Princeton's Net-Zero America study
Annex S: Air Quality Impacts (Methods and Supplemental Results)

Erin Mayfield[i] and Jesse Jenkins[ii]

i High Meadows Environmental Institute, Princeton University
ii Andlinger Center for Energy and the Environment and Department of Mechanical and Aerospace Engineering, Princeton University

With contributions from Yiming (Cady) Feng, Princeton University undergraduate class of 2024.

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<u>Note to reader:</u> All findings and modeling details in Annex S are preliminary. Annex S details the methods consistent with and provided as supporting information for *Net-Zero America: Potential Pathways, Infrastructure, and Inputs* (Larson *et al.* 2021). A manuscript which details the air quality modeling methods and results is currently in preparation and will undergo peer review.

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1 Methods

1.1 Scope

In this study, we model public health impacts from alternative pathways to reach net-zero emissions in the United States (US) by mid-Century. Specifically, we model premature mortality from exposure to primary fine particulate matter ($PM_{2.5}$) and secondary $PM_{2.5}$ formed from the atmospheric oxidation of nitrogen oxides (NO_x), sulfur dioxide (SO_2), and volatile organic compound (VOC) emissions.

We model several criteria air pollutant source emission categories that are relevant to decarbonization, including coal and natural gas electric power generation, fuel combustion in the residential sector (e.g. for space and water heating and cooking), fuel combustion in commercial sector, coal mining industrial processes, oil and gas extraction industrial processes, on-road mobile sources (vehicles), commercial cooking, and gas stations. Table 1 shows the emission source category coverage of this study relative to the 2017 US Environmental Protection Agency (EPA) National Emissions Inventory (NEI). More than half of current anthropogenic criteria air pollutant emissions (excluding fires and agriculture source categories) relevant to decarbonization are modeled in this study.[1] This study is not comprehensive of all criteria air pollutants (e.g., ammonia, carbon monoxide, black carbon) and source emission categories relevant to decarbonization, and it does not include hazardous air pollutants, nor does it consider public health outcomes other than mortality, such as illness and hospitalization.

Across emission source categories, we employ alternative emissions estimation approaches that vary in the degree of specificity based on the availability of data, relative contribution to total emissions, and nature of emissions. We model unit-level emissions for coal and natural gas electric power generation, county-level emissions by vehicle class and fuel type for on-road mobile sources, and county-level emissions by fuel type for other combustion emission source categories.

The following subsections describe the activity and emissions estimation approach for each source category, in addition to intermediate emissions results. The final subsection outlines the air quality impact modeling and monetization approach.

[1] Based on 2017 NEI emissions, we estimate 58%, 58%, 59%, and 69% of NO_x, $PM_{2.5}$, SO_2, and VOC emissions, respectively, from source categories relevant to decarbonization (other than fires and agriculture emissions) are covered in this study.

Table 1. Emissions source category coverage.

2017 Source Emissions Category	Directly impacted by greenhouse gas mitigation	Modeled in this study
Agriculture - Crops & Livestock Dust	✓	
Agriculture - Fertilizer Application		
Agriculture - Livestock Waste	✓	
Bulk Gasoline Terminals	✓	
Commercial Cooking	✓	✓
Dust - Construction Dust		
Dust - Paved Road Dust		
Dust - Unpaved Road Dust		
Fires - Agricultural Field Burning		
Fires - Prescribed Fires		
Fires - Wildfires		
Fuel Comb - Comm/Institutional - Biomass	✓	✓
Fuel Comb - Comm/Institutional - Coal	✓	✓
Fuel Comb - Comm/Institutional - Natural Gas	✓	✓
Fuel Comb - Comm/Institutional - Oil	✓	✓
Fuel Comb - Comm/Institutional - Other	✓	✓
Fuel Comb - Electric Generation - Biomass	✓	
Fuel Comb - Electric Generation - Coal	✓	✓
Fuel Comb - Electric Generation - Natural Gas	✓	✓
Fuel Comb - Electric Generation - Oil	✓	
Fuel Comb - Electric Generation - Other	✓	
Fuel Comb - Industrial Boilers, ICEs - Biomass	✓	
Fuel Comb - Industrial Boilers, ICEs - Coal	✓	
Fuel Comb - Industrial Boilers, ICEs - Natural Gas	✓	
Fuel Comb - Industrial Boilers, ICEs - Oil	✓	
Fuel Comb - Industrial Boilers, ICEs - Other	✓	
Fuel Comb - Residential - Natural Gas	✓	✓
Fuel Comb - Residential - Oil	✓	✓
Fuel Comb - Residential - Other	✓	✓
Fuel Comb - Residential - Wood	✓	✓
Gas Stations	✓	✓
Industrial Processes - Cement Manuf	✓	
Industrial Processes - Chemical Manuf	✓	
Industrial Processes - Ferrous Metals	✓	
Industrial Processes - Mining	✓	
Industrial Processes - NEC	✓	
Industrial Processes - Non-ferrous Metals	✓	
Industrial Processes - Oil & Gas Production	✓	
Industrial Processes - Petroleum Refineries	✓	
Industrial Processes - Pulp & Paper	✓	
Industrial Processes - Storage and Transfer	✓	
Miscellaneous Non-Industrial NEC	✓	
Mobile - Aircraft	✓	

