not adjust any FIPS-level county population information for the health impacts analysis.

65 Woods & Poole Economics Inc. 2015. Complete Demographic Database. Washington, DC. http://www.woodsandpoole.com/index.php.

of willingness to pay to avoid certain illnesses, the medical costs of treating illnesses, the value of lost wages, and the EPA-estimated value of a statistical life (VSL; applicable to mortality endpoints only).

Default valuation data for all health points in COBRA are reported in 2017$. For non-mortality health endpoints, ICF did not adjust valuation data to reflect changes in willingness to pay values, medical costs, or lost wages in 2020, 2030, 2040, and 2050. This makes the present results more directly comparable to those from the previous (2020) study.

Mortality, however, is typically found to be the driver for valuation given the magnitude of the VSL. Following EPA's guidance for economic analysis,[66] we use the VSL ($4.8 million in 1990$)[67] to estimate the value of avoided mortality. ICF used projected income growth data from the Organization for Economic Cooperation and Development (OECD) and consumer price index data from the Bureau of Labor Statistics (BLS) to project the original $4.8 million VSL estimate in 1990$ to the 2020, 2030, 2040, and 2050 analysis years.[68,69,70]

We do not consider other consumer costs in this valuation, such as differences in vehicle operations and maintenance, fuel costs, any tax revenue issues, etc. This valuation focuses entirely on monetized health and climate (Section6) benefits.

5.3. Results

5.3.1. Analysis Year Specific Impacts

Table 23 and Table 24 present total, national, annual estimates of the number of avoided adverse health effects and the economic value of these health risk reductions at 3% and 7% discount rates[71] from the Base and Non-Combustion Cases, respectively. Each is reported for the total vehicle class. That is, light- and heavy-duty vehicles modeled together. These economic values reflect the US population's willingness to pay to reduce risks of premature mortality or certain illnesses.[72] As such, these economic values represent monetized US public health benefits.

In addition to the national summaries for all vehicles presented here, Appendix D provides the same results resolved at a state level for each of the 48 states modeled plus DC.

At a 3% discount, total monetized public health benefits range from approximately $4.5 million in 2020 to $33.1 billion in 2050 under the Base Case considering all vehicle classes. The same approach under the Non-Combustion Case shows benefits ranging from approximately $4.9 million in 2020 to $62.4 billion in 2050. Adult mortality is the main driver of benefits of emissions changes under all electricity generation and vehicle

66 U.S. EPA. 2010. Guidelines for Preparing Economic Analyses. EPA 240-R-10-001.

67 Our approach is consistent with EPA regulatory impact analyses which use this value for VSL and adjust it for inflation and changes in income over time.

68 OECD (2020), "Long-term baseline projections, No. 103", OECD Economic Outlook: Statistics and Projections (database): https://www.oecd-ilibrary.org/economics/data/oecd-economic-outlook-statistics-and-projections/long-term-baseline-projections-no-103_68465614-en

69 Bureau of Labor Statistics, 2020 (Series ID: CUUR0000SA0,CUUS0000SA0): https://data.bls.gov/pdq/SurveyOutputServlet

70 Because ICF adjusted VSL for the mortality endpoint, but not other health endpoints, results may have a minor downward bias.

71 The 3% discount rate reflects society's valuation of differences in the timing of benefits; the 7% discount rate reflects the opportunity cost of capital to society.

72 For some health endpoints, the economic value estimates are based on the non-market valuation studies that estimate people's willingness to pay for reductions in these health risks. For other endpoints, non-market valuation studies are not readily available, and valuation is approximated using cost-of-illness methods that estimate medical costs and illness-related productivity losses.

scenarios, with an estimated decrease in the number of premature deaths among adults between 2,650 and 2,830 under the 2050 Base Case and between 5,010 and 5,350 under the 2050 Non-Combustion Case.

On a national level, reductions are seen in population weighted, annual $PM_{2.5}$ concentrations under the Base and Non-Combustion Cases. The annual concentration reductions under the Base Case are 0.000046 $\mu g/m^3$ in 2020, 0.012 $\mu g/m^3$ in 2030, 0.077 $\mu g/m^3$ in 2040, and 0.163 $\mu g/m^3$ in 2050. The annual concentration reductions under the Non-Combustion Case are 0.000048 $\mu g/m^3$ in 2020, 0.143 $\mu g/m^3$ in 2030, 0.294 $\mu g/m^3$ in 2040, and 0.297 $\mu g/m^3$ in 2050.

At a 3% discount and under the Base Case, total monetized public health benefits for the light duty vehicle class range from approximately $4.5 million in 2020 to $13.8 billion in 2050, while total monetized public health benefits for the heavy-duty vehicle class range from $0 in 2020 (before heavy vehicle electrification begins) to $19.2 billion in 2050. At a 3% discount and under the Non-Combustion Case, total monetized public health benefits for the light duty vehicle class range from approximately $4.9 million in 2020 to $41.1 billion in 2050, while total monetized public health benefits for the heavy-duty vehicle class range from $0 in 2020 to $42.9 billion in 2050.

Prior to completing this analysis, we were unsure if the sum of light duty and heavy-duty benefits would equal the total benefits, due to nonlinearities in the COBRA modeling. However, these results indicate that the light duty and heavy-duty benefits essentially equal the total vehicle class benefits under the Base Case. This implies that calculated benefits can be allocated to the light and heavy vehicles for the Base Case. However, as discussed above, benefits due to cleaning of the electric grid associated with baseline activity appear in both light and heavy vehicle results for the Non-Combustion Case, thus these results cannot be combined.

Table 23. Estimated annual health benefits under the Base Case, considering all vehicle classes combined for years 2020, 2030, 2040, and 2050

Health Endpoint	2020			2030		
	Change in the Number of Cases	Monetary Health Benefits (2017$)[a,b]		Change in the Number of Cases	Monetary Health Benefits (2017$)[a,b]	
		3% Discount	7% Discount		3% Discount	7% Discount
Mortality, low estimate[c,d]	0.48	$4,690,000	$4,220,000	171.00	$1,730,000,000	$1,560,000,000
Mortality, high estimate[d,e]	0.45	$4,360,000	$3,930,000	173.00	$1,740,000,000	$1,570,000,000
Infant Mortality	0.004	$35,000	$31,500	0.95	$9,630,000	$8,680,000
Nonfatal Heart Attacks, low estimate[f]	0.03	$4,890	$4,760	15.80	$2,500,000	$2,430,000
Nonfatal Heart Attacks, high estimate[g]	0.28	$45,500	$44,200	147.00	$23,200,000	$22,600,000
Hospital Admits, All Respiratory	0.10	$3,750	$3,750	42.90	$1,610,000	$1,610,000
Hospital Admits, Cardiovascular (except heart attacks)	0.10	$5,000	$5,000	41.20	$2,110,000	$2,110,000
Acute Bronchitis	1.04	$633	$633	275.00	$168,000	$168,000
Upper Respiratory Symptoms	18.70	$792	$792	4,970.00	$210,000	$210,000
Lower Respiratory Symptoms	13.20	$352	$352	3,490.00	$93,300	$93,300
Emergency Room Visits, Asthma	0.30	$171	$171	93.00	$52,400	$52,400
Minor Restricted Activity Days	560.00	$48,600	$48,600	148,000.00	$12,800,000	$12,800,000
Work Loss Days	95.90	$19,200	$19,200	25,100.00	$5,030,000	$5,030,000
Asthma Exacerbation	19.30	$1,420	$1,420	5,160.00	$379,000	$379,000
Total, low estimate		**$4,810,000**	**$4,340,000**		**$1,760,000,000**	**$1,590,000,000**
Total, high estimate		**$4,520,000**	**$4,090,000**		**$1,800,000,000**	**$1,620,000,000**
Population-Weighted Average Delta $PM_{2.5}$ (µg/m3)		0.000046			0.012	

Notes:

[a]The discount rate expresses future economic values in present terms. Not all health effects and associated economic values occur in the year of analysis.

[b]Adult mortality valuation is based on a Value of a Statistical Life (VSL; grown from EPA 1990 VSL using standard income growth data) calculated by ICF and is lagged 20 years (per COBRA Model guidance), not the default valuation in COBRA.

[c]Low estimate based on Krewski et al. (2009) (relative risk of 1.03 associated with a 10 $\mu g/m^3$ increase in $PM_{2.5}$), which applies to adults aged 30 to 99.

[d]Note: In some cases, the "low" estimate may be larger than the "high" estimate. This happens occasionally depending on county-specific population distribution and baseline health incidence.

[e]High estimate based on Di et al. (2017) (relative risk of 1.07 associated with a 10 $\mu g/m^3$ increase in $PM_{2.5}$), which applies to adults aged 65 to 99.

[f]Low estimate based on four acute myocardial infarction (AMI) studies.

[g]Low estimate based on Peter et al. (2001).

Health Endpoint	2040			2050		
	Change in the Number of Cases	Monetary Health Benefits (2017$)[a,b]		Change in the Number of Cases	Monetary Health Benefits (2017$)[a,b]	
		3% Discount	7% Discount		3% Discount	7% Discount
Mortality, low estimate[c]	1,220.00	$13,000,000,000	$11,700,000,000	2,650.00	$30,000,000,000	$27,100,000,000
Mortality, high estimate[d]	1,270.00	$13,600,000,000	$12,200,000,000	2,830.00	$32,100,000,000	$28,900,000,000
Infant Mortality	6.26	$66,600,000	$60,000,000	13.10	$148,000,000	$134,000,000
Nonfatal Heart Attacks, low estimate[e]	132.00	$20,800,000	$20,200,000	323.00	$50,900,000	$49,600,000
Nonfatal Heart Attacks, high estimate[f]	1,220.00	$193,000,000	$188,000,000	2,990.00	$472,000,000	$460,000,000
Hospital Admits, All Respiratory	345.00	$13,000,000	$13,000,000	822.00	$30,900,000	$30,900,000
Hospital Admits, Cardiovascular (except heart attacks)	331.00	$16,900,000	$16,900,000	792.00	$40,400,000	$40,400,000
Acute Bronchitis	1,930.00	$1,180,000	$1,180,000	4,310.00	$2,630,000	$2,630,000
Upper Respiratory Symptoms	35,000.00	$1,480,000	$1,480,000	78,200.00	$3,310,000	$3,310,000
Lower Respiratory Symptoms	24,600.00	$657,000	$657,000	54,900.00	$1,470,000	$1,470,000
Emergency Room Visits, Asthma	686.00	$386,000	$386,000	1,580.00	$892,000	$892,000
Minor Restricted Activity Days	1,040,000.00	$89,800,000	$89,800,000	2,310,000.00	$200,000,000	$200,000,000
Work Loss Days	176,000.00	$35,200,000	$35,200,000	392,000.00	$78,500,000	$78,500,000
Asthma Exacerbation	36,400.00	$2,670,000	$2,670,000	81,500.00	$5,980,000	$5,980,000
Total, low estimate		**$13,200,000,000**	**$11,900,000,000**		**$30,600,000,000**	**$27,600,000,000**
Total, high estimate		**$14,000,000,000**	**$12,600,000,000**		**$33,100,000,000**	**$29,900,000,000**
Population-Weighted Average Delta $PM_{2.5}$ (µg/m3)		0.077			0.163	

Notes:

[a]The discount rate expresses future economic values in present terms. Not all health effects and associated economic values occur in the year of analysis.

[b]Adult mortality valuation is based on a Value of a Statistical Life (VSL; grown from EPA 1990 VSL using standard income growth data) calculated by ICF and is lagged 20 years (per COBRA Model guidance), not the default valuation in COBRA.

[c]Low estimate based on Krewski et al. (2009) (relative risk of 1.03 associated with a 10 µg/m^3 increase in $PM_{2.5}$), which applies to adults aged 30 to 99. \

[d]High estimate based on Di et al. (2017) (relative risk of 1.07 associated with a 10 µg/m^3 increase in $PM_{2.5}$), which applies to adults aged 65 to 99.

[e]Low estimate based on four acute myocardial infarction (AMI) studies.

[f]Low estimate based on Peter et al. (2001).

Table 24. Estimated health benefits under the Non-Combustion Case, considering all vehicle classes combined for years 2020, 2030, 2040, and 2050

Health Endpoint	2020			2030		
	Change in the Number of Cases	Monetary Health Benefits (2017$)[a,b]		Change in the Number of Cases	Monetary Health Benefits (2017$)[a,b]	
		3% Discount	7% Discount		3% Discount	7% Discount
Mortality, low estimate[c,d]	0.52	$5,090,000	$4,580,000	2,610.00	$26,300,000,000	$23,700,000,000
Mortality, high estimate[d,e]	0.49	$4,750,000	$4,280,000	2,670.00	$27,000,000,000	$24,300,000,000
Infant Mortality	0.00	$37,300	$33,600	12.60	$128,000,000	$115,000,000
Nonfatal Heart Attacks, low estimate[f]	0.03	$5,590	$5,440	289.00	$45,700,000	$44,500,000
Nonfatal Heart Attacks, high estimate[g]	0.32	$52,000	$50,500	2,680.00	$424,000,000	$412,000,000
Hospital Admits, All Respiratory	0.11	$4,120	$4,120	685.00	$25,500,000	$25,500,000
Hospital Admits, Cardiovascular (except heart attacks)	0.11	$5,500	$5,500	671.00	$34,300,000	$34,300,000
Acute Bronchitis	1.09	$666	$666	3,250.00	$1,980,000	$1,980,000
Upper Respiratory Symptoms	19.70	$833	$833	58,800.00	$2,490,000	$2,490,000
Lower Respiratory Symptoms	13.90	$370	$370	41,300.00	$1,100,000	$1,100,000
Emergency Room Visits, Asthma	0.33	$183	$183	1,280.00	$722,000	$722,000
Minor Restricted Activity Days	589.00	$51,100	$51,100	1,750,000.00	$152,000,000	$152,000,000
Work Loss Days	101.00	$20,200	$20,200	296,000.00	$59,200,000	$59,200,000
Asthma Exacerbation	20.40	$1,490	$1,490	61,500.00	$4,510,000	$4,510,000
Total, low estimate		**$5,220,000**	**$4,700,000**		**$26,800,000,000**	**$24,100,000,000**
Total, high estimate		**$4,920,000**	**$4,450,000**		**$27,800,000,000**	**$25,100,000,000**
Population-Weighted Average Delta $PM_{2.5}$ (µg/m3)		0.000048			0.143	

Notes:

[a]The discount rate expresses future economic values in present terms. Not all health effects and associated economic values occur in the year of analysis.

[b]Adult mortality valuation is based on a Value of a Statistical Life (VSL; grown from EPA 1990 VSL using standard income growth data) calculated by ICF and is lagged 20 years (per COBRA Model guidance), not the default valuation in COBRA.

[c]Low estimate based on Krewski et al. (2009) (relative risk of 1.03 associated with a 10 $\mu g/m^3$ increase in $PM_{2.5}$), which applies to adults aged 30 to 99.

[d]Note: In some cases, the "low" estimate may be larger than the "high" estimate. This happens occasionally depending on county-specific population distribution and baseline health incidence.

[e]High estimate based on Di et al. (2017) (relative risk of 1.07 associated with a 10 $\mu g/m^3$ increase in $PM_{2.5}$), which applies to adults aged 65 to 99.

[f]Low estimate based on four acute myocardial infarction (AMI) studies.

[g]Low estimate based on Peter et al. (2001).

Health Endpoint	2040			2050		
	Change in the Number of Cases	Monetary Health Benefits (2017$)[a,b]		Change in the Number of Cases	Monetary Health Benefits (2017$)[a,b]	
		3% Discount	7% Discount		3% Discount	7% Discount
Mortality, low estimate[c]	5,170.00	$55,000,000,000	$49,500,000,000	5,010.00	$56,700,000,000	$51,100,000,000
Mortality, high estimate[d]	5,410.00	$57,600,000,000	$51,900,000,000	5,350.00	$60,500,000,000	$54,500,000,000
Infant Mortality	24.80	$264,000,000	$238,000,000	24.30	$275,000,000	$247,000,000
Nonfatal Heart Attacks, low estimate[e]	619.00	$97,600,000	$95,100,000	639.00	$101,000,000	$98,200,000
Nonfatal Heart Attacks, high estimate[f]	5,730.00	$904,000,000	$880,000,000	5,920.00	$934,000,000	$910,000,000
Hospital Admits, All Respiratory	1,500.00	$55,900,000	$55,900,000	1,570.00	$58,800,000	$58,800,000
Hospital Admits, Cardiovascular (except heart attacks)	1,460.00	$74,500,000	$74,500,000	1,530.00	$77,900,000	$77,900,000
Acute Bronchitis	7,190.00	$4,390,000	$4,390,000	7,800.00	$4,760,000	$4,760,000
Upper Respiratory Symptoms	130,000.00	$5,520,000	$5,520,000	142,000.00	$5,990,000	$5,990,000
Lower Respiratory Symptoms	91,400.00	$2,440,000	$2,440,000	99,300.00	$2,650,000	$2,650,000
Emergency Room Visits, Asthma	2,800.00	$1,570,000	$1,570,000	2,980.00	$1,680,000	$1,680,000
Minor Restricted Activity Days	3,870,000.00	$336,000,000	$336,000,000	4,190,000.00	$364,000,000	$364,000,000
Work Loss Days	655,000.00	$131,000,000	$131,000,000	711,000.00	$142,000,000	$142,000,000
Asthma Exacerbation	136,000.00	$10,000,000	$10,000,000	148,000.00	$10,900,000	$10,900,000
Total, low estimate		**$56,000,000,000**	**$50,500,000,000**		**$57,700,000,000**	**$52,100,000,000**
Total, high estimate		**$59,400,000,000**	**$53,600,000,000**		**$62,400,000,000**	**$56,300,000,000**
Population-Weighted Average Delta $PM_{2.5}$ (μg/m3)		0.294			0.297	

Notes:

[a]The discount rate expresses future economic values in present terms. Not all health effects and associated economic values occur in the year of analysis.

[b]Adult mortality valuation is based on a Value of a Statistical Life (VSL; grown from EPA 1990 VSL using standard income growth data) calculated by ICF and is lagged 20 years (per COBRA Model guidance), not the default valuation in COBRA.

[c]Low estimate based on Krewski et al. (2009) (relative risk of 1.03 associated with a 10 μg/m^3 increase in $PM_{2.5}$), which applies to adults aged 30 to 99.

[d]High estimate based on Di et al. (2017) (relative risk of 1.07 associated with a 10 μg/m^3 increase in $PM_{2.5}$), which applies to adults aged 65 to 99.

[e]Low estimate based on four acute myocardial infarction (AMI) studies.

[f]Low estimate based on Peter et al. (2001).

The adoption of light duty vehicle scenario emission reductions results in immediate changes in 2020 health benefits, whereas changes in health benefits do not appear in these decade-resolved, annual results until 2030 under the heavy-duty vehicle scenario. This is expected based on the varied EV penetration rates of the two vehicle classes.

Although nationally benefits start immediately, there are some states that show disbenefits early in the Scenario. This is notable in cases where the power grid is particularly "dirty" such that baseline EGU emissions are high. In those cases, adopting the light duty vehicle Scenario could result in disbenefits in the near-term. For example, estimates for the light duty vehicles scenario Base Case in Florida indicate disbenefits in 2020 and 2030, with positive benefits beginning in 2040 and continuing through 2050. However, estimates for the light duty vehicles scenario Non-Combustion Case in Florida indicate disbenefits only in 2020 (when the two Cases are nearly identical), with positive benefits beginning in 2030 and continuing through 2050. Due to the alignment of the heavy-duty vehicles Scenario phase in with the reduced grid emissions, estimated health benefits in Florida are never negative, and range from $46 million to $1.3 billion under the Base Case and from $1.7 billion to $3.5 billion under the Non-Combustion Case. Overall, the analysis indicates that the electrification of light duty vehicles proceeding faster than the electrification of heavy-duty vehicles could be more taxing to public health in some locations if emissions from the electrification grid are not reducing at a similar rate. Because of the more synergistic progression of vehicle emissions reductions and electrification grid emissions reductions under the heavy-duty vehicles scenario, this option results in fewer disbenefits to those individual states subject to seeing negative benefits in the near term.

5.3.2. Cumulative Impacts

We also postprocessed health benefits results from COBRA to show cumulative impacts of the proposed scenarios covering the entire period from 2020 to 2050. We calculated cumulative impacts using piecewise linear interpolation of the discounted monetized health benefits between the modeled years: 2020, 2030, 2040, and 2050. Under vehicle scenarios where 2020 monetized health benefits were zero (heavy-duty vehicle class scenarios), we interpolated between zero dollar values in 2020 and nonzero dollar values in 2030 to reflect nonzero heavy-duty zero emission vehicle sales that occur within the period (e.g., from 2021 to 2029; see Table 5).

Table 25 and Table 26 present cumulative estimates of the total national number of avoided adverse health effects and the economic value of these health risk reductions at 3% and 7% discount rates[73] from the Case and Non-Combustion Cases, respectively, when coupled with the light duty, heavy-duty, and total vehicle scenarios.[74] These economic values reflect the US population's willingness to

73 The 3% discount rate reflects society's valuation of differences in the timing of benefits; the 7% discount rate reflects the opportunity cost of capital to society.