Mobile - Commercial Marine Vessels	✓	
Mobile - Locomotives	✓	
Mobile - Non-Road Equipment - Diesel	✓	
Mobile - Non-Road Equipment - Gasoline	✓	
Mobile - Non-Road Equipment - Other	✓	
Mobile - On-Road Diesel Heavy Duty Vehicles	✓	✓
Mobile - On-Road Diesel Light Duty Vehicles	✓	✓
Mobile - On-Road non-Diesel Heavy Duty Vehicles	✓	✓
Mobile - On-Road non-Diesel Light Duty Vehicles	✓	✓
Mobile - Commercial Marine Vessels	✓	
Solvent - Consumer & Commercial Solvent Use		
Solvent - Degreasing		
Solvent - Dry Cleaning		
Solvent - Graphic Arts		
Solvent - Industrial Surface Coating & Solvent Use		
Solvent - Non-Industrial Surface Coating		
Waste Disposal		
Biogenics - Vegetation and Soil	✓	

1.2 Fuel combustion – electric generation – coal

We model county-level emissions from 2020 to 2050 associated with coal electric power generation. We employ the downscaled thermal capacity projections, including generator-specific retirement schedules (see Annex E), in addition to regional capacity factor projections from the RIO modeling (see Annex A). We also develop generator-specific emission factors based on generator- or plant-level emissions reported by the US Energy Information Administration (EIA) in EIA-923 survey filings for 2018, US EPA Emissions & Generation Resource Integrated Database (eGRID) for plants and generating units in 2016, and the US EPA NEI for 2017 [1]–[3]. Given inconsistencies across the emissions datasets, we develop a data hierarchy, where we first adopt the 2018 EIA plant-level emissions factors (if available). Where EIA plant-level emissions data is unavailable, we derive and apply generic marginal emission factors by prime mover, coal fuel type, and SO_2 emissions abatement technology based on average 2018 EIA plant-level emissions. Combining emission factors with projected regional capacity factors from RIO outputs and generator-specific retirement schedules, we estimate future emissions for each generator and scenario. Figure 1 and Figure 2 depict emission projections associated with coal electric power generation.