74 We use linear interpolation between estimated number of cases and monetary benefits during the years 2020, 2030, 2040, and 2050 to calculate cumulative benefits. Because the value of a statistical life used to determine mortality health benefits differs for each year evaluated in COBRA, this approach results in a cumulative disbenefit for the mortality, low estimate but a positive cumulative monetized benefit in Ohio under the Base electricity Case light duty vehicle class scenario, under which disbenefits are estimated until 2050. Note that this is unusual, only occurring in OH.

pay to reduce risks of premature mortality or certain illnesses.[75] As such, these economic values represent monetized US public health benefits.

At a 3% discount, cumulative monetized public health benefits from 2020 to 2050 range from approximately $318 billion to $339 billion in the Base Case and total vehicles scenario. Under the Non-Combustion Case, cumulative benefits from 2020 to 2050 range from approximately $1.1 trillion to $1.2 trillion. Cumulative monetized public health benefits from 2020 to 2050 under the Base Case are shown for all vehicle classes at 3% and 7% discount rates, respectively, in Figure 13 and Figure 14. Cumulative monetized public health benefits from 2020 to 2050 under the Non-Combustion Case are shown for all vehicle classes at 3% and 7% discount rates, respectively, in Figure 15 and Figure 16. Note that these figures show cumulative values from 2020 through the charted year. That is the values corresponding to 2030 in these charts represent cumulative impacts from 2020 through 2030.

Adult mortality is the main driver of benefits of emissions changes under all electricity generation and vehicle scenarios, with an estimated decrease in the number of premature deaths among adults between 28,500 and 30,000 under the Base Case, total vehicles Class and between 105,000 and 110,000 under the Non-Combustion Case, total vehicles Class.

Under the Base Case, the cumulative number of avoided adverse health effects is greater for the heavy-duty vehicles scenario compared to the light duty vehicles scenario. For example, estimates indicate between 11,600 and 12,200 avoided mortality cases under the light duty Base Case scenario and between 16,900and 17,800 avoided mortality cases under the heavy-duty Base Case scenario. The difference between light duty and heavy-duty avoided adverse health effects shrinks in the Non-Combustion Case, where estimates indicate between 85,400 and 89,300 avoided mortality cases under the light duty Non-Combustion Case scenario and between 83,100 and 86,900 avoided mortality cases under the heavy-duty Non-Combustion Case scenario. As indicated above, benefits for the Non-Combustion Case include changes to emissions from the baseline grid which appear in both light- and heavy vehicle classes. Thus, the total vehicle class benefits do not equal the sum of light and heavy vehicle classes.

75 For some health endpoints, the economic value estimates are based on the non-market valuation studies that estimate people's willingness to pay for reductions in these health risks. For other endpoints, non-market valuation studies are not readily available, and valuation is approximated using cost-of-illness methods that estimate medical costs and illness-related productivity losses.

Table 25. Estimated cumulative health benefits under the Base Case from 2020 to 2050, for each vehicle Class.

Health Endpoint	Change in the Number of Cases	Monetary Health Benefits (2017$)[a,b]	
		3% Discount	7% Discount
2020-2050, Base Case, Light Duty Vehicle Class			
Mortality, low estimate[c]	11,600.00	128,000,000,000	115,000,000,000
Mortality, high estimate[d]	12,200.00	134,000,000,000	121,000,000,000
Infant Mortality	60.30	659,000,000	594,000,000
Nonfatal Heart Attacks, low estimate[e]	1,240.00	195,000,000	190,000,000
Nonfatal Heart Attacks, high estimate[f]	11,500.00	1,810,000,000	1,760,000,000
Hospital Admits, All Respiratory	3,350.00	126,000,000	126,000,000
Hospital Admits, Cardiovascular (except heart attacks)	3,190.00	163,000,000	163,000,000
Acute Bronchitis	19,600.00	12,000,000	12,000,000
Upper Respiratory Symptoms	356,000.00	15,000,000	15,000,000
Lower Respiratory Symptoms	250,000.00	6,680,000	6,680,000
Emergency Room Visits, Asthma	6,880.00	3,880,000	3,880,000
Minor Restricted Activity Days	10,500,000.00	914,000,000	914,000,000
Work Loss Days	1,790,000.00	359,000,000	359,000,000
Asthma Exacerbation	370,000.00	27,100,000	27,100,000
Total, low estimate		**$130,000,000,000**	**$117,000,000,000**
Total, high estimate		**$138,000,000,000**	**$125,000,000,000**
2020-2050, Base Case, Heavy-Duty Vehicle Class			
Mortality, low estimate[c]	16,900.00	$185,000,000,000	$167,000,000,000
Mortality, high estimate[d]	17,800.00	$195,000,000,000	$176,000,000,000
Infant Mortality	84.00	$919,000,000	$828,000,000
Nonfatal Heart Attacks, low estimate[e]	2,010.00	$317,000,000	$309,000,000
Nonfatal Heart Attacks, high estimate[f]	18,700.00	$2,950,000,000	$2,870,000,000
Hospital Admits, All Respiratory	5,050.00	$189,000,000	$189,000,000
Hospital Admits, Cardiovascular (except heart attacks)	4,890.00	$249,000,000	$249,000,000
Acute Bronchitis	26,200.00	$16,000,000	$16,000,000
Upper Respiratory Symptoms	474,000.00	$20,100,000	$20,100,000
Lower Respiratory Symptoms	333,000.00	$8,910,000	$8,910,000
Emergency Room Visits, Asthma	9,620.00	$5,420,000	$5,420,000
Minor Restricted Activity Days	14,000,000.00	$1,220,000,000	$1,220,000,000
Work Loss Days	2,380,000.00	$476,000,000	$476,000,000
Asthma Exacerbation	494,000.00	$36,300,000	$36,300,000
Total, low estimate		**$188,000,000,000**	**$170,000,000,000**
Total, high estimate		**$201,000,000,000**	**$182,000,000,000**
2020-2050, Base Case, Total Vehicle Class			

Health Endpoint	Change in the Number of Cases	Monetary Health Benefits (2017$)[a,b]	
		3% Discount	7% Discount
Mortality, low estimate[c]	28,500.00	$312,000,000,000	$281,000,000,000
Mortality, high estimate[d]	30,000.00	$329,000,000,000	$297,000,000,000
Infant Mortality	144.00	$1,580,000,000	$1,420,000,000
Nonfatal Heart Attacks, low estimate[e]	3,250.00	$513,000,000	$499,000,000
Nonfatal Heart Attacks, high estimate[f]	30,200.00	$4,750,000,000	$4,630,000,000
Hospital Admits, All Respiratory	8,400.00	$316,000,000	$316,000,000
Hospital Admits, Cardiovascular (except heart attacks)	8,080.00	$413,000,000	$413,000,000
Acute Bronchitis	45,800.00	$28,000,000	$28,000,000
Upper Respiratory Symptoms	830,000.00	$35,100,000	$35,100,000
Lower Respiratory Symptoms	582,000.00	$15,600,000	$15,600,000
Emergency Room Visits, Asthma	16,500.00	$9,290,000	$9,290,000
Minor Restricted Activity Days	24,500,000.00	$2,130,000,000	$2,130,000,000
Work Loss Days	4,170,000.00	$835,000,000	$835,000,000
Asthma Exacerbation	864,000.00	$63,400,000	$63,400,000
Total, low estimate		**$318,000,000,000**	**$287,000,000,000**
Total, high estimate		**$339,000,000,000**	**$307,000,000,000**

Notes:

[a]The discount rate expresses future economic values in present terms. Not all health effects and associated economic values occur in the year of analysis.

[b]Adult mortality valuation is based on a Value of a Statistical Life (VSL; grown from EPA 1990 VSL using standard income growth data) calculated by ICF and is lagged 20 years (per COBRA Model guidance), not the default valuation in COBRA.

[c]Low estimate based on Krewski et al. (2009) (relative risk of 1.03 associated with a 10 μg/m^3 increase in PM2.5), which applies to adults aged 30 to 99.

[d]High estimate based on Di et al. (2017) (relative risk of 1.07 associated with a 10 μg/m^3 increase in PM2.5), which applies to adults aged 65 to 99.

[e]Low estimate based on four acute myocardial infarction (AMI) studies.

[f]Low estimate based on Peter et al. (2001).

Table 26. Estimated cumulative health benefits under the Non-Combustion Case from 2020 to 2050 for each vehicle Class.[76]

Health Endpoint	Change in the Number of Cases	Monetary Health Benefits (2017$)[a,b]	
		3% Discount	7% Discount
2020-2050, Non-Combustion Case, Light Duty Vehicle Class			
Mortality, low estimate[c]	85,400.00	908,000,000,000	817,000,000,000
Mortality, high estimate[d]	89,300.00	949,000,000,000	855,000,000,000
Infant Mortality	410.00	4,350,000,000	3,920,000,000
Nonfatal Heart Attacks, low estimate[e]	10,200.00	1,610,000,000	1,570,000,000
Nonfatal Heart Attacks, high estimate[f]	94,500.00	14,900,000,000	14,500,000,000
Hospital Admits, All Respiratory	24,500.00	915,000,000	915,000,000
Hospital Admits, Cardiovascular (except heart attacks)	23,900.00	1,220,000,000	1,220,000,000
Acute Bronchitis	117,000.00	71,500,000	71,500,000
Upper Respiratory Symptoms	2,120,000.00	89,700,000	89,700,000
Lower Respiratory Symptoms	1,490,000.00	39,800,000	39,800,000
Emergency Room Visits, Asthma	45,900.00	25,900,000	25,900,000
Minor Restricted Activity Days	63,000,000.00	5,460,000,000	5,460,000,000
Work Loss Days	10,700,000.00	2,140,000,000	2,140,000,000
Asthma Exacerbation	2,220,000.00	163,000,000	163,000,000
Total, low estimate		**$924,000,000,000**	**$833,000,000,000**
Total, high estimate		**$978,000,000,000**	**$884,000,000,000**
2020-2050, Non-Combustion Case, Heavy-Duty Vehicle Class			
Mortality, low estimate[c]	83,100.00	$885,000,000,000	$797,000,000,000
Mortality, high estimate[d]	86,900.00	$926,000,000,000	$834,000,000,000
Infant Mortality	398.00	$4,230,000,000	$3,810,000,000
Nonfatal Heart Attacks, low estimate[e]	10,000.00	$1,590,000,000	$1,540,000,000
Nonfatal Heart Attacks, high estimate[f]	93,000.00	$14,700,000,000	$14,300,000,000
Hospital Admits, All Respiratory	24,000.00	$896,000,000	$896,000,000
Hospital Admits, Cardiovascular (except heart attacks)	23,500.00	$1,200,000,000	$1,200,000,000
Acute Bronchitis	114,000.00	$69,300,000	$69,300,000
Upper Respiratory Symptoms	2,060,000.00	$87,000,000	$87,000,000
Lower Respiratory Symptoms	1,440,000.00	$38,600,000	$38,600,000
Emergency Room Visits, Asthma	44,600.00	$25,100,000	$25,100,000
Minor Restricted Activity Days	61,000,000.00	$5,300,000,000	$5,300,000,000

76 Note that light and heavy vehicle classes do not sum to total for the Non-Combustion Case due to allocating the base electric load, as discussed earlier.

Health Endpoint	Change in the Number of Cases	Monetary Health Benefits (2017$)[a,b]	
		3% Discount	7% Discount
Work Loss Days	10,300,000.00	$2,070,000,000	$2,070,000,000
Asthma Exacerbation	2,150,000.00	$158,000,000	$158,000,000
Total, low estimate		**$901,000,000,000**	**$812,000,000,000**
Total, high estimate		**$955,000,000,000**	**$862,000,000,000**
2020-2050, Non-Combustion Case, Total Vehicle Class			
Mortality, low estimate[c]	105,000.00	$1,120,000,000,000	$1,010,000,000,000
Mortality, high estimate[d]	110,000.00	$1,180,000,000,000	$1,060,000,000,000
Infant Mortality	508.00	$5,430,000,000	$4,890,000,000
Nonfatal Heart Attacks, low estimate[e]	12,600.00	$1,990,000,000	$1,940,000,000
Nonfatal Heart Attacks, high estimate[f]	117,000.00	$18,400,000,000	$17,900,000,000
Hospital Admits, All Respiratory	30,500.00	$1,140,000,000	$1,140,000,000
Hospital Admits, Cardiovascular (except heart attacks)	29,700.00	$1,520,000,000	$1,520,000,000
Acute Bronchitis	147,000.00	$89,900,000	$89,900,000
Upper Respiratory Symptoms	2,670,000.00	$113,000,000	$113,000,000
Lower Respiratory Symptoms	1,870,000.00	$50,100,000	$50,100,000
Emergency Room Visits, Asthma	57,200.00	$32,200,000	$32,200,000
Minor Restricted Activity Days	79,200,000.00	$6,870,000,000	$6,870,000,000
Work Loss Days	13,400,000.00	$2,690,000,000	$2,690,000,000
Asthma Exacerbation	2,790,000.00	$205,000,000	$205,000,000
Total, low estimate		**$1,140,000,000,000**	**$1,030,000,000,000**
Total, high estimate		**$1,220,000,000,000**	**$1,100,000,000,000**

Notes:

[a]The discount rate expresses future economic values in present terms. Not all health effects and associated economic values occur in the year of analysis.

[b]Adult mortality valuation is based on a Value of a Statistical Life (VSL; grown from EPA 1990 VSL using standard income growth data) calculated by ICF and is lagged 20 years (per COBRA Model guidance), not the default valuation in COBRA.

[c]Low estimate based on Krewski et al. (2009) (relative risk of 1.03 associated with a 10 μg/m^3 increase in $PM_{2.5}$), which applies to adults aged 30 to 99.

[d]High estimate based on Di et al. (2017) (relative risk of 1.07 associated with a 10 μg/m^3 increase in $PM_{2.5}$), which applies to adults aged 65 to 99.

[e]Low estimate based on four acute myocardial infarction (AMI) studies.

[f]Low estimate based on Peter et al. (2001).

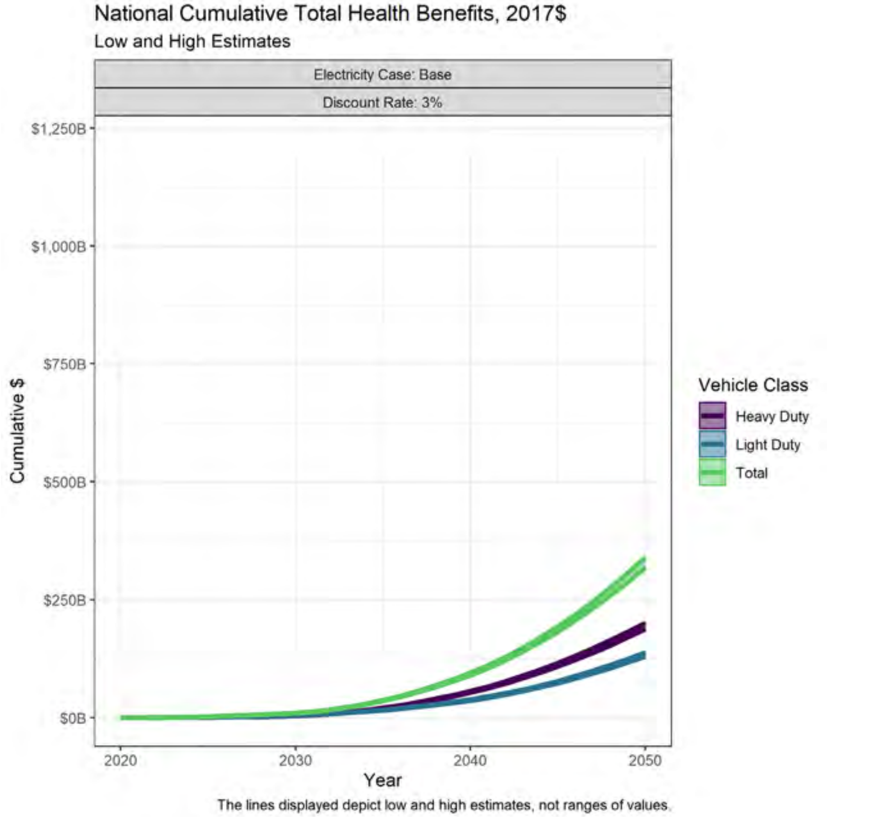
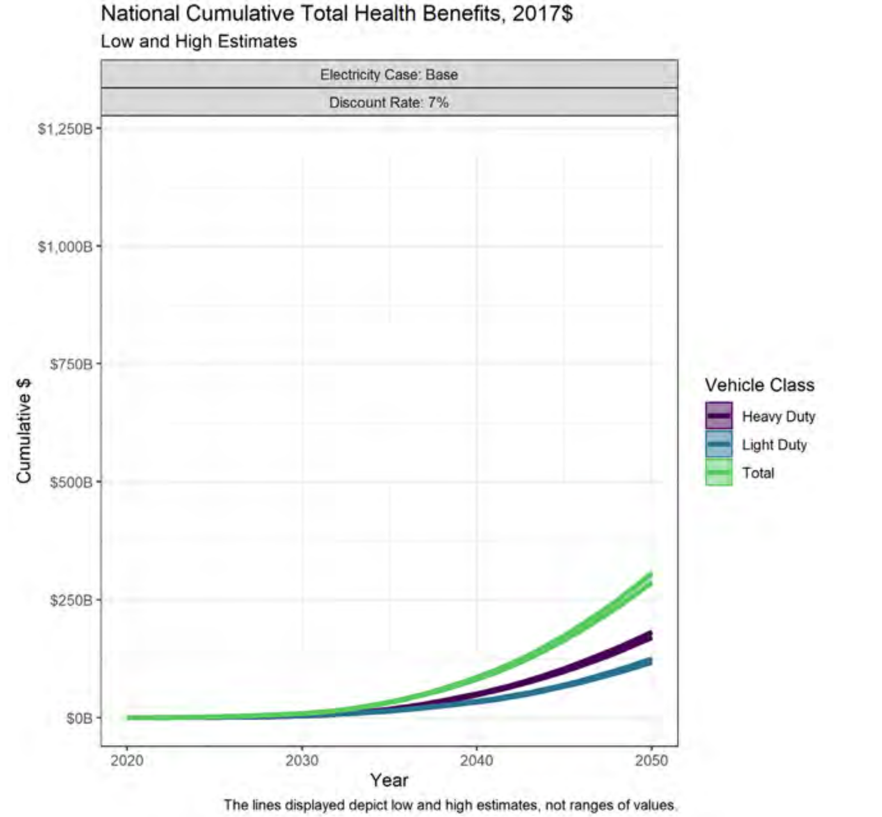
Figure 13. Estimated cumulative health benefits at 3% discount rate under the Base Case from 2020 to 2050	Figure 14. Estimated cumulative health benefits at 7% discount rate under the Base Case from 2020 to 2050
	