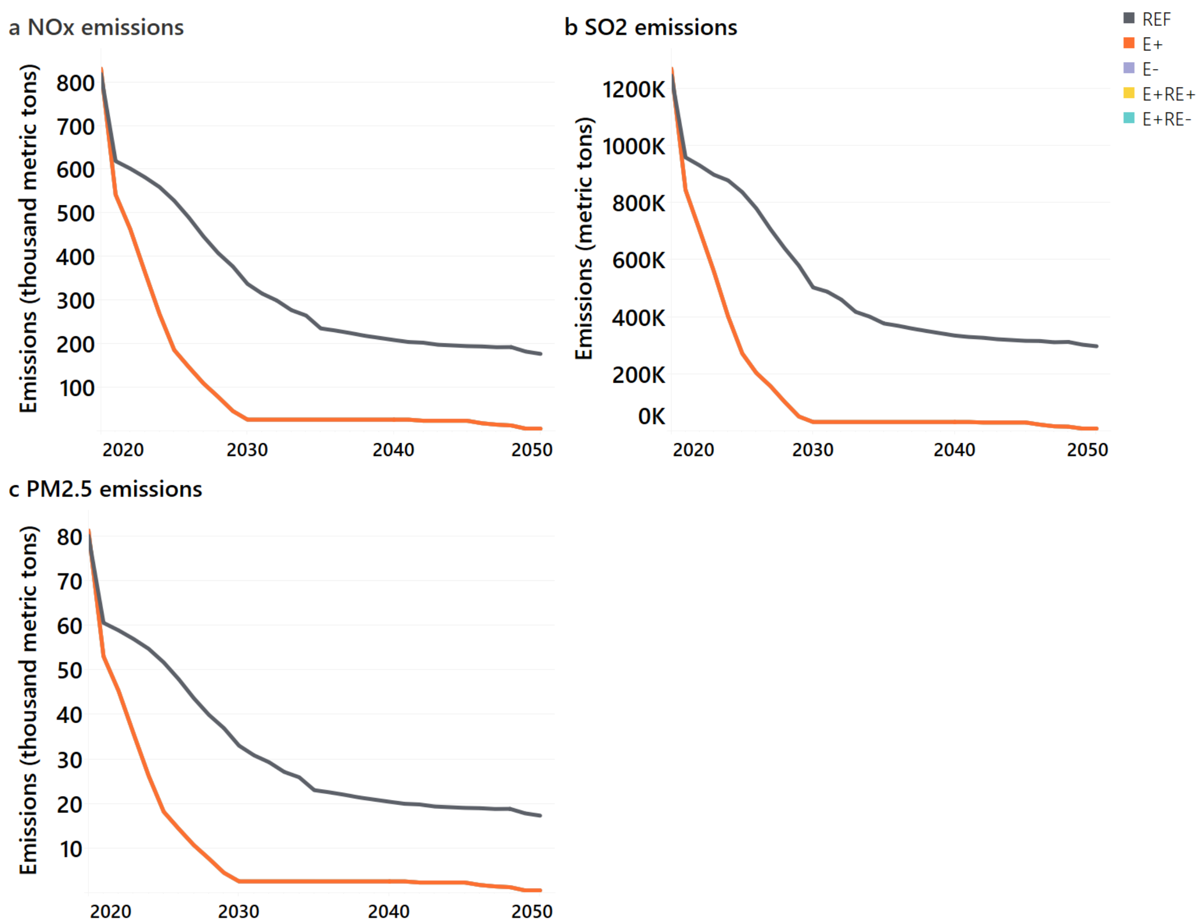


Figure 1. Annual emissions associated with coal electric power generation by scenario.

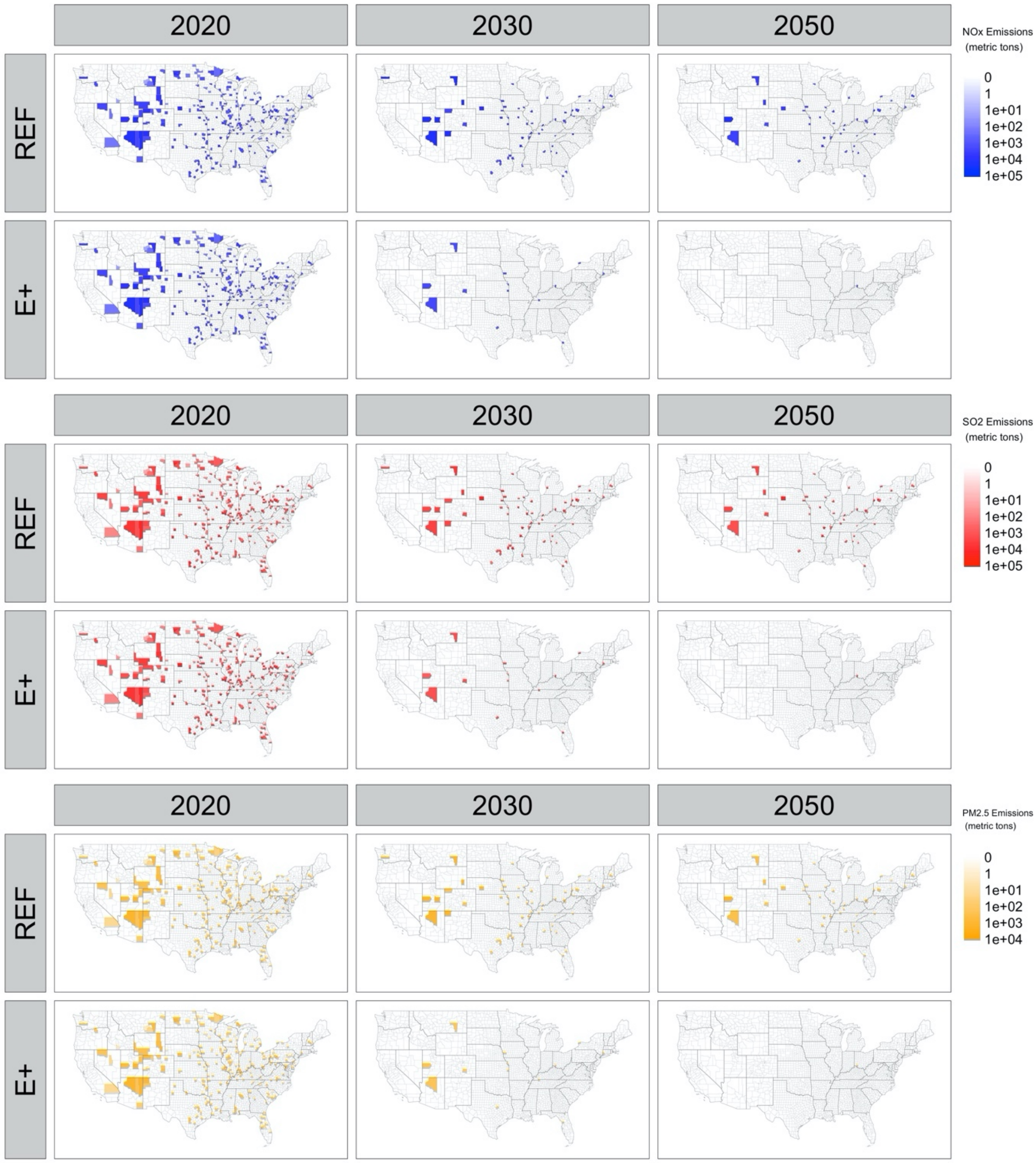


Figure 2. Annual, county-level emissions associated with coal electric power generation by scenario.

1.3 Fuel combustion – electric generation – natural gas

We model county-level emissions from 2020 to 2050 associated with natural gas electric power generation. We employ the downscaled thermal capacity projections, including generator-specific retirement and conversion schedules (see Annex E), in addition to regional capacity factor projections from the RIO modeling (Annex A). We also develop generator-specific emission factors based on generator- or plant-level emissions reported by the US EIA in EIA-923 survey filings for 2018, US EPA eGRID for plants and generating units in 2016, and the US EPA NEI for 2017 [1]–[3]. Given inconsistencies across the emissions datasets, we develop a data hierarchy, where we first adopt the 2018 EIA plant-level emissions factors (if available). To account for missing data and new capacity, we derive and apply generic marginal emission factors by prime mover type based on 2018 EIA plant-level emissions. Combining emission factors with projected regional capacity factors and generator-specific retirement schedules, we estimate future emissions for each generator and scenario. Figure 3 and Figure 4 depict emission projections associated with natural gas electric power generation.