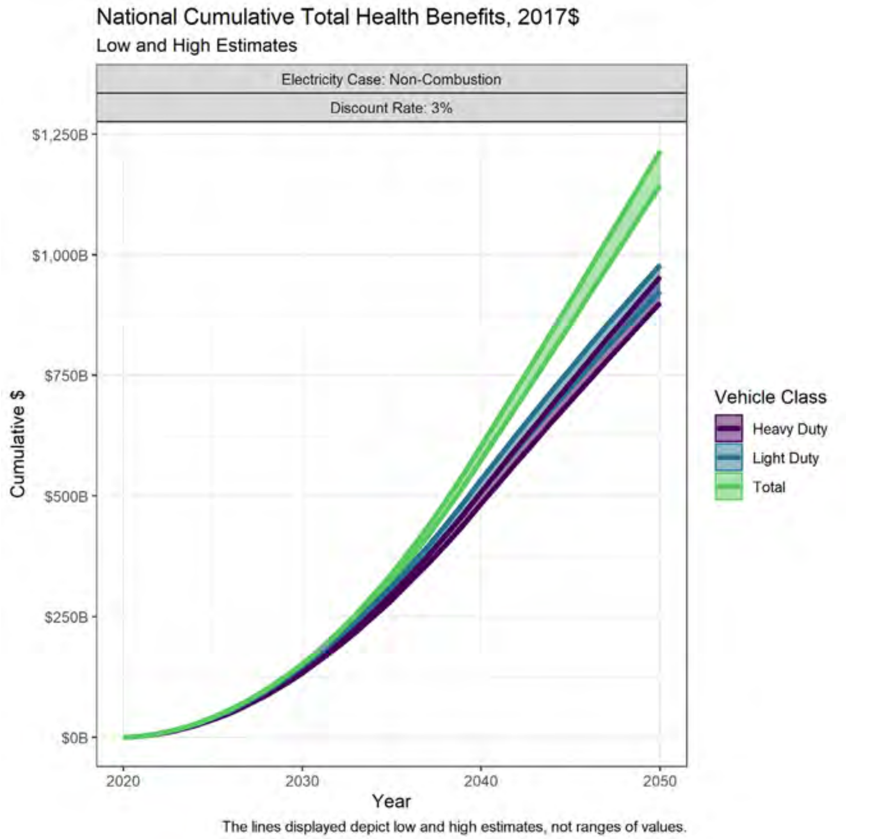
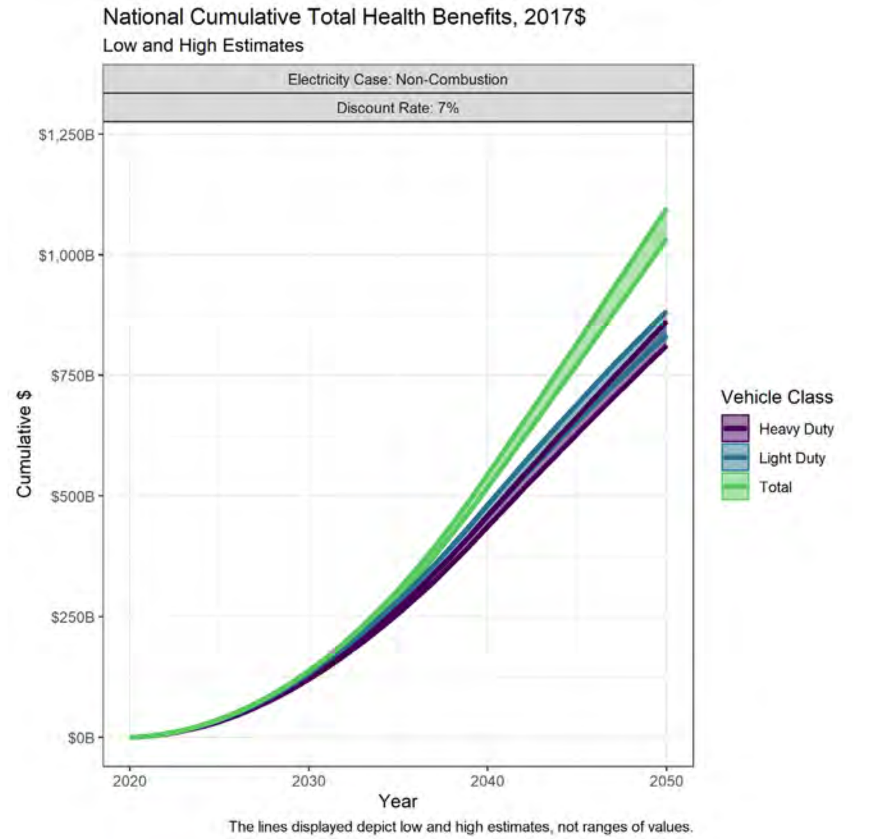
Figure 15. Estimated cumulative health benefits at 3% discount rate under the Non-Combustion Case from 2020 to 2050	Figure 16. Estimated cumulative health benefits at 7% discount rate under the Non-Combustion Case from 2020 to 2050
	

Figure 17 and Figure 18 show estimated cumulative health benefits by state in 2050 for each electrification Case and for the Total vehicle Class. Our estimates indicate that California and Texas will experience the greatest monetized health benefits. Note that these results are not per-capita. This is likely due to the large populations and proximity of those populations to major roadways in these states. The health impact estimates indicate that states like Pennsylvania and Florida will experience large health benefits, but these benefits trail those of states such as California and Texas likely due to populations and the benefits of cleaning the electric grid. States with large populations of older residents, potentially including Florida, may experience greater health benefits because such populations are more sensitive to changes in baseline mortality, respiratory, and cardiovascular health effect incidence. Appendix D contains state cumulative total health benefits for both the Base and Non-Combustion Cases, all vehicle classes, and both discount rates.

Figure 17: Estimated cumulative health benefits by state at 3% discount rate under the Base Case and all vehicle classes by 2050

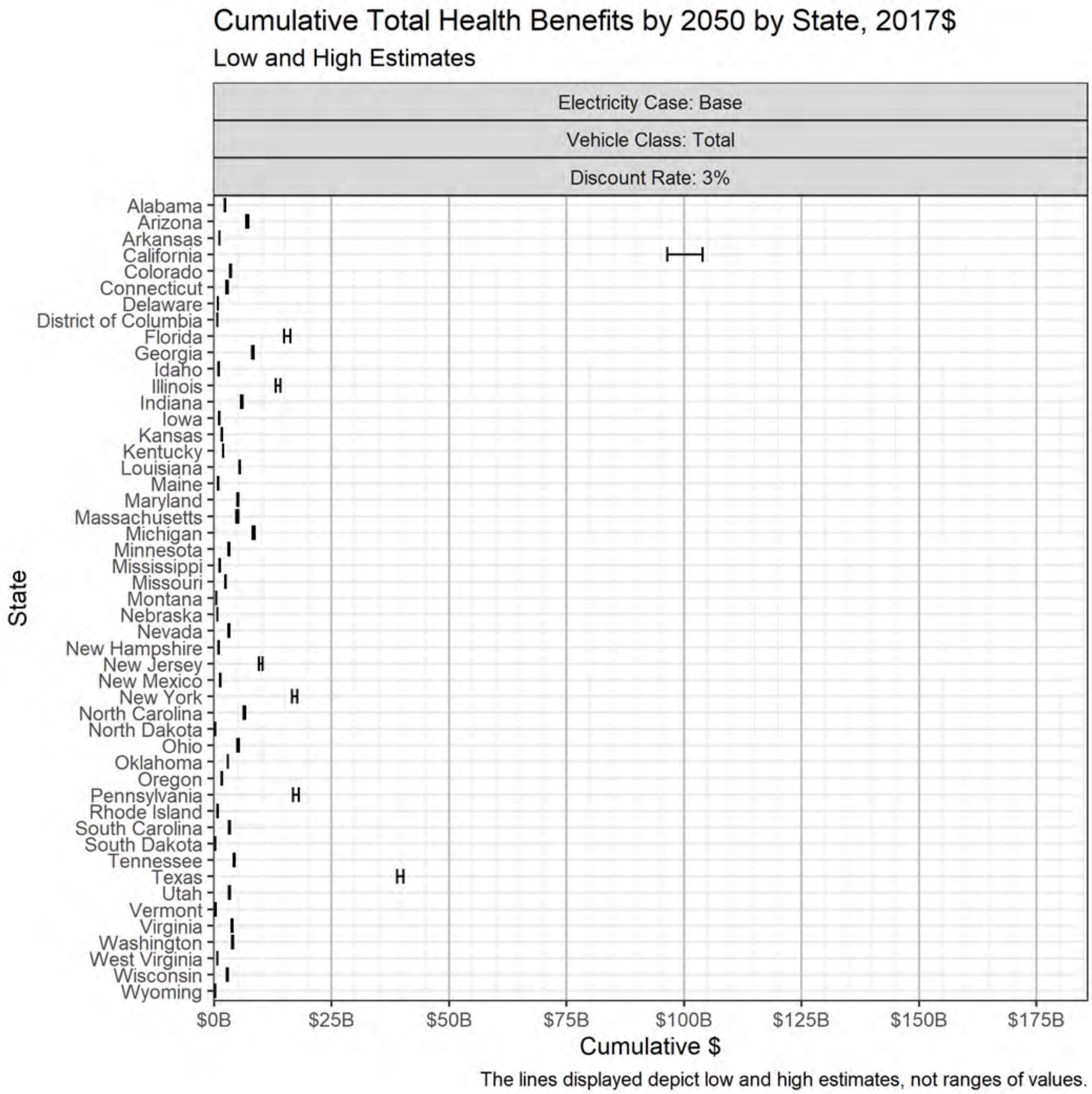
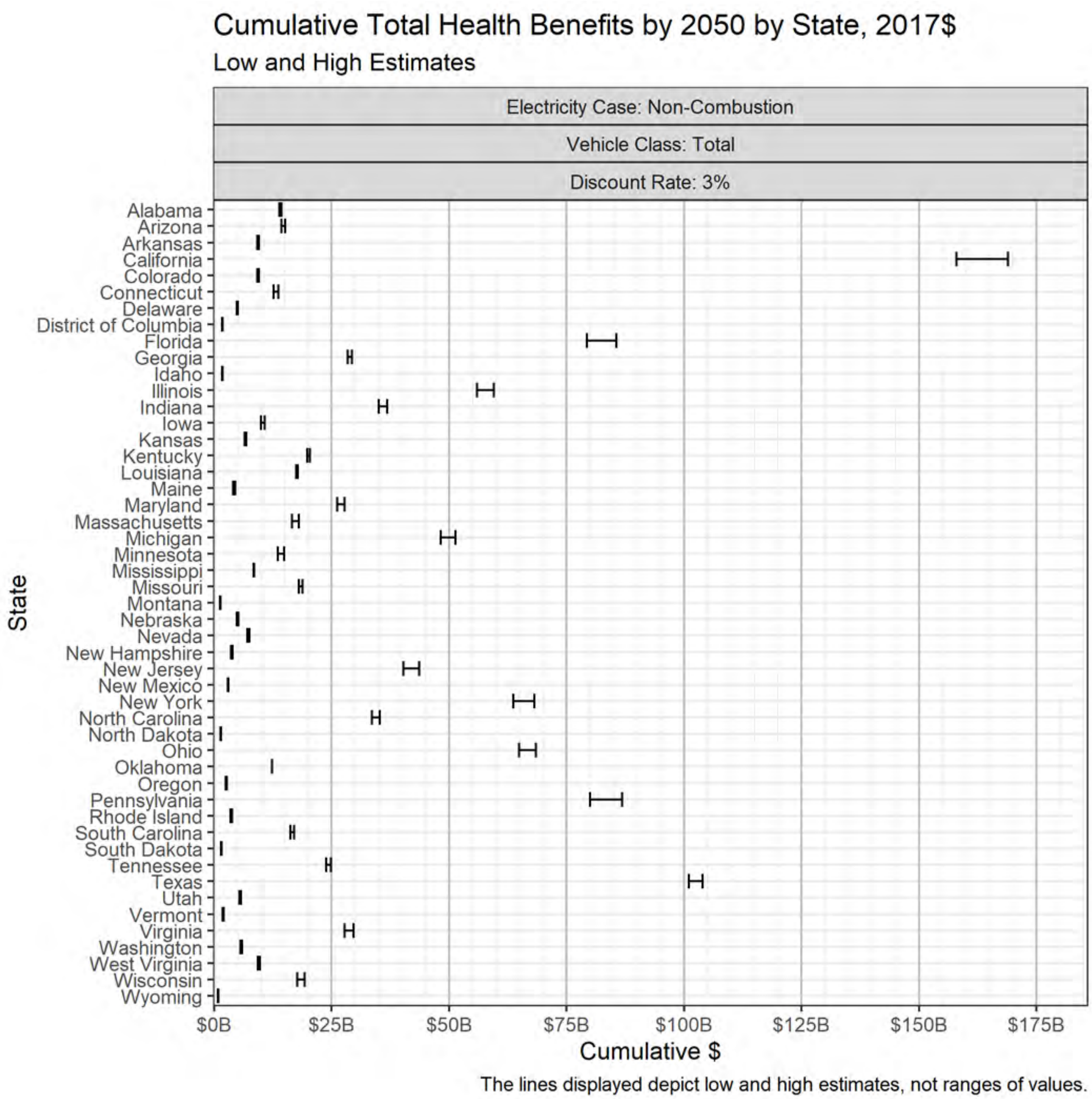


Figure 18: Estimated cumulative health benefits by state at 3% discount rate under the Non-Combustion Case and all vehicle classes by 2050



5.3.3. Demographic and Metro Area Resolution of Impacts

We also determined how the benefits of each electrification Case would be shared among communities and demographic groups. This section summarizes those benefits.

We first calculated summary results for each modeled year (2020, 2030, 2040, and 2050) and cumulative results (2020–2050) for two categories:

- a list of 25 of the largest metropolitan areas in the country; and
- groups of counties across the country sorted into bins by the percent of the population that identifies as people of color (POC).

The list of the 25 metropolitan ("metro") areas of interest were identified by the American Lung Association.[77] The geographic boundaries of these metro areas are defined by the counties included in the 2020 Census Bureau's definitions for that metro's Combined Statistical Areas (CSA),[78] except for San Diego, CA. The San Diego, CA metro area is equivalent to San Diego County in our analysis, as San Diego does not belong to a CSA.

The percent of the population identifying as a person of color is defined using Annual County Resident Population Estimates by Age, Sex, Race, and Hispanic Origin for 2020 from the Census Bureau's Vintage 2020 Population Estimates.[79] "Person of color" is defined here as the sum of the male and female estimates of all racial and ethnic groups other than *Not Hispanic, White alone*.[80] Note that many counties may have much higher share of POC than the aggregated metro areas shown in Table 29 and Table 30.

Summary by Metro Area

Table 27 shows total monetized health benefits per capita at a 3% discount rate, total monetized health benefits at a 3% discount rate, and avoided premature mortality cases (shown as the sum of adult and infant mortality cases; see Appendix C) for each modeled year by metro area for all vehicle classes under the Base electricity Case.

Total health benefits under the Base electricity Case in 2050 range from about $129 million (Portland, OR) to $5.41 billion (Los Angeles, CA). In the earliest modeled year, 2020, estimated total health benefits under the Base electricity Case are highest for the Los Angeles, CA,[81] San Francisco, CA, followed by the Houston, TX metro area. Benefits in the New York, NY metro area exceed benefits in the Houston area by 2030 and exceed benefits in the San Francisco, CA area by 2040. Patterns in the number of avoided mortality cases correspond to patterns shown in the estimated total monetized health benefits. Per capita, total health benefits under the Base electricity Case in the horizon year, 2050, range from about $28 (Portland, OR) to $217 (Los Angeles, CA). The Houston, TX, Los Angeles, CA, and San Francisco, CA metro areas show the greatest per capita benefits in both 2020 and 2030. In the near term, 2030, per capita benefits range from –$1.30 (a disbenefit) in the St. Louis area to a benefit of nearly $22 in Los Angeles. In both 2040 and 2050, the Los Angeles, CA, San Francisco, CA, and Pittsburgh, PA metro areas show the greatest per capita benefits.

---

77 Email from William Barrett to Seth Hartley, Anna Belova, and Kate Munson, December 20, 2021. Originally, 28 were considered. The 25 published here are the top 25 ranked by population of the original 28 metros. Kansas City, Las Vegas, and Fresno ranked lower than 25th in this definition, and are not shown.

78 A map of the Census Bureau's 2020 CSA definitions can be found here: https://www.census.gov/geographies/reference-maps/2020/geo/csa.html

79 Census Bureau County Population by Characteristics: 2010-2020 https://www.census.gov/programs-surveys/popest/technical-documentation/research/evaluation-estimates/2020-evaluation-estimates/2010s-county-detail.html

80 Specifically, this is defined as: NHBA_male + NHBA_female + NHIA_male + NHIA_female + NHAA_male + NHAA_female + NHNA_male + NHNA_female + NHTOM_male + NHTOM_female + H_male + H_female. In this formulation: NHBA refers to "not Hispanic, Black or African American alone", NHIA is "Not Hispanic, American Indian and Alaska Native alone", NHAA is "Not Hispanic, Asian alone", NHNA is "Not Hispanic, Native Hawaiian and Other Pacific Island alone", NHTOM is "Not Hispanic, two or more races", and H is "all Hispanic".

81 Here we refer to the metro areas by their dominant or most well-known city. The full name is provided in the tables.

As discussed in Section 5.3.1 with respect to state-level benefits, there are some metro areas that show disbenefits under the Base Case electrification. In 2020 (Cleveland, OH, Miami, FL, Orlando, FL, and St. Louis, MO), while Washington, D.C. showed a small total disbenefit (de minimus on a per capita basis). By 2030, only the St. Louis, MO area showed disbenefits, and benefits among all metro areas were positive in the later years. Again, this is attributable to cases where local power generation is particularly "dirty" such that electricity generation emissions are high. In such cases, adopting the electrification Scenario results in overall disbenefits in these metro areas in the near-term. Even under the Base electrification Case, however, these become net benefits in the longer-term years.

For comparison, under the Non-Combustion electricity Case in 2050 (shown by Table 28) total health benefits range from about $152 million (Portland, OR) to $6.81 billion (Los Angeles, CA). Estimated total health benefits under the Non-Combustion electricity Case in 2020 are highest for the Los Angeles, CA, San Francisco, CA, and Houston, TX metro areas. In 2050, estimated total health benefits under the Non-Combustion electricity Case are highest for the Los Angeles, CA, New York, NY, and San Francisco, CA metro areas. Per capita, total health benefits under the Non-Combustion electricity Case in 2050 range from about $33 (Portland, OR) to $363 (Pittsburgh, PA). Per capita, total health benefits under the Non-Combustion electricity Case are highest for the Los Angeles, CA, San Francisco, CA, and Houston, TX metro areas in 2020, while estimated per capita benefits are greatest for the Pittsburgh, PA, Cleveland, OH, and Detroit, MI metro areas in 2030 and 2040. In 2050, estimated per capita benefits are greatest for the Pittsburgh, PA, Los Angeles, CA, and Philadelphia, PA metro areas.

Similar to the Base electricity Case, some metro areas show disbenefits in 2020. In this Case, they were limited to Cleveland, OH, Miami, FL, Orlando, Fl, St. Louis, MO, and Washington, D.C. (Miami and DC were neutral on a per-capita basis). However, under the Non-Combustion electricity Case, disbenefits are remediated more quickly, such that no metro areas that show disbenefits in 2030. This is due to the synergistic cleanup of the grid with reduced vehicle emissions under the Non-Combustion electricity Case in years 2030 to 2050.

Table 29 shows cumulative annual health benefits between 2020 and 2050. These tables show calculated benefits, including total monetized health benefits at a 3% discount rate, avoided premature mortality cases (including both adult and infant mortality cases), avoided hospital admits (all respiratory), avoided upper respiratory symptoms, avoided lower respiratory symptoms, and avoided emergency room visits for asthma for all vehicle classes under the Base electricity Case.

Cumulative benefits for the metro areas of interest under the Base electricity Case range from $1.34 billion (St. Louis, MO) to $63.1 billion (Los Angeles, CA). The top three greatest total cumulative health benefits under the Base electricity Case accrue to Los Angeles, CA ($63 billion), New York, NY ($25 billion), and San Francisco, CA ($23 billion). The top three greatest avoided premature mortality cases and avoided hospital admissions for respiratory symptoms also accrue to these metro areas. The top three metro areas with the greatest number of avoided respiratory symptoms and emergency room visits for asthma are Houston, TX, Los Angeles, CA, New York, NY.

Table 30 displays the same metrics for all vehicle classes under the Non-Combustion electricity case. Cumulative benefits for the metro areas of interest under the Non-Combustion electricity Case are roughly 50% larger than under the Base Case, ranging from $ 2.09 billion (Portland, OR) to $95.5 billion (Los Angeles, CA). The top three greatest total cumulative health benefits under the Non-Combustion electricity Case accrue to Los Angeles, CA ($96 billion), New York, NY ($84 billion), and

Chicago, IL ($46 billion). These three metro areas also show the highest values for avoided premature mortality cases, avoided hospital admissions for respiratory symptoms, and emergency room visits for asthma under this electricity Case. However, the top three metro areas with the greatest number of avoided respiratory symptoms are Los Angeles, CA, New York, NY, and Houston, TX.

Overall, variability in the health benefits outcomes among metro areas is driven by the magnitude and distribution of emissions changes between the affected sectors (i.e., on-road, electricity generation, refining) and their proximity to the metro area's population. In other words, across all Scenarios, metro areas with large, dense populations, particularly those close to roadways, tend to have higher benefits compared to less densely populated metro areas, while metro areas near the largest, dirtiest power plants, particularly coal-fired plants, tend to show disbenefits until the Scenario eliminates those emissions.

Table 27: Estimated annual health benefits by metro under the Base Case, considering all vehicle classes and 3% DR for years 2020, 2030, 2040, and 2050

	Total Health Benefits (High Estimate) Per Capita, 2017$				Total Health Benefits (High Estimate), Million 2017$				Avoided Premature Mortality Cases (High Estimate)			
Metro Area	**2020**	**2030**	**2040**	**2050**	**2020**	**2030**	**2040**	**2050**	**2020**	**2030**	**2040**	**2050**
Atlanta--Athens-Clarke County--Sandy Springs, GA-AL	$0.01	$3.83	$30.40	$62.70	$0.055	$30.9	$281	$653	0.0054	2.96	25.6	55.9
Boston-Worcester-Providence, MA-RI-NH-CT	$0.02	$4.57	$30.00	$62.20	$0.134	$40.1	$274	$580	0.0134	3.87	25.1	49.9
Charlotte-Concord, NC-SC	$0.01	$3.72	$28.30	$60.10	$0.03	$12.3	$108	$260	0.00294	1.18	9.82	22.3
Chicago-Naperville, IL-IN-WI	$0.05	$11.10	$65.40	$135.00	$0.528	$120	$733	$1,550	0.0527	11.6	66.9	133.0
Cleveland-Akron-Canton, OH	-$0.01	$2.69	$31.80	$99.10	-$0.044	$9.73	$114	$345	-0.00439	0.942	10.5	29.8
Dallas-Fort Worth, TX-OK	$0.01	$4.77	$33.50	$69.80	$0.112	$45.9	$377	$907	0.0111	4.40	34.4	77.7
Denver-Aurora, CO	$0.03	$4.76	$25.30	$46.90	$0.096	$19.7	$119	$246	0.0095	1.89	10.8	21.0
Detroit-Warren-Ann Arbor, MI	$0.02	$7.45	$53.30	$121.00	$0.111	$40.0	$284	$631	0.0112	3.88	26.2	54.6
Houston-The Woodlands, TX	$0.08	$14.30	$70.00	$125.00	$0.61	$126	$724	$1,500	0.0604	12.0	65.7	128.0
Los Angeles-Long Beach, CA	$0.12	$21.90	$123.00	$217.00	$2.38	$470	$2,860	$5,410	0.239	45.7	264.0	470.0
Miami-Port St. Lucie-Fort Lauderdale, FL	-$0.01	$2.51	$28.90	$74.20	-$0.046	$20.4	$265	$756	-0.00456	1.96	24.3	65.1
Minneapolis-St. Paul, MN-WI	$0.01	$3.44	$23.40	$53.60	$0.042	$15.7	$117	$288	0.00417	1.51	10.7	24.8
New York-Newark, NY-NJ-CT-PA	$0.02	$6.21	$42.00	$88.80	$0.524	$152	$1,060	$2,270	0.0521	14.6	96.5	195.0
Orlando-Lakeland-Deltona, FL	-$0.01	$1.37	$18.30	$48.30	-$0.027	$6.48	$99.7	$300	-0.00278	0.613	9.03	25.6
Philadelphia-Reading-Camden, PA-NJ-DE-MD	$0.05	$10.30	$60.80	$126.00	$0.336	$79.2	$483	$1,020	0.0337	7.64	44.3	88.0
Phoenix-Mesa, AZ	$0.02	$5.39	$33.80	$61.10	$0.121	$32.3	$238	$498	0.0121	3.11	21.8	42.9
Pittsburgh-New Castle-Weirton, PA-OH-WV	$0.04	$12.50	$78.00	$179.00	$0.114	$32.5	$199	$438	0.0115	3.16	18.3	38.0
Portland-Vancouver-Salem, OR-WA	$0.02	$3.20	$16.50	$28.20	$0.064	$11.9	$68.7	$129.	0.00643	1.15	6.3	11.2
Sacramento-Roseville, CA	$0.05	$9.78	$52.50	$93.90	$0.142	$29.4	$174	$339	0.0142	2.83	15.9	29.2
Salt Lake City-Provo-Orem, UT	$0.02	$5.67	$38.00	$74.10	$0.055	$17.1	$130	$283	0.00553	1.64	11.9	24.3
San Diego-Chula Vista-Carlsbad, CA	$0.06	$12.30	$73.60	$139.00	$0.211	$47.7	$314	$646	0.0209	4.56	28.5	55.2
San Jose-San Francisco-Oakland, CA	$0.10	$17.70	$91.00	$163.00	$1.02	$189	$1,050	$1,980	0.102	18.3	96.0	171.0
Seattle-Tacoma, WA	$0.02	$3.50	$19.20	$33.30	$0.094	$19.2	$117	$224	0.00943	1.85	10.8	19.3

Metro Area	Total Health Benefits (High Estimate) Per Capita, 2017$				Total Health Benefits (High Estimate), Million 2017$				Avoided Premature Mortality Cases (High Estimate)			
	2020	2030	2040	2050	2020	2030	2040	2050	2020	2030	2040	2050
St. Louis-St. Charles-Farmington, MO-IL	-$0.04	-$1.30	$12.40	$55.50	-$0.108	-$4.03	$39.5	$179.	-0.0108	-0.391	3.61	15.4
Washington-Baltimore-Arlington, DC-MD-VA-WV-PA	$0.00	$2.10	$21.50	$58.40	-$0.031	$24.3	$277	$831	-0.00314	2.34	25.3	71.4

Table 28: Estimated annual health benefits by metro under the Non-Combustion Case, considering all vehicle classes and 3% discount rate for years 2020, 2030, 2040, and 2050

	Total Health Benefits (High Estimate) Per Capita, 2017$				Total Health Benefits (High Estimate), Million 2017$				Avoided Premature Mortality Cases (High Estimate)			
Metro Area	**2020**	**2030**	**2040**	**2050**	**2020**	**2030**	**2040**	**2050**	**2020**	**2030**	**2040**	**2050**
Atlanta--Athens-Clarke County--Sandy Springs, GA-AL	$0.01	$52.00	$112.00	$111.00	$0.06	$420	$1,030	$1,160	0.00593	40.3	94.2	98.9
Boston-Worcester-Providence, MA-RI-NH-CT	$0.02	$60.50	$124.00	$119.00	$0.141	$530	$1,130	$1,110	0.0141	51.2	103.0	95.9
Charlotte-Concord, NC-SC	$0.01	$59.20	$120.00	$112.00	$0.032	$195	$456	$484	0.00321	18.8	41.7	41.5
Chicago-Naperville, IL-IN-WI	$0.05	$95.60	$202.00	$215.00	$0.543	$1,030	$2,260	$2,480	0.0542	99.1	206.0	213.0
Cleveland-Akron-Canton, OH	-$0.01	$159.00	$278.00	$240.00	-$0.034	$575	$994	$834	-0.00344	55.7	91.4	72.1
Dallas-Fort Worth, TX-OK	$0.01	$58.00	$122.00	$122.00	$0.119	$557	$1,370	$1,590	0.0118	53.5	125.0	136.0
Denver-Aurora, CO	$0.03	$29.30	$65.70	$72.60	$0.097	$121	$308	$381	0.00967	11.6	28.0	32.4
Detroit-Warren-Ann Arbor, MI	$0.02	$143.00	$272.00	$246.00	$0.123	$766	$1,450	$1,280	0.0124	74.2	133.0	111.0
Houston-The Woodlands, TX	$0.08	$63.90	$154.00	$180.00	$0.616	$562	$1,590	$2,160	0.061	53.8	144.0	184.0
Los Angeles-Long Beach, CA	$0.12	$58.00	$196.00	$273.00	$2.39	$1,250	$4,560	$6,810	0.24	121.0	422.0	592.0
Miami-Port St. Lucie-Fort Lauderdale, FL	$0.00	$93.50	$198.00	$192.00	-$0.036	$760	$1,820	$1,950	-0.00355	73.2	166.0	168.0
Minneapolis-St. Paul, MN-WI	$0.01	$59.80	$116.00	$109.00	$0.046	$272	$576	$585	0.00456	26.2	52.8	50.3
New York-Newark, NY-NJ-CT-PA	$0.02	$76.90	$165.00	$170.00	$0.549	$1,880	$4,150	$4,340	0.0546	181.0	379.0	373.0
Orlando-Lakeland-Deltona, FL	-$0.01	$55.40	$116.00	$116.00	-$0.024	$262	$631	$718	-0.00244	25.1	57.4	61.4
Philadelphia-Reading-Camden, PA-NJ-DE-MD	$0.05	$127.00	$256.00	$249.00	$0.349	$974	$2,030	$2,010	0.035	94.0	186.0	173.0
Phoenix-Mesa, AZ	$0.02	$28.90	$75.40	$88.30	$0.123	$173	$530	$721	0.0124	16.7	48.6	62.0
Pittsburgh-New Castle-Weirton, PA-OH-WV	$0.05	$201.00	$381.00	$363.00	$0.122	$524	$972	$891	0.0123	50.9	89.6	77.3
Portland-Vancouver-Salem, OR-WA	$0.02	$7.31	$23.60	$33.00	$0.064	$27.2	$98.3	$152.	0.00645	2.64	9.02	13.1
Sacramento-Roseville, CA	$0.05	$40.90	$109.00	$136.00	$0.143	$123	$363	$491	0.0143	11.8	33.2	42.3
Salt Lake City-Provo-Orem, UT	$0.02	$21.30	$66.30	$95.10	$0.056	$64.1	$227	$364	0.00561	6.16	20.7	31.2
San Diego-Chula Vista-Carlsbad, CA	$0.06	$44.10	$136.00	$189.00	$0.213	$171	$582	$876	0.021	16.3	52.8	74.9
San Jose-San Francisco-Oakland, CA	$0.10	$65.00	$178.00	$225.00	$1.03	$696	$2,050	$2,730	0.103	67.3	188.0	236.0
Seattle-Tacoma, WA	$0.02	$8.42	$27.60	$39.00	$0.095	$46.2	$169	$263	0.00947	4.46	15.5	22.6

Metro Area	Total Health Benefits (High Estimate) Per Capita, 2017$				Total Health Benefits (High Estimate), Million 2017$				Avoided Premature Mortality Cases (High Estimate)			
	2020	2030	2040	2050	2020	2030	2040	2050	2020	2030	2040	2050
St. Louis-St. Charles-Farmington, MO-IL	-$0.03	$115.00	$186.00	$151.00	-$0.102	$356.	$593.	$487.	-0.0102	34.3	54.3	41.8
Washington-Baltimore-Arlington, DC-MD-VA-WV-PA	$0.00	$77.90	$148.00	$138.00	-$0.019	$902	$1,910	$1,960	-0.00188	86.8	175.0	169.0

Table 29: Estimated cumulative annual health benefits, 2020-2050, by metro area under the Base Case, considering all vehicle classes and 3% discount rate

Metro Area	2020 Population	Total Health Benefits (High Estimate), Billion 2017$	Avoided Premature Mortality Cases (High Estimate)	Hospital Admits, All Respiratory	Upper Respiratory Symptoms	Lower Respiratory Symptoms	Emergency Room Visits, Asthma	Asthma Exacerbation
Atlanta--Athens-Clarke County--Sandy Springs, GA-AL	6,930,000	$6.71	593	182	19,000	13,400	457	20,100
Boston-Worcester-Providence, MA-RI-NH-CT	8,290,000	$6.33	564	152	11,800	8,310	361	12,500
Charlotte-Concord, NC-SC	2,850,000	$2.63	233	72	7,110	5,000	166	7,420
Chicago-Naperville, IL-IN-WI	9,770,000	$17.0	1,520	455	39,200	27,500	1,030	40,800
Cleveland-Akron-Canton, OH	3,580,000	$3.13	278	71	4,880	3,420	113	5,060
Dallas-Fort Worth, TX-OK	8,190,000	$9.22	815	236	29,000	20,400	653	30,300
Denver-Aurora, CO	3,650,000	$2.74	242	76	9,520	6,700	190	10,000
Detroit-Warren-Ann Arbor, MI	5,320,000	$6.71	601	125	13,000	9,100	289	13,300
Houston-The Woodlands, TX	7,340,000	$16.8	1,480	450	64,400	45,200	1,380	66,500
Los Angeles-Long Beach, CA	18,600,000	$63.1	5,690	1,440	150,000	105,000	2,020	156,000
Miami-Port St. Lucie-Fort Lauderdale, FL	6,910,000	$7.01	620	197	11,900	8,340	321	12,300
Minneapolis-St. Paul, MN-WI	4,050,000	$2.91	258	56	7,840	5,510	99	8,050
New York-Newark, NY-NJ-CT-PA	22,500,000	$24.6	2,180	616	61,900	43,500	1,440	63,500
Orlando-Lakeland-Deltona, FL	4,230,000	$2.71	237	107	4,130	2,910	125	4,370
Philadelphia-Reading-Camden, PA-NJ-DE-MD	7,210,000	$11.2	1,000	271	24,800	17,400	773	25,800
Phoenix-Mesa, AZ	5,110,000	$5.45	485	115	14,500	10,200	289	15,300
Pittsburgh-New Castle-Weirton, PA-OH-WV	2,590,000	$4.72	424	72	6,260	4,390	161	6,520
Portland-Vancouver-Salem, OR-WA	3,280,000	$1.52	136	23	3,740	2,640	71	3,890
Sacramento-Roseville, CA	2,650,000	$3.9	348	78	9,560	6,710	147	9,970
Salt Lake City-Provo-Orem, UT	2,670,000	$3.03	269	55	13,400	9,430	100	14,100
San Diego-Chula Vista-Carlsbad, CA	3,330,000	$7.17	635	192	15,900	11,200	379	16,700

Metro Area	2020 Population	Total Health Benefits (High Estimate), Billion 2017$	Avoided Premature Mortality Cases (High Estimate)	Hospital Admits, All Respiratory	Upper Respiratory Symptoms	Lower Respiratory Symptoms	Emergency Room Visits, Asthma	Asthma Exacerbation
San Jose-San Francisco-Oakland, CA	9,610,000	$23.2	2,080	609	58,200	40,800	884	60,800
Seattle-Tacoma, WA	4,950,000	$2.6	232	41	6,720	4,720	127	6,870
St. Louis-St. Charles-Farmington, MO-IL	2,910,000	$1.34	117	39	3,010	2,110	68	3,100
Washington-Baltimore-Arlington, DC-MD-VA-WV-PA	9,870,000	$7.59	669	206	20,100	14,100	475	20,600

Table 30: Estimated cumulative annual health benefits by 2050 by metro under the Non-Combustion Case, considering all vehicle classes and 3% discount rate

Metro Area	2020 Population	Total Health Benefits (High Estimate), Billion 2017$	Avoided Premature Mortality Cases (High Estimate)	Hospital Admits, All Respiratory	Upper Respiratory Symptoms	Lower Respiratory Symptoms	Emergency Room Visits, Asthma	Asthma Exacerbation
Atlanta--Athens-Clarke County--Sandy Springs, GA-AL	6,930,000	$20.9	1,890	552	56,300	39,500	1,350	59,400
Boston-Worcester-Providence, MA-RI-NH-CT	8,290,000	$22.7	2,070	539	40,700	28,600	1,250	43,000
Charlotte-Concord, NC-SC	2,850,000	$9.17	833	239	22,200	15,600	520	23,200
Chicago-Naperville, IL-IN-WI	9,770,000	$46.5	4,230	1,250	108,000	75,800	2,840	113,000
Cleveland-Akron-Canton, OH	3,580,000	$20.3	1,870	456	30,300	21,200	707	31,500
Dallas-Fort Worth, TX-OK	8,190,000	$28.0	2,530	705	84,600	59,300	1,910	88,300
Denver-Aurora, CO	3,650,000	$6.39	574	173	21,400	15,000	428	22,500
Detroit-Warren-Ann Arbor, MI	5,320,000	$29.2	2,690	544	53,200	37,300	1,210	55,100
Houston-The Woodlands, TX	7,340,000	$33.4	3,000	893	126,000	88,200	2,700	130,000
Los Angeles-Long Beach, CA	18,600,000	$95.5	8,680	2,180	231,000	162,000	3,130	241,000
Miami-Port St. Lucie-Fort Lauderdale, FL	6,910,000	$36.5	3,320	1,060	60,300	42,200	1,770	62,300
Minneapolis-St. Paul, MN-WI	4,050,000	$11.7	1,070	225	29,800	20,900	368	30,700
New York-Newark, NY-NJ-CT-PA	22,500,000	$84.2	7,660	2,040	200,000	140,000	4,570	206,000
Orlando-Lakeland-Deltona, FL	4,230,000	$12.9	1,160	479	21,200	14,900	631	22,400
Philadelphia-Reading-Camden, PA-NJ-DE-MD	7,210,000	$41.1	3,760	988	83,400	58,400	2,630	86,600
Phoenix-Mesa, AZ	5,110,000	$11.0	994	232	29,000	20,400	579	30,700
Pittsburgh-New Castle-Weirton, PA-OH-WV	2,590,000	$19.9	1,830	318	25,000	17,500	688	26,100
Portland-Vancouver-Salem, OR-WA	3,280,000	$2.09	189	32	5,100	3,590	97	5,310
Sacramento-Roseville, CA	2,650,000	$7.56	683	154	18,600	13,100	288	19,400
Salt Lake City-Provo-Orem, UT	2,670,000	$4.91	440	92	22,500	15,800	173	23,600

Metro Area	2020 Population	Total Health Benefits (High Estimate), Billion 2017$	Avoided Premature Mortality Cases (High Estimate)	Hospital Admits, All Respiratory	Upper Respiratory Symptoms	Lower Respiratory Symptoms	Emergency Room Visits, Asthma	Asthma Exacerbation
San Diego-Chula Vista-Carlsbad, CA	3,330,000	$12.4	1,100	331	27,900	19,600	662	29,200
San Jose-San Francisco-Oakland, CA	9,610,000	$42.5	3,850	1,070	108,000	75,300	1,610	113,000
Seattle-Tacoma, WA	4,950,000	$3.6	324	57	9,250	6,510	174	9,460
St. Louis-St. Charles-Farmington, MO-IL	2,910,000	$12.2	1,120	331	25,000	17,500	593	25,800
Washington-Baltimore-Arlington, DC-MD-VA-WV-PA	9,870,000	$38.9	3,540	1,050	101,000	70,700	2,390	104,000

Summary by Demographics

As an indication of, "who would benefit" from the transition described by the scenario, we consolidated the COBRA-based, county-resolved health benefits with county demographics. Per direction from the Lung Association, the demographic metric we considered is the share of the county population that identifies as People of Color (POC). As noted above, POC here is defined as identifying as any racial or ethnic groups other than *Not Hispanic, White alone*.[80]

We ranked counties by the percent of the population identifying as POC and then aggregated results into bins corresponding to the top 10, 50, 100, and 500 county and county equivalents based on county share of POC.[82,83] Figure 19 shows the counties in each of the selected bins in the national context as a map. Our results are limited to the top 500 counties by share of POC. After approximately the 700th county in ranked order, the share of POC reaches the national average value of 38.4%.[84]

Figure 19: Distribution of counties by % population persons of color

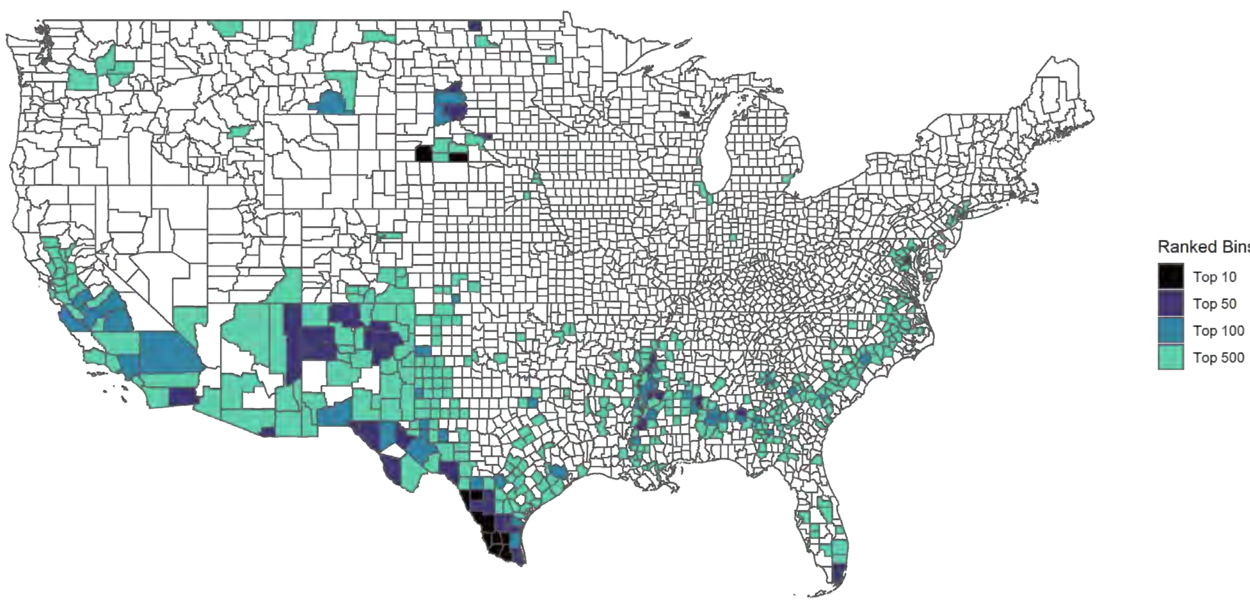


Table 32 shows total monetized health benefits per capita at a 3% discount rate, total monetized health benefits at a 3% discount rate, and percent of total national monetized health benefits at a 3% discount rate for each modeled year and by counties with the highest percentage of the population identifying as a person of color for all vehicle classes under the Base electricity Case.

82 For context, the U.S. has just over 3,100 county and county equivalents in the lower 48 states and Washington, D.C.
83 Importantly, this metric is share of population within the county, not the count of population by county. Thus high ranked counties by POC share may also be low in total population.
84 Calculated by subtracting percent white alone from 100%. https://www.census.gov/library/stories/2021/08/improved-race-ethnicity-measures-reveal-united-states-population-much-more-multiracial.html

On a per-capita basis, total health benefits under the Base electricity Case are similar among the top 10 and top 50 counties ranked by POC share. For example, in 2050 the value is $61.30 among top 10 counties and $74.70 among the top 50 counties. However, per capita total health benefits under the Base electricity Case increase significantly among the top 100 counties ($139.00 in 2050) and then reduce somewhat among the top 500 counties ($105.00 in 2050).

Monetized health benefits among the top 100 ranked counties account for over 60% of total national health benefits in 2020, but this percentage decreases in later years (32% in 2030, 25.7% in 2040, and 21.9% in 2050). The large percent of total national health benefits values in 2020 among the top 100 ranked counties (60%) and the top 500 ranked counties (141%) are both likely due to the presence of counties with disbenefits. That is, the total benefits in the top 500 counties can be greater than the national total (all counties) because the estimated health impacts among several of the remaining 2,608 counties show disbenefits. (See Section 5.3.1.) Thus, the national total benefits estimate is smaller than the benefit accrued to the top 500 counties. The smaller share in later years is likely due to the reduced occurrence of estimated disbenefits among individual counties as the Scenario unfolds. For reference, in 2050 under the Base electricity Case for all vehicles, the top 100 POC counties make up just over 3% of all counties modeled but see nearly 22% of the national health benefits.