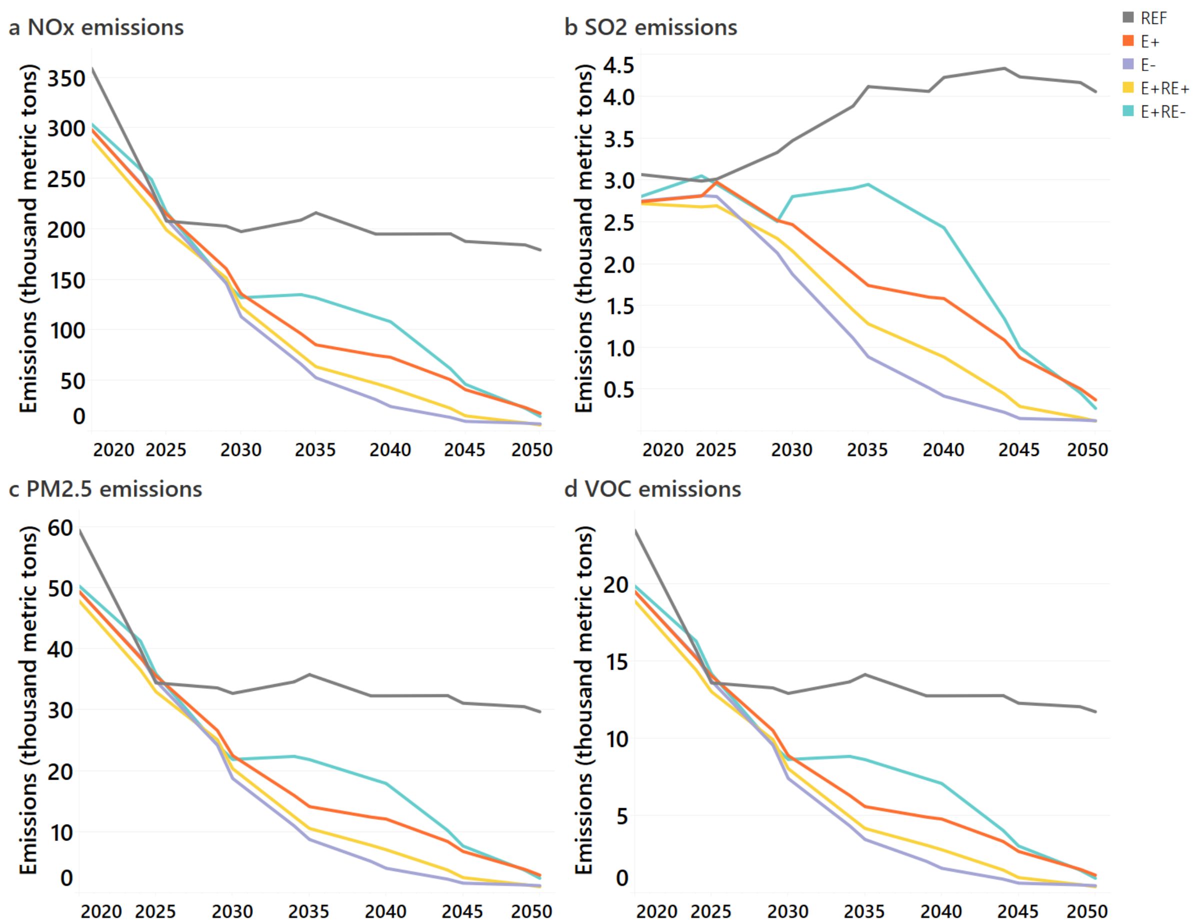


Figure 3. Annual emissions associated with natural gas electric power generation by scenario.