Table 33 shows the same metrics, but for the Non-Combustion electricity Case. These follow a similar trend as under the Base electricity Case, with increasing benefits among the top 10, 50, and 100 counties and a reduction in per capita benefits among the top 500 counties (except for 2030). Per capita benefits are $103 among the top 10 counties, $134 among the top 50 counties, $195 among the top 100 counties, and $163 among the top 500 counties in 2050. In 2020, the top 100 ranked counties account for over 55% of total national health benefits. The influence of disbenefits in some counties can also be seen here in the top 500 ranked county percent of total national health benefits metric for 2020.

Interestingly, while the total benefits estimate under the Non-Combustion electricity Case is significantly larger than that under the Base electricity Case, the share of national benefits in each bin – although still relatively large – is smaller under the Non-Combustion electricity case. This is likely due to the increased importance of electricity generating emissions reductions to total benefits under the Non-Combustion electricity Case, which may be spread around the country more evenly in terms of demographics (i.e., high POC vs. other counties).

Table 34 shows cumulative annual health benefits between 2020 and 2050, including total monetized health benefits at a 3% discount rate, percent of total national monetized health benefits at a 3% discount rate, avoided premature mortality cases (including both adult and infant mortality cases), avoided hospital admissions (all respiratory), avoided upper respiratory symptoms, avoided lower respiratory symptoms, and avoided emergency room visits for asthma for under the Base electricity Case. Total monetized health benefits in counties ranked as having high populations of people of color range from $1.57 billion (top 10 counties) to $209 billion (top 500 counties). As with the individual years, the percent of total cumulative health benefits increases as additional top ranked counties are added, but the benefits are somewhat top-loaded: 0.46% of national benefits among the top 10 counties ranked by POC (0.3% of all counties in the lower 48 states plus DC), 2.83% of benefits among top 50 counties (1.6% of counties), 24.0% among top 100 counties (3% of counties), and 61.7% among top 500 counties ranked by POC share (16% of counties). The numbers of avoided cases of adverse health endpoints follow a similar trend. Note that we do not present per capita results for cumulative impacts due to the changing populations over time.

Similarly, Table 35 shows cumulative annual health benefits between 2020 and 2050 under the Non-Combustion electricity Case. Total monetized health benefits in counties ranked as having high populations of people of color range from $4.19 billion (top 10 counties) to $487 billion (top 500 counties). The percent of total health benefits increases as additional top ranked counties are added: 0.34% among top 10 counties, 2.39% among top 50 counties, 12.8% among top 100 counties, and 40.1% among top 500 counties. The numbers of avoided health endpoint cases follow a similar trend.

Total health benefits under the Non-Combustion electricity Case are roughly double the total health benefits under the Base electricity Case for all top rank categories. As above, compared to the Non-Combustion electricity Case, the Base electricity Case shows a larger share of national cumulative benefits among the top 100 and top 500 counties ranked as share of POC. This is likely due to the increased benefits of cleaning the grid (including reductions in the base load) relative to transportation, and the trends of demographics near different source categories.[85]

85 Frumkin, Howard. "Guest editorial: health, equity, and the built environment." Environmental health perspectives 113.5 (2005): A290-A291; Austin, Elena, et al. "Distinct ultrafine particle profiles associated with aircraft and roadway traffic." Environmental science & technology 55.5 (2021): 2847-2858.

Table 31: Estimated annual health benefits by counties ranked by % population persons of color under the Base Case, considering all vehicle classes and 3% discount rate for years 2020, 2030, 2040, and 2050

		Total Health Benefits (High estimate) Per Capita, 2017$				Total Health Benefits (High estimate), Million 2017$				Percent of Total National Health Benefits (High Estimate)			
County Rank	**Range of 2020 % Population POC**	**2020**	**2030**	**2040**	**2050**	**2020**	**2030**	**2040**	**2050**	**2020**	**2030**	**2040**	**2050**
Top 10 Counties	92.40% to 97.30%	$0.01	$3.82	$27.50	$61.30	$0.02	$6.87	$60.4	$162.	0.44%	0.38%	0.43%	0.49%
Top 50 Counties	80.10% to 97.30%	$0.01	$4.35	$33.40	$74.70	$0.113	$45.4	$389.	$955.	2.51%	2.53%	2.78%	2.89%
Top 100 Counties	70.60% to 97.30%	$0.07	$13.00	$74.40	$139.00	$2.72	$577.	$3,600.	$7,250.	60.20%	32.00%	25.70%	21.90%
Top 500 Counties	44.60% to 97.30%	$0.05	$9.39	$54.80	$105.00	$6.38	$1,430.	$9,120.	$18,900.	141.00%	79.70%	65.30%	57.20%

Table 32: Estimated annual health benefits by counties ranked by % population persons of color under the Non-Combustion Case, considering all vehicle classes and 3% discount rate for years 2020, 2030, 2040, and 2050

		Total Health Benefits (High estimate) Per Capita, 2017$				Total Health Benefits (High estimate), Million 2017$				Percent of Total National Health Benefits (High Estimate)			
County Rank	**Range of 2020 % Population POC**	**2020**	**2030**	**2040**	**2050**	**2020**	**2030**	**2040**	**2050**	**2020**	**2030**	**2040**	**2050**
Top 10 Counties	92.40% to 97.30%	$0.01	$38.80	$90.60	$103.00	$0.021	$69.7	$199.	$274.	0.42%	0.25%	0.34%	0.44%
Top 50 Counties	80.10% to 97.30%	$0.01	$53.00	$121.00	$134.00	$0.121	$553.	$1,400.	$1,720.	2.46%	1.99%	2.36%	2.75%
Top 100 Counties	70.60% to 97.30%	$0.07	$56.40	$153.00	$195.00	$2.75	$2,500.	$7,410.	$10,200.	55.80%	8.99%	12.50%	16.30%
Top 500 Counties	44.60% to 97.30%	$0.05	$59.60	$141.00	$163.00	$6.5	$9,100.	$23,500.	$29,300.	132.00%	32.70%	39.60%	46.90%

Table 33: Estimated cumulative annual health benefits, 2020-2050, by counties ranked by % population persons of color under the Base Case, considering the Total vehicle class and 3% discount rate

County Rank	Range of 2020 % Population POC	Total Health Benefits (High estimate), Billion 2017$	Percent of Total National Health Benefits (High estimate)	Avoided Premature Mortality Cases (High estimate)	Hospital Admits, All Respiratory	Upper Respiratory Symptoms	Lower Respiratory Symptoms	Emergency Room Visits, Asthma
Top 10 Counties	92.40% to 97.30%	$1.57	0.46%	138	45	7,150	5,010	130
Top 50 Counties	80.10% to 97.30%	$9.6	2.83%	852	223	28,900	20,300	569
Top 100 Counties	70.60% to 97.30%	$81.6	24.0%	7,310	1,960	235,000	165,000	3,680
Top 500 Counties	44.60% to 97.30%	$209.0	61.7%	18,700	5,260	566,000	397,000	10,600

Table 34: Estimated cumulative annual health benefits, 2020-2050, by counties ranked by % population persons of color under the Non-Combustion Case, considering the Total vehicle class and 3% discount rate

County Rank	Range of 2020 % Population POC	Total Health Benefits (High estimate), Billion 2017$	Percent of Total National Health Benefits (High	Avoided Premature Mortality Cases (High estimate)	Hospital Admits, All Respiratory	Upper Respiratory Symptoms	Lower Respiratory Symptoms	Emergency Room Visits, Asthma
Top 10 Counties	92.40% to 97.30%	$4.19	0.34%	376	121	19,800	13,900	358
Top 50 Counties	80.10% to 97.30%	$29.0	2.39%	2,630	660	85,300	59,700	1,610
Top 100 Counties	70.60% to 97.30%	$155.0	12.8%	14,000	3,710	459,000	321,000	7,570
Top 500 Counties	44.60% to 97.30%	$487.0	40.1%	44,100	12,500	1,310,000	919,000	26,000

6. Climate Benefits

6.1. Social Cost of Carbon

In addition to the direct health benefit to populations who will be exposed to improved levels of air quality from the Scenario, we also evaluated the benefits anticipated due to reductions in GHG emissions for the vehicle electrification Scenario. We considered both the reduction in direct (downstream) emissions from increased electrification as well as the global upstream emission changes from fuel production and increased load on the electric grid under both the Base and Non-Combustion Cases.[86] We monetized these values using the Social Cost of Carbon (SCC).

The Social Cost of CO_2 emissions (SC-CO_2) is a measure, in dollars, of the long-term damage done by a ton of carbon dioxide (CO_2) emissions in a given year. We used the interim SCC values published in February 2021 by the Interagency Working Group on Social Cost of Greenhouse Gases, United States Government[87]. Final values are expected to be published in the next few months. This dollar figure also represents the value of damages avoided for a small emission reduction (i.e., the benefit of a CO_2 reduction). As emission reductions include all GHG emissions quantified in this analysis and reported in terms of CO_2-equivalent, we applied the SC-CO_2 metric to estimate the benefits from avoided greenhouse gas emissions due to implementation of the vehicle electrification scenario.

SC-CO_2 is intended to be a comprehensive estimate of climate change damages and includes changes in net agricultural productivity, human health, property damages from increased flood risk, and value of ecosystem services. However, not all important damages are included due to data limitations. Once published, the final Biden administration values could differ substantially from those used here. They are anticipated to “consider climate risk, environmental justice, and intergenerational equity”[88].

For reference, the Social Cost of CO_2, in 2020 dollars per metric ton of CO2, for emissions occurring in year 2020, with a 3 percent discount rate is $51. For emissions in 2050, the same metric is valued at $85.

6.2. Calculated Benefits

Table 27 summarizes the results of the calculated benefits of the changes in GHG emissions expected under the electrification Scenario with both the Base and Non-Combustion Cases. These results use a 3 percent average discount rate. We have also updated the values to 2017 dollars to be consistent with the calculated health results using the Bureau of Labor Statistics CPI Inflation calculator. Values are shown in 2017 dollars and metric tons of GHG pollutant (as CO_2e).

Please note that CO_2e reductions here are calculated as the sum in changes from up- and downstream activities associated with vehicle electrification. That is, no BAU curve for sector-wide emissions for refining and electricity generation was developed for GHGs. (See Sections 4.2 and 4.3.)

---

86 The grid mixes used for each Case were discussed in Section 4.2. Note that the GREET emission factors used with these grid mixes include fugitive CH4 emissions during natural gas extraction and transport.
87 https://www.whitehouse.gov/wp-content/uploads/2021/02/TechnicalSupportDocument_SocialCostofCarbonMethaneNitrousOxide.pdf
88 https://www.eenews.net/articles/here-comes-the-social-cost-of-carbon-will-it-address-ej/

Thus, there are no additional SCC benefits from "cleaning the grid" under the Non-Combustion case reflected here, only the incremental changes associated with vehicle electrification (under each electricity Case). This is consistent with the previous (2020) study but differs from the reductions used for health benefits (Section 5).

Table 35. Avoided Social Costs from GHG Reductions (metric tons of CO_2e), in 2017$ with a 3% Discount Rate.

Year	Base Case GHG Reduction (MT CO_2e)	Base Case Avoided Social Cost of CO_2e emissions	Non-Combustion Case GHG Reduction (MT CO_2e)	Non-Combustion Case Avoided Social Cost of CO_2e emissions
2020	1,200,000	$57,800,000	1,200,000	$57,900,000
2030	187,000,000	$11,000,000,000	227,000,000	$13,300,000,000
2040	879,000,000	$60,800,000,000	1,200,000,000	$83,000,000,000
2050	1,440,000,000	$116,000,000,000	1,810,000,000	$145,000,000,000
Cumulative 2020-2050	18,600,000,000	$1,360,000,000,000	24,200,000,000	$1,760,000,000,000

Appendix A: Detailed Emissions Summaries

Base Case Electrification, full emissions breakdown. Note that all GHG values shown here are domestic. (Global net GHG values are shown in Table 19)

Year	NOx	SO_2	VOC	$PM_{2.5}$ Total	CO2 Equivalent	NH_3
Downstream: Total Onroad Emissions						
Scenario						
2020	2,499,886	9,851	1,114,249	74,967	1,868,232,366	101,963
2030	1,132,406	7,251	606,958	40,860	1,411,442,122	82,761
2040	447,500	2,737	324,728	22,937	549,889,901	34,529
2050	91,194	573	120,053	16,318	114,362,760	7,632
BAU						
2020	2,500,170	9,861	1,114,721	74,991	1,869,885,514	102,064
2030	1,206,804	8,560	660,353	44,407	1,646,134,788	97,241
2040	1,007,353	8,266	561,626	40,044	1,604,560,779	99,762
2050	1,090,001	8,707	547,522	42,169	1,702,235,605	107,896
Change in Emissions, Nationally						
2020	-284	-10	-473	-24	-1,653,148	-101
2030	-74,398	-1,309	-53,395	-3,547	-234,692,666	-14,480
2040	-559,853	-5,529	-236,899	-17,106	-1,054,670,878	-65,233
2050	-998,808	-8,134	-427,469	-25,851	-1,587,872,845	-100,265
Change, percent						
2020	0%	0%	0%	0%	0%	0%
2030	-6%	-15%	-8%	-8%	-14%	-15%
2040	-56%	-67%	-42%	-43%	-66%	-65%
2050	-92%	-93%	-78%	-61%	-93%	-93%
Upstream: 1-Base (National) Electricity Case						
Crude, Feedstock, Refining and Transportation Emissions Avoided from Electrification, Domestic						
2020	-444	-128	-559	-35	-423,762	N/A
2030	-58,969	-16,772	-70,405	-4,592	-55,843,321	N/A
2040	-253,090	-69,370	-280,342	-19,250	-237,717,792	N/A
2050	-384,751	-106,847	-405,604	-28,989	-355,975,180	N/A
Additional Emissions due to Additional Grid Load						
2020	564	472	90	48	814,384	N/A
2030	62,208	51,557	10,209	5,271	91,735,747	N/A
2040	236,890	184,649	40,357	19,902	354,537,666	N/A
2050	250,195	101,807	53,207	19,526	400,155,528	N/A
Net Emissions Change from Avoided Crude, Feedstock, Refining and Transport Emissions, and Additional EGUs, Domestic						
2020	120	344	-469	12	390,621	N/A
2030	3,239	34,786	-60,196	679	35,892,426	N/A
2040	102,888	115,279	-239,985	652	116,819,874	N/A

Year	NOx	SO_2	VOC	$PM_{2.5}$ Total	CO2 Equivalent	NH_3
2050	-134,556	-5,040	-352,398	-9,463	44,180,347	N/A
Total BAU Emissions, Domestic						
2020	1,627,345	935,258	3,329,915	177,376	N/A	47,540
2030	1,711,797	888,074	4,058,346	179,275	N/A	45,431
2040	1,667,947	815,711	3,999,499	175,000	N/A	44,030
2050	1,554,016	478,227	4,011,338	145,070	N/A	37,206
Percent Net Change in Emissions from BAU, National Scenario, Domestic						
2020	0%	0%	0%	0%	N/A	N/A
2030	0%	4%	-1%	0%	N/A	N/A
2040	-1%	14%	-6%	0%	N/A	N/A
2050	-9%	-1%	-9%	-7%	N/A	N/A
Combined						
Net Emissions Change, Nationally						
2020	-165	334	-942	-12	-1,262,526	N/A
2030	-71,159	33,476	-113,592	-2,868	-198,800,240	N/A
2040	-576,052	109,751	-478,032	-16,455	-937,851,005	N/A
2050	-1,133,364	-13,174	-779,867	-35,314	-1,543,692,498	N/A
National BAU						
2020	4,127,515	945,119	4,444,636	252,367	N/A	149,604
2030	2,918,601	896,634	4,718,699	223,682	N/A	142,672
2040	2,675,300	823,977	4,561,125	215,044	N/A	143,792
2050	2,644,017	486,934	4,558,861	187,239	N/A	145,102
Percent Net Change in Emissions from BAU, National Scenario, Domestic						
2020	0%	0%	0%	0%	N/A	N/A
2030	-2%	4%	-2%	-1%	N/A	N/A
2040	-22%	13%	-10%	-8%	N/A	N/A
2050	-43%	-3%	-17%	-19%	N/A	N/A

Non-Combustion Case Electrification, full emissions breakdown. Note that all GHG values shown here are domestic. (Global net GHG values are shown in). Here both baseline and new load from the Scenario are assigned to the Non-Combustion Case electric grid.

Year	NOx	SO2	VOC	$PM_{2.5}$ Total	CO2 Equivalent	NH3
Downstream: Total Onroad Emissions						
Scenario						
2020	2,499,886	9,851	1,114,249	74,967	1,868,232,366	101,963
2030	1,132,406	7,251	606,958	40,860	1,411,442,122	82,761
2040	447,500	2,737	324,728	22,937	549,889,901	34,529
2050	91,194	573	120,053	16,318	114,362,760	7,632
BAU						
2020	2,500,170	9,861	1,114,721	74,991	1,869,885,514	102,064
2030	1,206,804	8,560	660,353	44,407	1,646,134,788	97,241
2040	1,007,353	8,266	561,626	40,044	1,604,560,779	99,762
2050	1,090,001	8,707	547,522	42,169	1,702,235,605	107,896
Change in Emissions, Nationally						
2020	-284	-10	-473	-24	-1,653,148	-101
2030	-74,398	-1,309	-53,395	-3,547	-234,692,666	-14,480
2040	-559,853	-5,529	-236,899	-17,106	-1,054,670,878	-65,233
2050	-998,808	-8,134	-427,469	-25,851	-1,587,872,845	-100,265
Change, percent						
2020	0%	0%	0%	0%	0%	0%
2030	-6%	-15%	-8%	-8%	-14%	-15%
2040	-56%	-67%	-42%	-43%	-66%	-65%
2050	-92%	-93%	-78%	-61%	-93%	-93%
Upstream: 3-Non-Combustion Renewables Case, for additional EV load and rest of grid						
Feedstock, Crude, Refining, and Transportation Emissions Reductions, Domestic						
2020	-444	-128	-559	-35	-423,762	N/A
2030	-58,969	-16,772	-70,405	-4,592	-55,843,321	N/A
2040	-253,090	-69,370	-281,490	-19,250	-237,717,792	N/A
2050	-384,751	-106,847	-405,604	-28,989	-355,975,180	N/A
Additional Upstream Emissions due to Additional Grid Load, Non-Combustion Case						
2020	546	462	90	47	812,076	N/A
2030	28,484	10,188	6,418	2,208	47,719,961	N/A
2040	1,314	34	389	44	315,064	N/A
2050	1,799	47	533	61	431,504	N/A
Net Upstream Emissions Change: Avoided Crude, Feedstock, Refining and Transport Emissions, and Additional EGUs, Non-Combustion Case, Domestic						
2020	102	334	-469	12	388,314	N/A
2030	-30,485	-6,583	-63,987	-2,384	-8,123,360	N/A
2040	-251,776	-69,336	-281,101	-19,206	-237,402,729	N/A
2050	-382,952	-106,800	-405,071	-28,928	-355,543,677	N/A

Year	NOx	SO2	VOC	$PM_{2.5}$ Total	CO2 Equivalent	NH3
Total BAU Upstream Emissions, Non-Combustion Case with Non-Combustion BAU, Domestic						
2020	1,627,345	935,258	3,329,915	177,376	N/A	47,540
2030	1,352,499	370,812	4,046,127	117,279	N/A	27,605
2040	1,004,626	225,274	3,964,576	70,378	N/A	11,121
2050	1,027,456	235,077	3,976,751	71,990	N/A	11,082
Percent Net Change in Upstream Emissions from Upstream BAU, Non-Combustion Case, Non-Combustion Load, National Scenario, Domestic						
2020	0%	0%	0%	0%	N/A	N/A
2030	-2%	-2%	-2%	-2%	N/A	N/A
2040	-25%	-31%	-7%	-27%	N/A	N/A
2050	-37%	-45%	-10%	-40%	N/A	N/A
Combined						
Net Emissions Change, Nationally						
2020	-182	324	-941	-13	-1,264,834	N/A
2030	-104,883	-7,892	-117,382	-5,931	-242,816,026	N/A
2040	-811,629	-74,865	-517,999	-36,313	-1,292,073,607	N/A
2050	-1,381,760	-114,935	-832,540	-54,779	-1,943,416,522	N/A
National BAU						
2020	4,127,515	945,119	4,444,636	252,367	N/A	149,604
2030	2,559,304	379,372	4,706,480	161,686	N/A	124,846
2040	2,011,979	233,540	4,526,202	110,422	N/A	110,883
2050	2,117,457	243,784	4,524,273	114,159	N/A	118,978
Percent Net Change in Emissions from BAU, National Scenario, Domestic						
2020	0%	0%	0%	0%	N/A	N/A
2030	-4%	-2%	-2%	-4%	N/A	N/A
2040	-40%	-32%	-11%	-33%	N/A	N/A
2050	-65%	-47%	-18%	-48%	N/A	N/A

Appendix B: COBRA Emission Tiers Incorporated in Calculating the BAU Emission Inventory

Tier 1 Number	Tier 2 Number	Tier 3 Number	Tier 1 Name	Tier 2 Name	Tier 3 Name	Notes
Upstream Petroleum – Refining, Storage, and Transport						
2	2	1	Fuel Combustion: Industrial	Oil	Residual	
2	2	2	Fuel Combustion: Industrial	Oil	Distillate	
2	2	99	Fuel Combustion: Industrial	Oil	Other	
2	3	1	Fuel Combustion: Industrial	Gas	Natural	
2	3	2	Fuel Combustion: Industrial	Gas	Process	
2	3	99	Fuel Combustion: Industrial	Gas	Other	
2	4	99	Fuel Combustion: Industrial	Other	Other	
6	1	1	Petroleum & Related Industries	Oil & Gas Production	Natural Gas	*Included in BAU. However, Scenario reductions in upstream emissions will not be applied to natural gas production Tiers in health modeling.*
6	1	99	Petroleum & Related Industries	Oil & Gas Production	Other	
6	2	1	Petroleum & Related Industries	Petroleum Refineries & Related Industries	Fluid Catalytic Cracking Units	
6	2	2	Petroleum & Related Industries	Petroleum Refineries & Related Industries	Vacuum Distillation	
6	2	3	Petroleum & Related Industries	Petroleum Refineries & Related Industries	Process Unit Turnarounds	
6	2	4	Petroleum & Related Industries	Petroleum Refineries & Related Industries	Petroleum Refinery Fugitives	

Tier 1 Number	Tier 2 Number	Tier 3 Number	Tier 1 Name	Tier 2 Name	Tier 3 Name	Notes
6	2	99	Petroleum & Related Industries	Petroleum Refineries & Related Industries	Other	
6	3	99	Petroleum & Related Industries	Asphalt Manufacturing	Other	*Included in BAU. However, Scenario reductions in upstream emissions will not be applied to asphalt manufacturing Tiers in health modeling.*
7	99	1	Other Industrial Processes	Miscellaneous Industrial Processes	Ethanol Production	
9	1	1	Storage & Transport	Bulk Terminals & Plants	Fixed Roof	
9	1	2	Storage & Transport	Bulk Terminals & Plants	Floating Roof	
9	1	3	Storage & Transport	Bulk Terminals & Plants	Variable Vapor Space	
9	1	4	Storage & Transport	Bulk Terminals & Plants	External Floating Roof With Seals	
9	1	5	Storage & Transport	Bulk Terminals & Plants	Internal Floating Roof With Seals	
9	1	6	Storage & Transport	Bulk Terminals & Plants	Underground Tanks	
9	1	7	Storage & Transport	Bulk Terminals & Plants	Area Source: Gasoline	
9	1	99	Storage & Transport	Bulk Terminals & Plants	Other	
9	2	1	Storage & Transport	Petroleum & Petroleum Product Storage	Fixed Roof Gasoline	
9	2	2	Storage & Transport	Petroleum & Petroleum Product Storage	Fixed Roof Crude	
9	2	3	Storage & Transport	Petroleum & Petroleum Product Storage	Floating Roof Gasoline	
9	2	4	Storage & Transport	Petroleum & Petroleum Product Storage	Floating Roof Crude	
9	2	5	Storage & Transport	Petroleum & Petroleum Product Storage	External Floating Roof / Seal Gasoline	
9	2	6	Storage & Transport	Petroleum & Petroleum Product Storage	External Floating Roof / Seal Crude	

Tier 1 Number	Tier 2 Number	Tier 3 Number	Tier 1 Name	Tier 2 Name	Tier 3 Name	Notes
9	2	7	Storage & Transport	Petroleum & Petroleum Product Storage	Internal Floating Roof / Seal Gasoline	
9	2	8	Storage & Transport	Petroleum & Petroleum Product Storage	Internal Floating Roof / Seal Crude	
9	2	9	Storage & Transport	Petroleum & Petroleum Product Storage	Variable Vapor Space Gasoline	
9	2	10	Storage & Transport	Petroleum & Petroleum Product Storage	Area Source: Gasoline	
9	2	99	Storage & Transport	Petroleum & Petroleum Product Storage	Other	
9	3	1	Storage & Transport	Petroleum & Petroleum Product Transport	Gasoline Loading: Normal / Splash	
9	3	2	Storage & Transport	Petroleum & Petroleum Product Transport	Gasoline Loading: Balanced / Submerged	
9	3	3	Storage & Transport	Petroleum & Petroleum Product Transport	Gasoline Loading: Normal / Submerged	
9	3	4	Storage & Transport	Petroleum & Petroleum Product Transport	Gasoline Loading: Clean / Submerged	
9	3	5	Storage & Transport	Petroleum & Petroleum Product Transport	Marine Vessel Loading: Gasoline	
9	3	99	Storage & Transport	Petroleum & Petroleum Product Transport	Other	
9	4	99	Storage & Transport	Service Stations: Stage I	Other	
9	5	99	Storage & Transport	Service Stations: Stage II	Other	
9	6	99	Storage & Transport	Service Stations: Breathing & Emptying	Other	
Electricity Generating Units						
1	1	1	Fuel Combustion: Electric Utility	Coal	Bituminous	
1	1	2	Fuel Combustion: Electric Utility	Coal	Subbituminous	

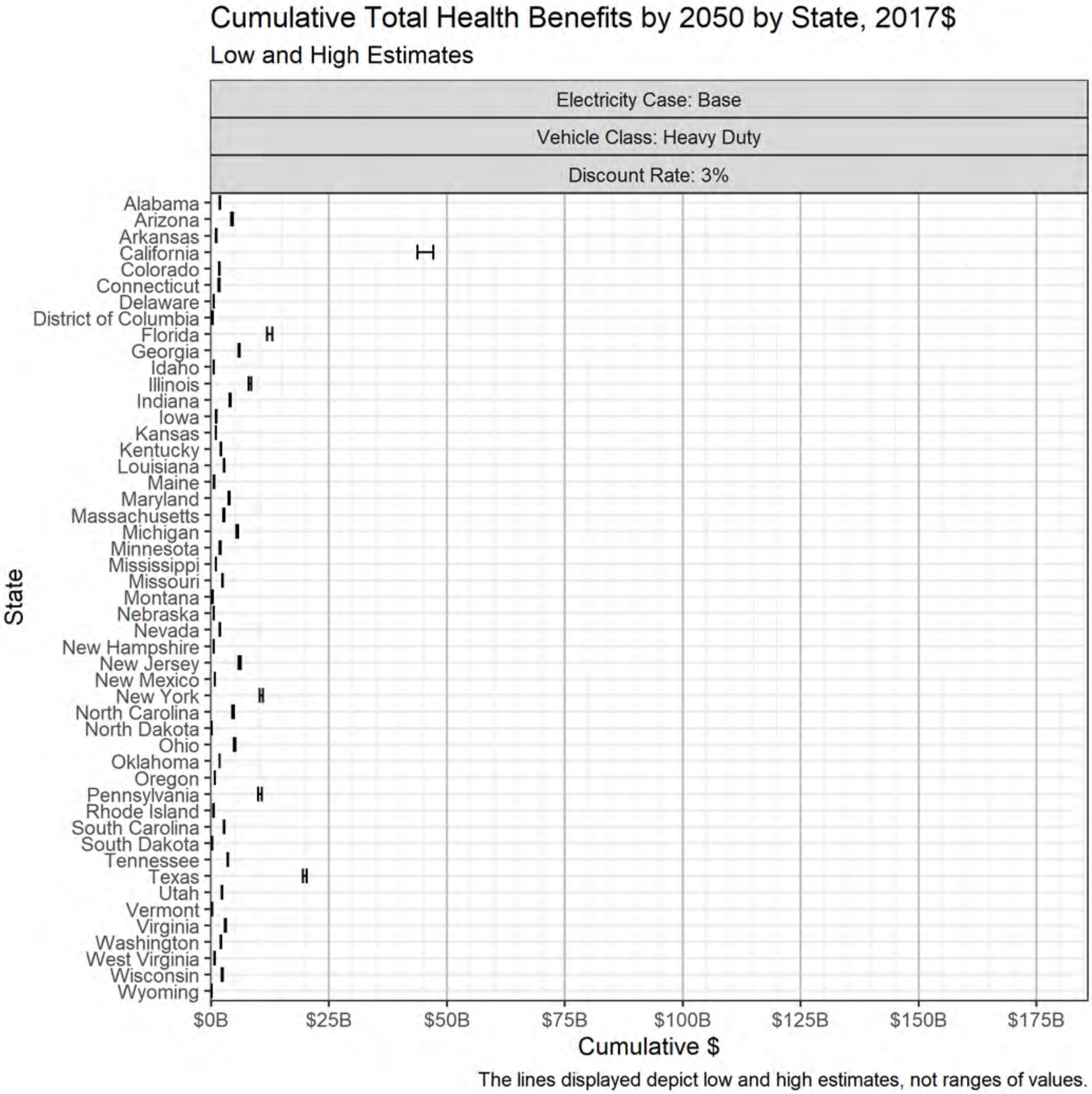
Tier 1 Number	Tier 2 Number	Tier 3 Number	Tier 1 Name	Tier 2 Name	Tier 3 Name	Notes
1	1	3	Fuel Combustion: Electric Utility	Coal	Anthracite & Lignite	
1	2	1	Fuel Combustion: Electric Utility	Oil	Residual	
1	2	2	Fuel Combustion: Electric Utility	Oil	Distillate	
1	3	1	Fuel Combustion: Electric Utility	Gas	Natural	
1	3	2	Fuel Combustion: Electric Utility	Gas	Process	
1	4	99	Fuel Combustion: Electric Utility	Other	Other	
1	5	99	Fuel Combustion: Electric Utility	Internal Combustion	Other	

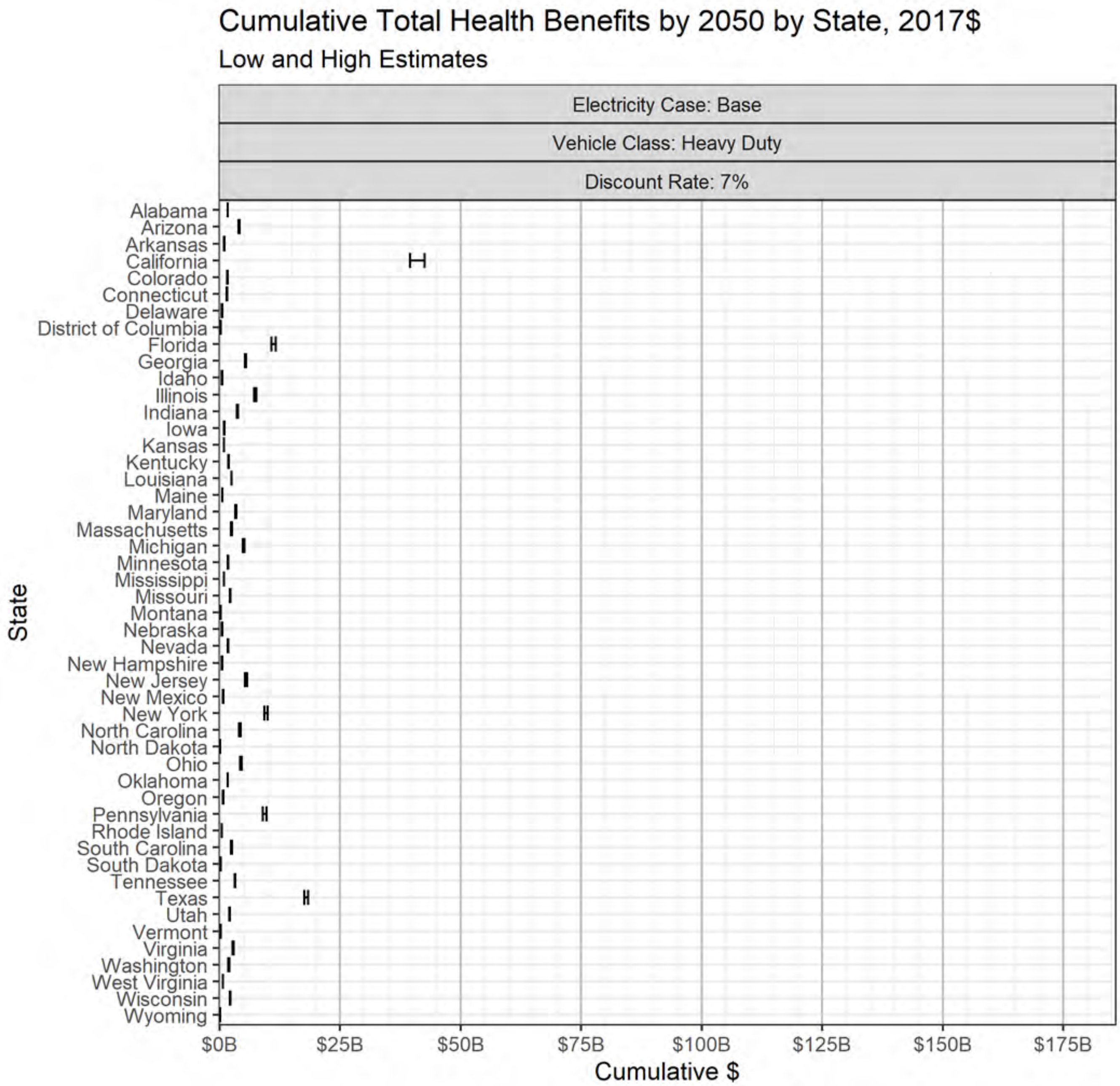
Appendix C: COBRA Health Endpoints

Health Endpoint	Author(s)	Year	Applicable Ages
Acute Bronchitis	Dockery et al.	1996	8-12
Acute Myocardial Infarction, Nonfatal (high)	Peters et al.	2001	18-99
Acute Myocardial Infarction, Nonfatal (low)	Pope et al.	2006	0-99
Acute Myocardial Infarction, Nonfatal (low)	Sullivan et al.	2005	0-99
Acute Myocardial Infarction, Nonfatal (low)	Zanobetti and Schwartz	2006	0-99
Acute Myocardial Infarction, Nonfatal (low)	Zanobetti et al.	2009	0-99
Asthma Exacerbation, Cough	Mar et al.	2004	6-17
Asthma Exacerbation, Cough	Ostro et al.	2001	6-17
Asthma Exacerbation, Shortness of Breath	Mar et al.	2004	6-17
Asthma Exacerbation, Shortness of Breath	Ostro et al.	2001	6-17
Asthma Exacerbation, Wheeze	Ostro et al.	2001	6-17
Asthma Exacerbation, Cough	Mar et al.	2004	18-18
Asthma Exacerbation, Cough	Ostro et al.	2001	18-18
Asthma Exacerbation, Shortness of Breath	Mar et al.	2004	18-18
Asthma Exacerbation, Shortness of Breath	Ostro et al.	2001	18-18
Asthma Exacerbation, Wheeze	Ostro et al.	2001	18-18
Emergency Room Visits, Asthma	Mar et al.	2010	0-99
Emergency Room Visits, Asthma	Slaughter et al.	2005	0-99
Emergency Room Visits, Asthma	Glad et al.	2012	0-99
HA, All Cardiovascular (less Myocardial Infarctions)	Moolgavkar	2000	18-64
HA, All Cardiovascular (less Myocardial Infarctions)	Bell et al.	2008	65-99
HA, All Cardiovascular (less Myocardial Infarctions)	Peng et al.	2008	65-99
HA, All Cardiovascular (less Myocardial Infarctions)	Peng et al.	2009	65-99
HA, All Cardiovascular (less Myocardial Infarctions)	Zanobetti et al	2009	65-99
HA, All Respiratory	Zanobetti et al	2009	65-99
HA, All Respiratory	Kloog et al.	2012	65-99
HA, Asthma	Babin et al.	2007	0-17
HA, Asthma	Sheppard	2003	0-17
HA, Chronic Lung Disease	Moolgavkar	2000	18-64
Lower Respiratory Symptoms	Schwartz and Neas	2000	7-14
Minor Restricted Activity Days	Ostro and Rothschild	1989	18-64
Mortality, All Cause (low)	Krewski et al.	2009	30-99
Mortality, All Cause (high)	Di et al.	2017	65-99
Infant Mortality	Woodruff et al.	1997	0-0
Upper Respiratory Symptoms	Pope et al.	1991	9-11
Work Loss Days	Ostro	1987	18-64

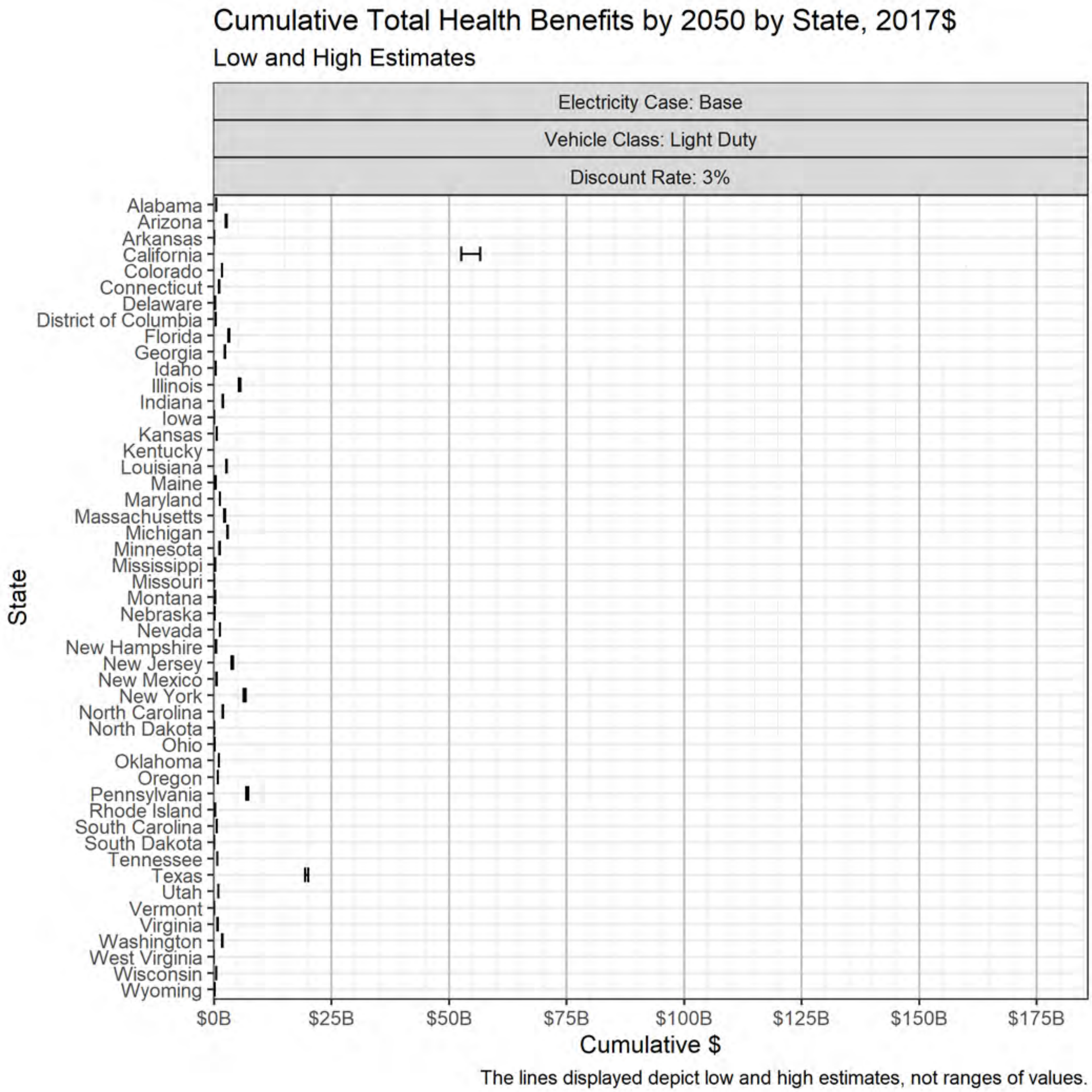
Appendix D: Cumulative Total Health Benefits by State by 2050

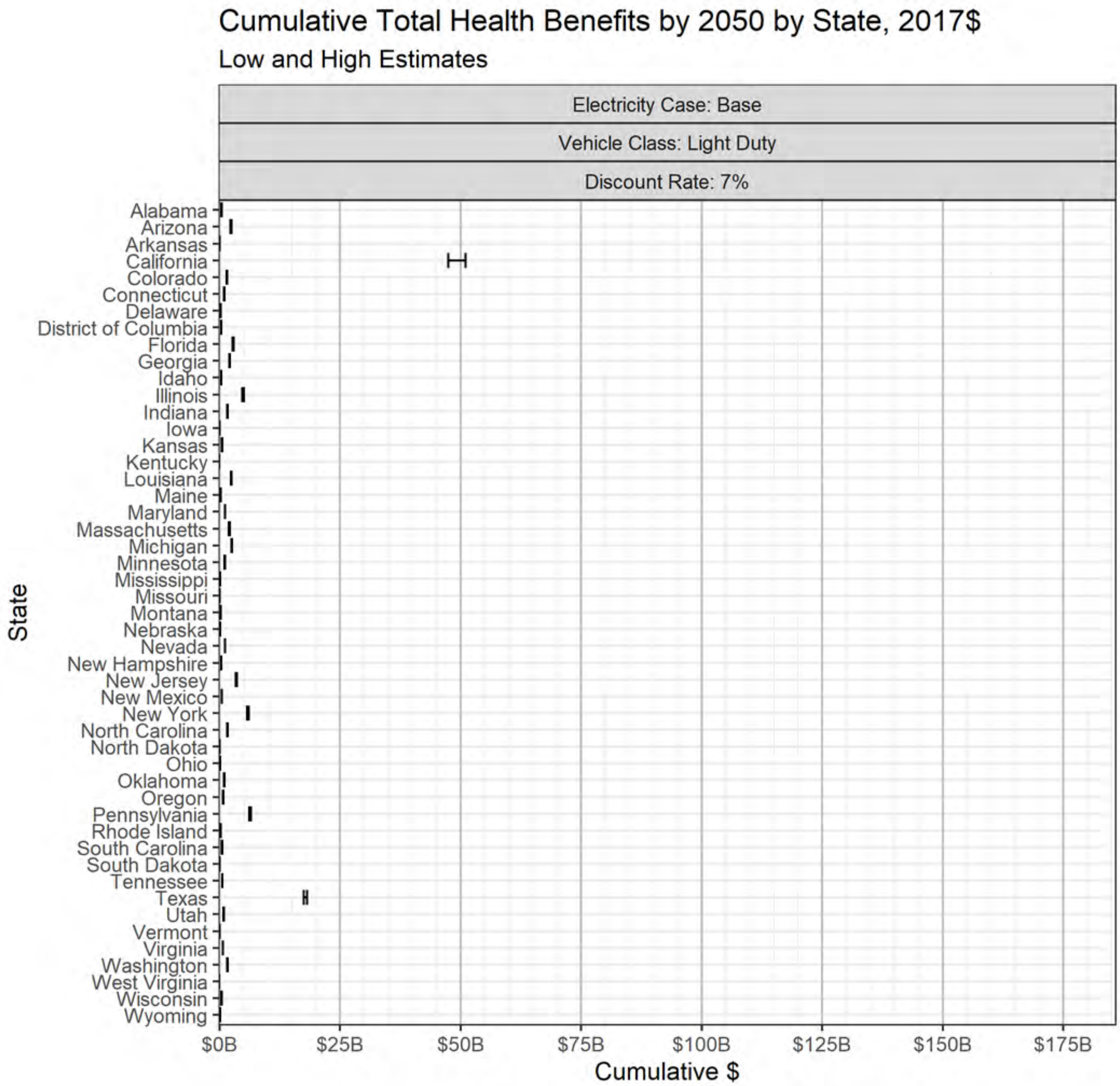
The following plots show the cumulative total health benefits by State by 2050 for each electricity case, vehicle class, and discount rate.