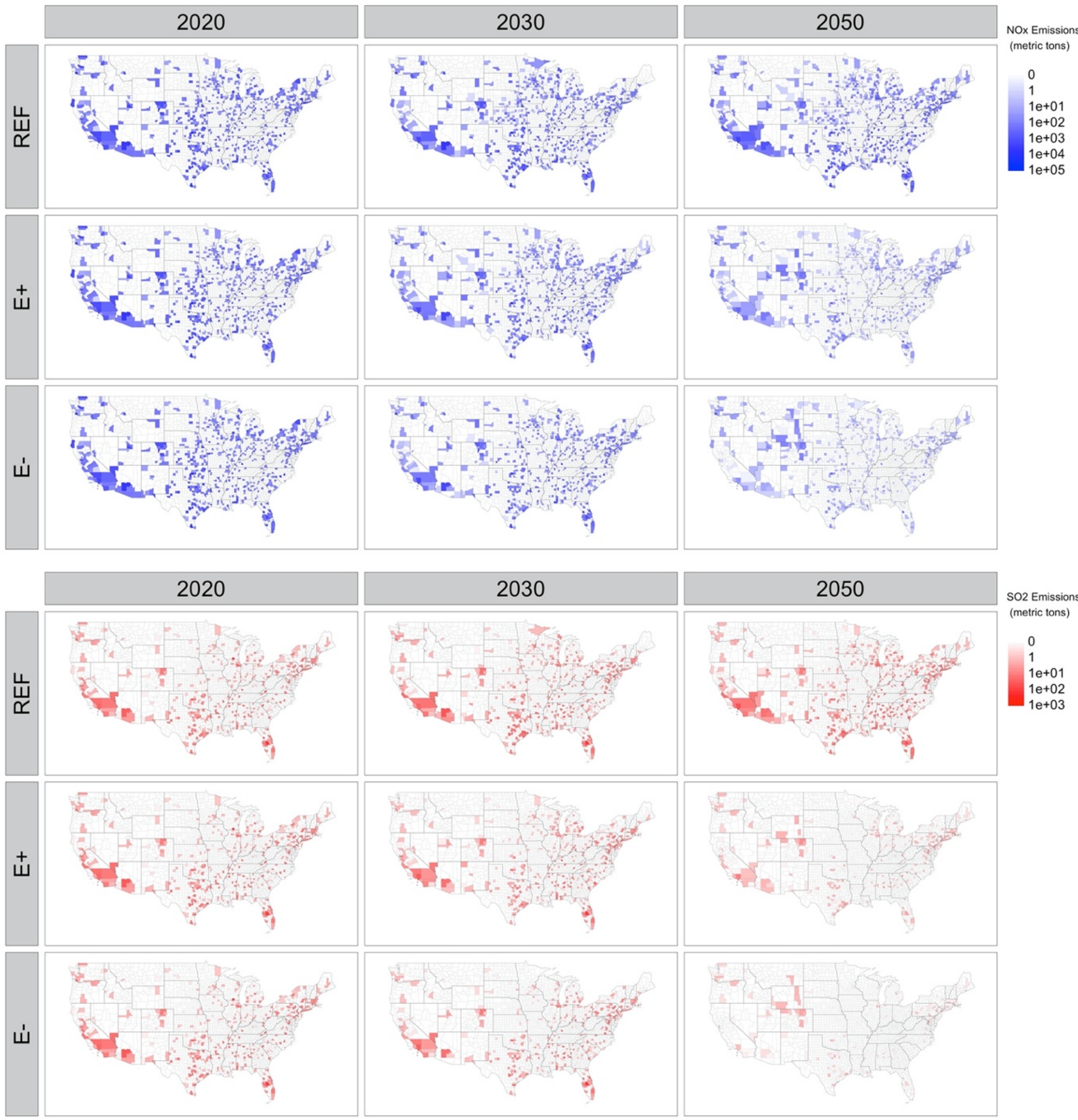


Figure 4. Annual, county-level emissions associated with natural gas electric power generation by scenario.