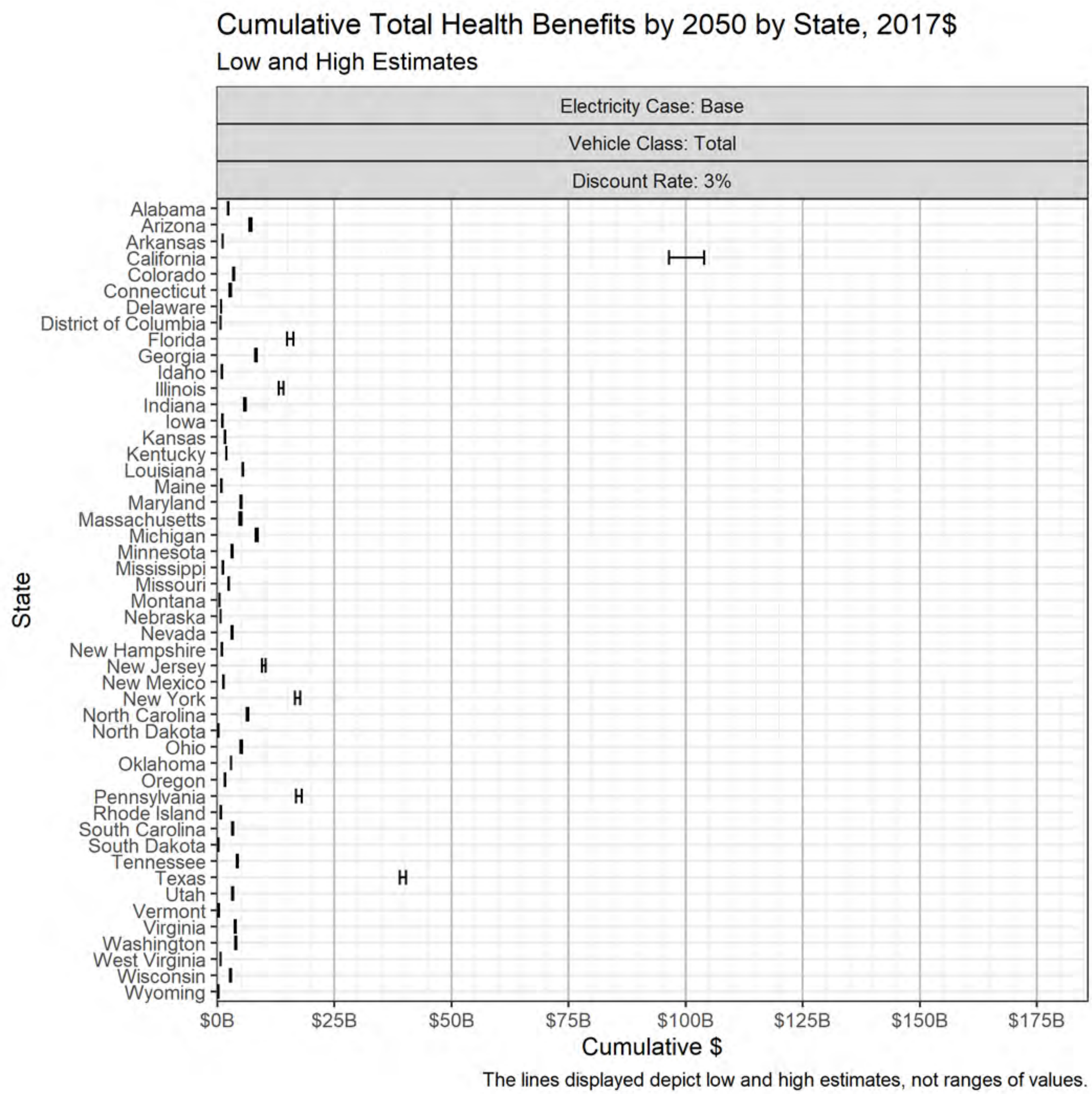


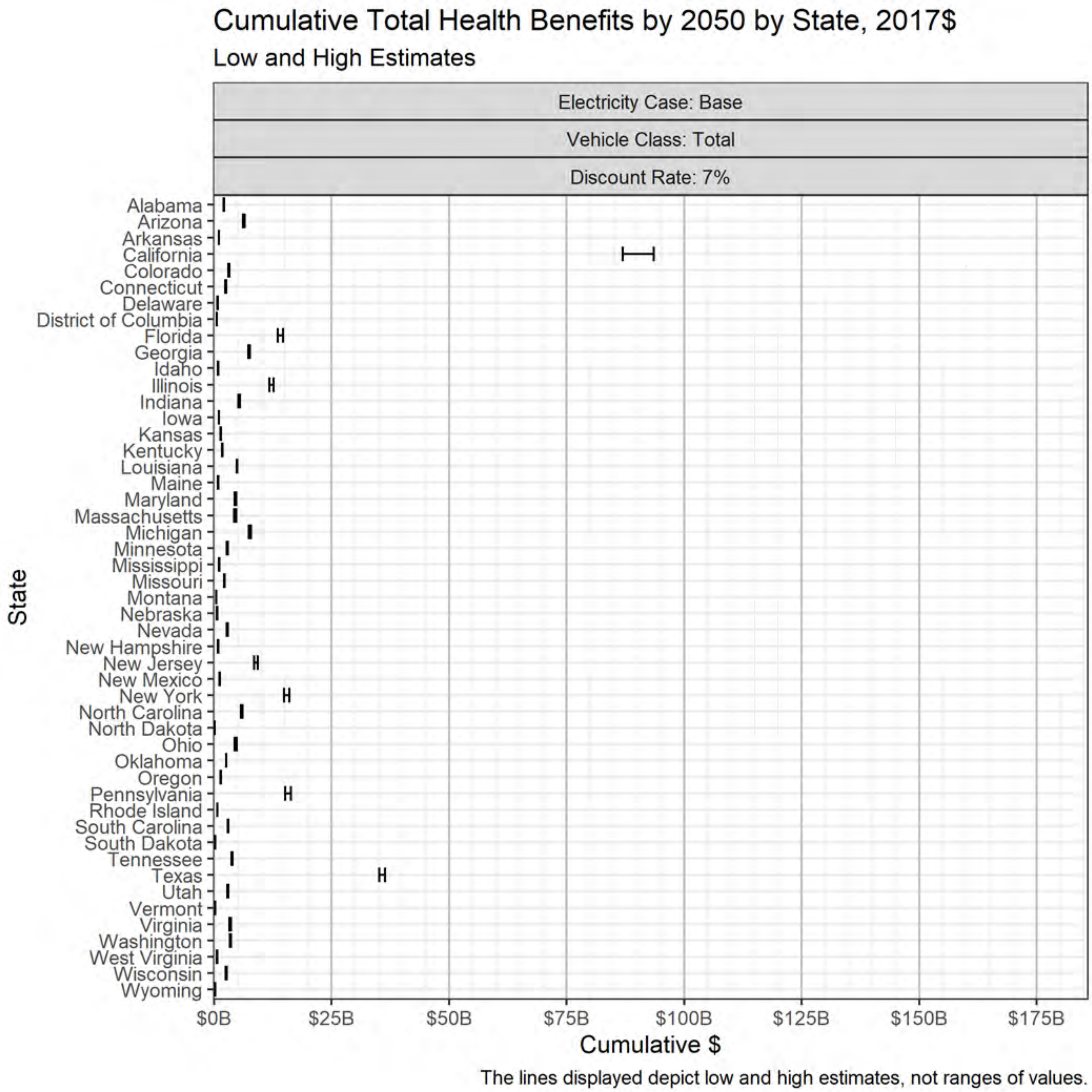
The lines displayed depict low and high estimates, not ranges of values.

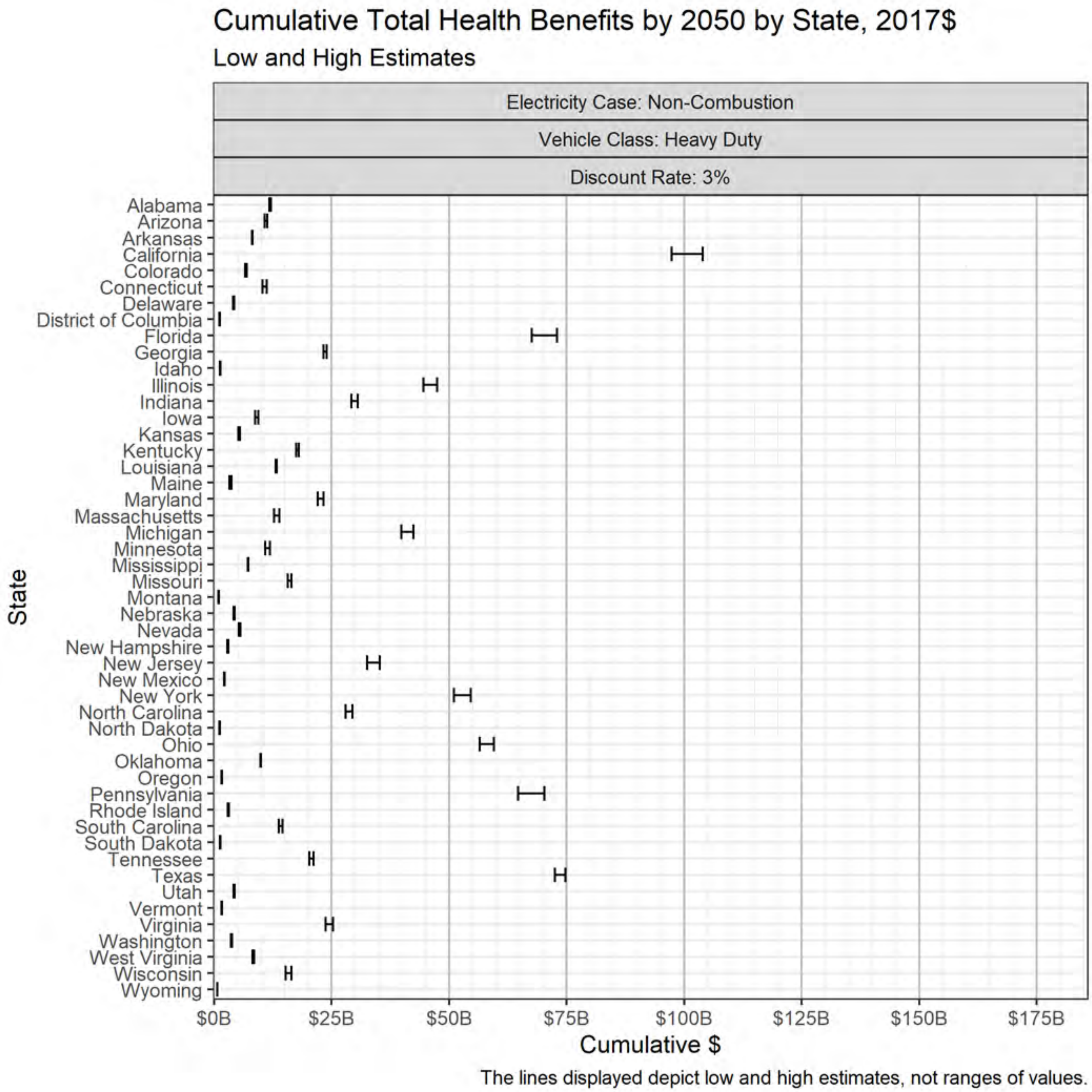

Cumulative Total Health Benefits by 2050 by State, 2017$
Low and High Estimates
Electricity Case: Base
Vehicle Class: Light Duty
Discount Rate: 3%
State
Alabama
Arizona
Arkansas
California
Colorado
Connecticut
Delaware
District of Columbia
Florida
Georgia
Idaho
Illinois
Indiana
Iowa
Kansas
Kentucky
Louisiana
Maine
Maryland
Massachusetts
Michigan
Minnesota
Mississippi
Missouri
Montana
Nebraska
Nevada
New Hampshire
New Jersey
New Mexico
New York
North Carolina
North Dakota
Ohio
Oklahoma
Oregon
Pennsylvania
Rhode Island
South Carolina
South Dakota
Tennessee
Texas
Utah
Vermont
Virginia
Washington
West Virginia
Wisconsin
Wyoming
$0B
$25B
$50B
$75B
$100B
$125B
$150B
$175B
Cumulative $
The lines displayed depict low and high estimates, not ranges of values.

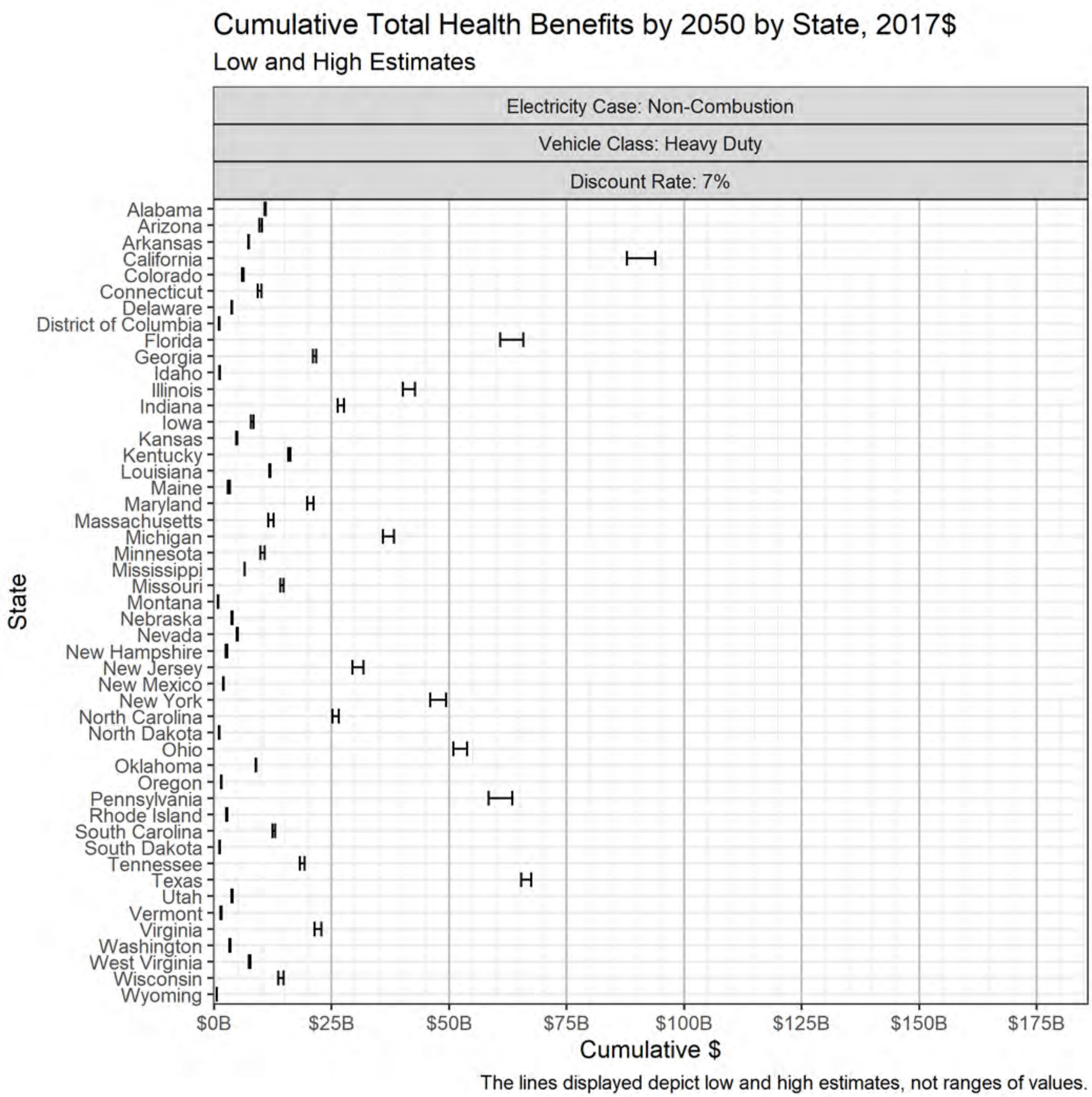


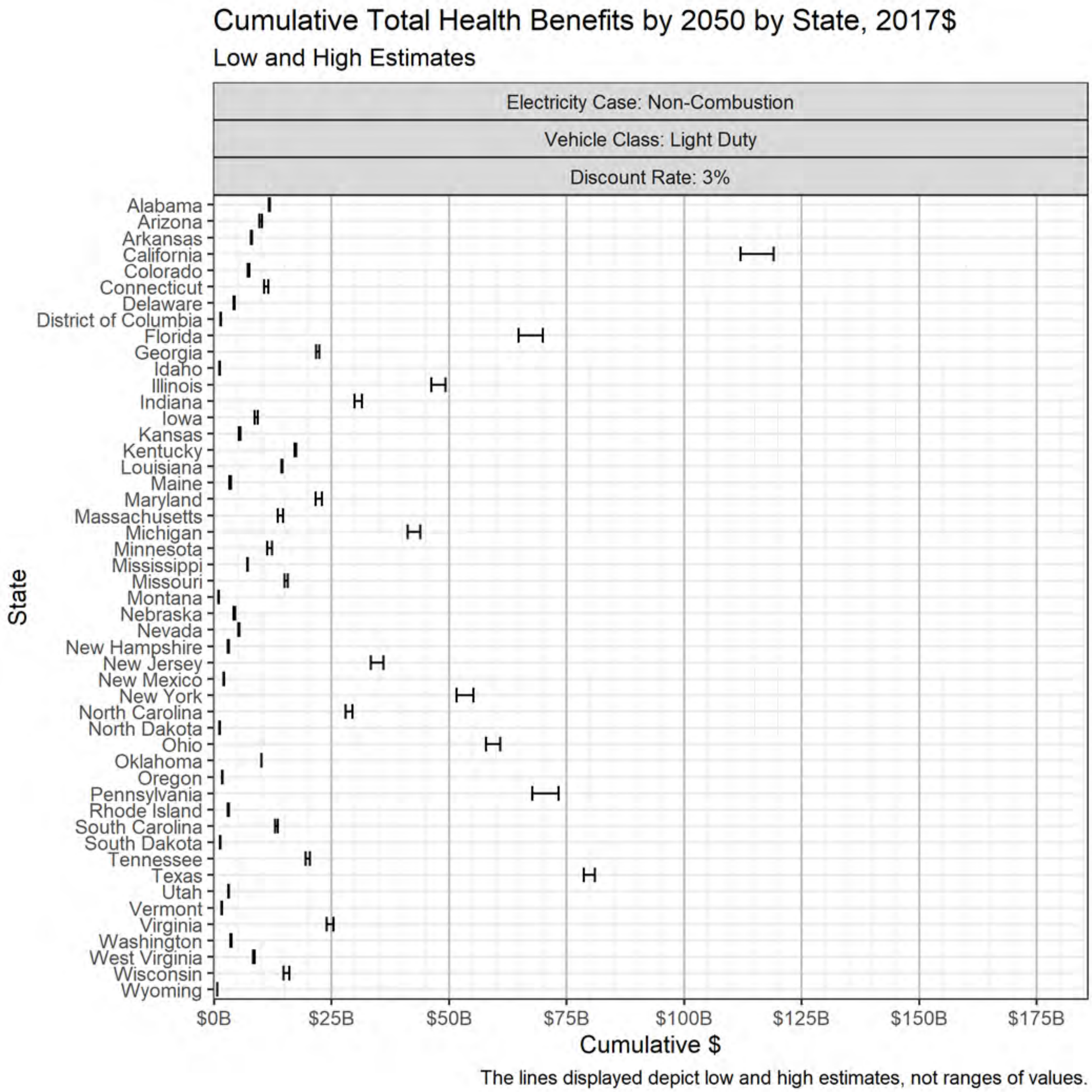
The lines displayed depict low and high estimates, not ranges of values.

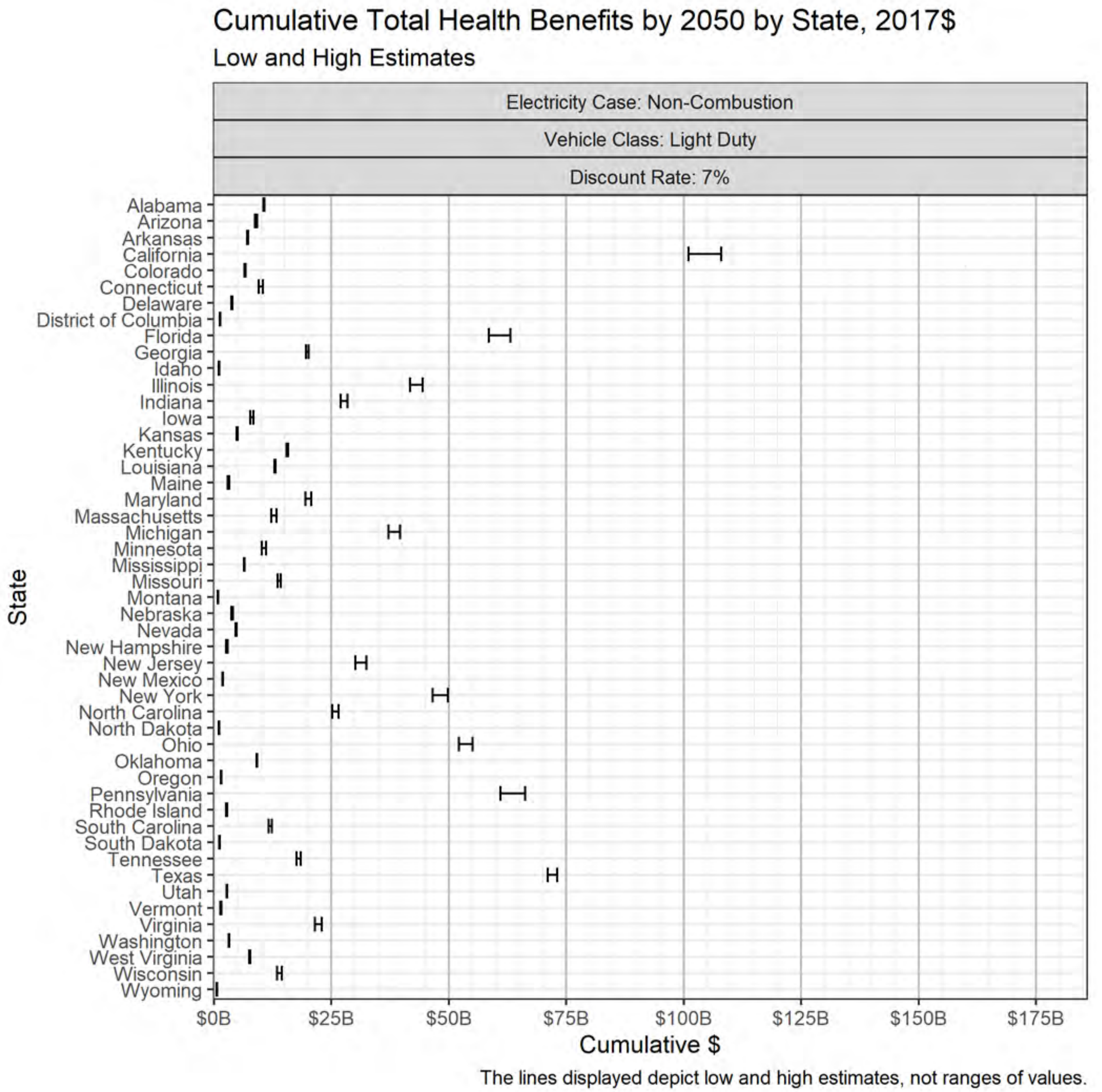

Cumulative Total Health Benefits by 2050 by State, 2017$
Low and High Estimates
Electricity Case: Base
Vehicle Class: Total
Discount Rate: 3%
State
Alabama
Arizona
Arkansas
California
Colorado
Connecticut
Delaware
District of Columbia
Florida
Georgia
Idaho
Illinois
Indiana
Iowa
Kansas
Kentucky
Louisiana
Maine
Maryland
Massachusetts
Michigan
Minnesota
Mississippi
Missouri
Montana
Nebraska
Nevada
New Hampshire
New Jersey
New Mexico
New York
North Carolina
North Dakota
Ohio
Oklahoma
Oregon
Pennsylvania
Rhode Island
South Carolina
South Dakota
Tennessee
Texas
Utah
Vermont
Virginia
Washington
West Virginia
Wisconsin
Wyoming
$0B
$25B
$50B
$75B
$100B
$125B
$150B
$175B
Cumulative $
The lines displayed depict low and high estimates, not ranges of values.

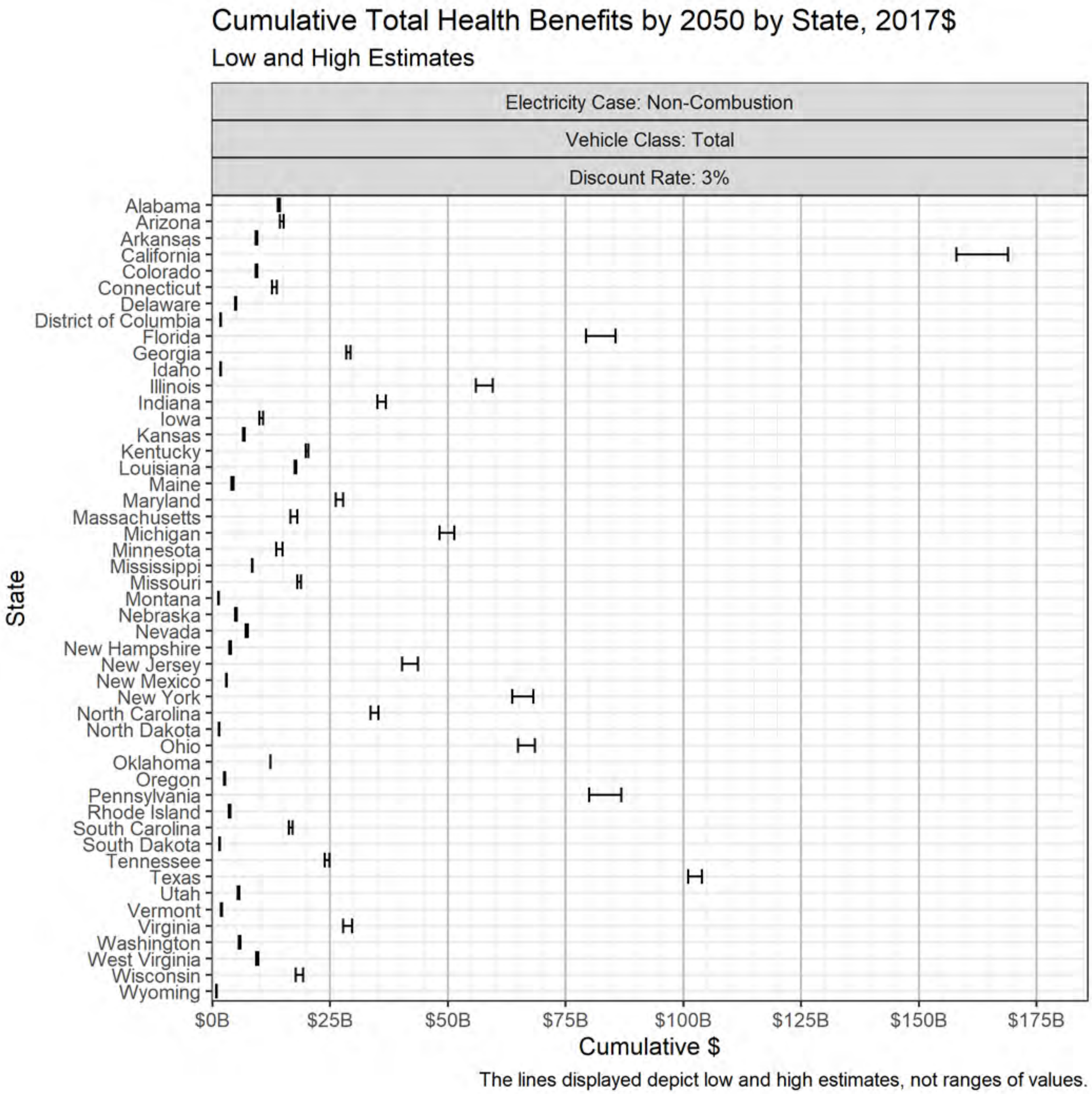

Cumulative Total Health Benefits by 2050 by State, 2017$
Low and High Estimates
Electricity Case: Base
Vehicle Class: Total
Discount Rate: 7%
State
Alabama
Arizona
Arkansas
California
Colorado
Connecticut
Delaware
District of Columbia
Florida
Georgia
Idaho
Illinois
Indiana
Iowa
Kansas
Kentucky
Louisiana
Maine
Maryland
Massachusetts
Michigan
Minnesota
Mississippi
Missouri
Montana
Nebraska
Nevada
New Hampshire
New Jersey
New Mexico
New York
North Carolina
North Dakota
Ohio
Oklahoma
Oregon
Pennsylvania
Rhode Island
South Carolina
South Dakota
Tennessee
Texas
Utah
Vermont
Virginia
Washington
West Virginia
Wisconsin
Wyoming
$0B
$25B
$50B
$75B
$100B
$125B
$150B
$175B
Cumulative $
The lines displayed depict low and high estimates, not ranges of values.


Cumulative Total Health Benefits by 2050 by State, 2017$
Low and High Estimates
Electricity Case: Non-Combustion
Vehicle Class: Heavy Duty
Discount Rate: 3%
State
Alabama
Arizona
Arkansas
California
Colorado
Connecticut
Delaware
District of Columbia
Florida
Georgia
Idaho
Illinois
Indiana
Iowa
Kansas
Kentucky
Louisiana
Maine
Maryland
Massachusetts
Michigan
Minnesota
Mississippi
Missouri
Montana
Nebraska
Nevada
New Hampshire
New Jersey
New Mexico
New York
North Carolina
North Dakota
Ohio
Oklahoma
Oregon
Pennsylvania
Rhode Island
South Carolina
South Dakota
Tennessee
Texas
Utah
Vermont
Virginia
Washington
West Virginia
Wisconsin
Wyoming
$0B
$25B
$50B
$75B
$100B
$125B
$150B
$175B
Cumulative $
The lines displayed depict low and high estimates, not ranges of values.

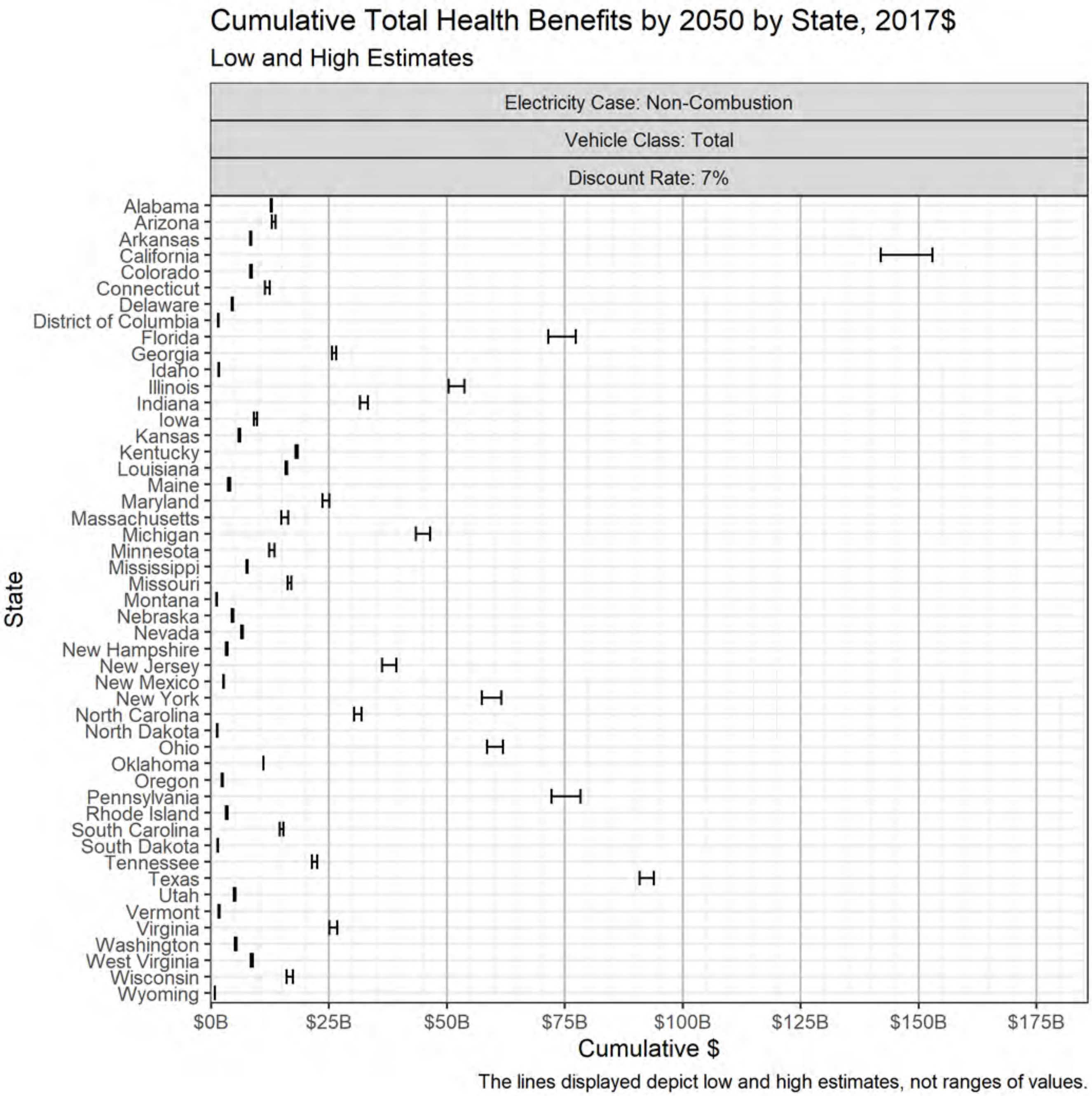

Cumulative Total Health Benefits by 2050 by State, 2017$
Low and High Estimates
Electricity Case: Non-Combustion
Vehicle Class: Heavy Duty
Discount Rate: 7%
State
Alabama
Arizona
Arkansas
California
Colorado
Connecticut
Delaware
District of Columbia
Florida
Georgia
Idaho
Illinois
Indiana
Iowa
Kansas
Kentucky
Louisiana
Maine
Maryland
Massachusetts
Michigan
Minnesota
Mississippi
Missouri
Montana
Nebraska
Nevada
New Hampshire
New Jersey
New Mexico
New York
North Carolina
North Dakota
Ohio
Oklahoma
Oregon
Pennsylvania
Rhode Island
South Carolina
South Dakota
Tennessee
Texas
Utah
Vermont
Virginia
Washington
West Virginia
Wisconsin
Wyoming
$0B
$25B
$50B
$75B
$100B
$125B
$150B
$175B
Cumulative $
The lines displayed depict low and high estimates, not ranges of values.


Cumulative Total Health Benefits by 2050 by State, 2017$
Low and High Estimates
Electricity Case: Non-Combustion
Vehicle Class: Light Duty
Discount Rate: 3%
State
Alabama
Arizona
Arkansas
California
Colorado
Connecticut
Delaware
District of Columbia
Florida
Georgia
Idaho
Illinois
Indiana
Iowa
Kansas
Kentucky
Louisiana
Maine
Maryland
Massachusetts
Michigan
Minnesota
Mississippi
Missouri
Montana
Nebraska
Nevada
New Hampshire
New Jersey
New Mexico
New York
North Carolina
North Dakota
Ohio
Oklahoma
Oregon
Pennsylvania
Rhode Island
South Carolina
South Dakota
Tennessee
Texas
Utah
Vermont
Virginia
Washington
West Virginia
Wisconsin
Wyoming
$0B
$25B
$50B
$75B
$100B
$125B
$150B
$175B
Cumulative $
The lines displayed depict low and high estimates, not ranges of values.


Cumulative Total Health Benefits by 2050 by State, 2017$
Low and High Estimates
Electricity Case: Non-Combustion
Vehicle Class: Light Duty
Discount Rate: 7%
State
Alabama
Arizona
Arkansas
California
Colorado
Connecticut
Delaware
District of Columbia
Florida
Georgia
Idaho
Illinois
Indiana
Iowa
Kansas
Kentucky
Louisiana
Maine
Maryland
Massachusetts
Michigan
Minnesota
Mississippi
Missouri
Montana
Nebraska
Nevada
New Hampshire
New Jersey
New Mexico
New York
North Carolina
North Dakota
Ohio
Oklahoma
Oregon
Pennsylvania
Rhode Island
South Carolina
South Dakota
Tennessee
Texas
Utah
Vermont
Virginia
Washington
West Virginia
Wisconsin
Wyoming
$0B
$25B
$50B
$75B
$100B
$125B
$150B
$175B
Cumulative $
The lines displayed depict low and high estimates, not ranges of values.



Cumulative Total Health Benefits by 2050 by State, 2017$
Low and High Estimates
Electricity Case: Non-Combustion
Vehicle Class: Total
Discount Rate: 3%
State
Alabama
Arizona
Arkansas
California
Colorado
Connecticut
Delaware
District of Columbia
Florida
Georgia
Idaho
Illinois
Indiana
Iowa
Kansas
Kentucky
Louisiana
Maine
Maryland
Massachusetts
Michigan
Minnesota
Mississippi
Missouri
Montana
Nebraska
Nevada
New Hampshire
New Jersey
New Mexico
New York
North Carolina
North Dakota
Ohio
Oklahoma
Oregon
Pennsylvania
Rhode Island
South Carolina
South Dakota
Tennessee
Texas
Utah
Vermont
Virginia
Washington
West Virginia
Wisconsin
Wyoming
$0B
$25B
$50B
$75B
$100B
$125B
$150B
$175B
Cumulative $
The lines displayed depict low and high estimates, not ranges of values.


Cumulative Total Health Benefits by 2050 by State, 2017$
Low and High Estimates
Electricity Case: Non-Combustion
Vehicle Class: Total
Discount Rate: 7%
State
Alabama
Arizona
Arkansas
California
Colorado
Connecticut
Delaware
District of Columbia
Florida
Georgia
Idaho
Illinois
Indiana
Iowa
Kansas
Kentucky
Louisiana
Maine
Maryland
Massachusetts
Michigan
Minnesota
Mississippi
Missouri
Montana
Nebraska
Nevada
New Hampshire
New Jersey
New Mexico
New York
North Carolina
North Dakota
Ohio
Oklahoma
Oregon
Pennsylvania
Rhode Island
South Carolina
South Dakota
Tennessee
Texas
Utah
Vermont
Virginia
Washington
West Virginia
Wisconsin
Wyoming
$0B
$25B
$50B
$75B
$100B
$125B
$150B
$175B
Cumulative $
The lines displayed depict low and high estimates, not ranges of values.

icf.com

twitter.com/ICF
linkedin.com/company/icf-international
facebook.com/ThisIsICF
#thisisicf

About ICF

ICF (NASDAQ:ICFI) is a global consulting and digital services company with over 7,000 full- and part-time employees, but we are not your typical consultants. At ICF, business analysts and policy specialists work together with digital strategists, data scientists and creatives. We combine unmatched industry expertise with cutting-edge engagement capabilities to help organizations solve their most complex challenges. Since 1969, public and private sector clients have worked with ICF to navigate change and shape the future. Learn more at icf.com.