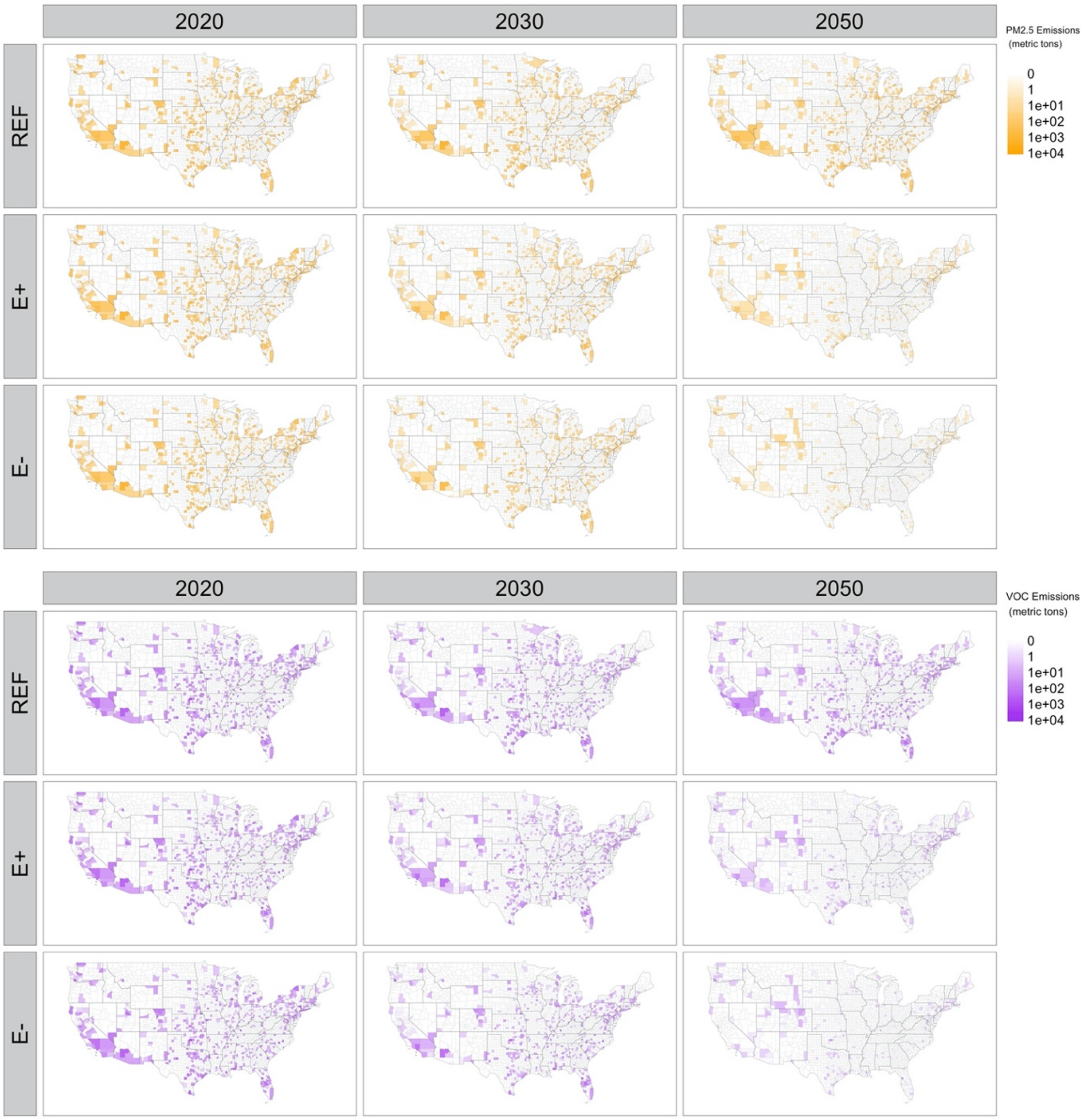


Figure 4. Annual, county-level emissions associated with natural gas electric power generation by scenario. (continued)

1.4 Fuel combustion – commercial/institutional

We model county-level emissions from 2020 to 2050 associated with fuel combustion in the commercial sector. We use county-level emissions reported in the 2017 NEI associated with commercial-sector combustion of coal, natural gas, oil (i.e., kerosene, residual oil, distillate oil), and other fuels (i.e., liquefied petroleum gas [lpg]) [2]. Using annual, state-level fuel consumption reported in the State Energy Data Systems (SEDS), we scale the 2017 emissions to 2019 (the most recent consumption data) [4]. To project future emissions from 2020 to 2050, we scale 2019 emissions using state-level, commercial-sector fuel demand projections, including coal, natural gas, oil (i.e., kerosene, residual oil, diesel), and other fuel (i.e., gasoline, lpg) consumption associated with heating and cooling demands from EnergyPathways (see Annex

A) for three demand scenarios (i.e., REF, E+, E-). Emission projections are depicted in Figure 5 through Figure 12.

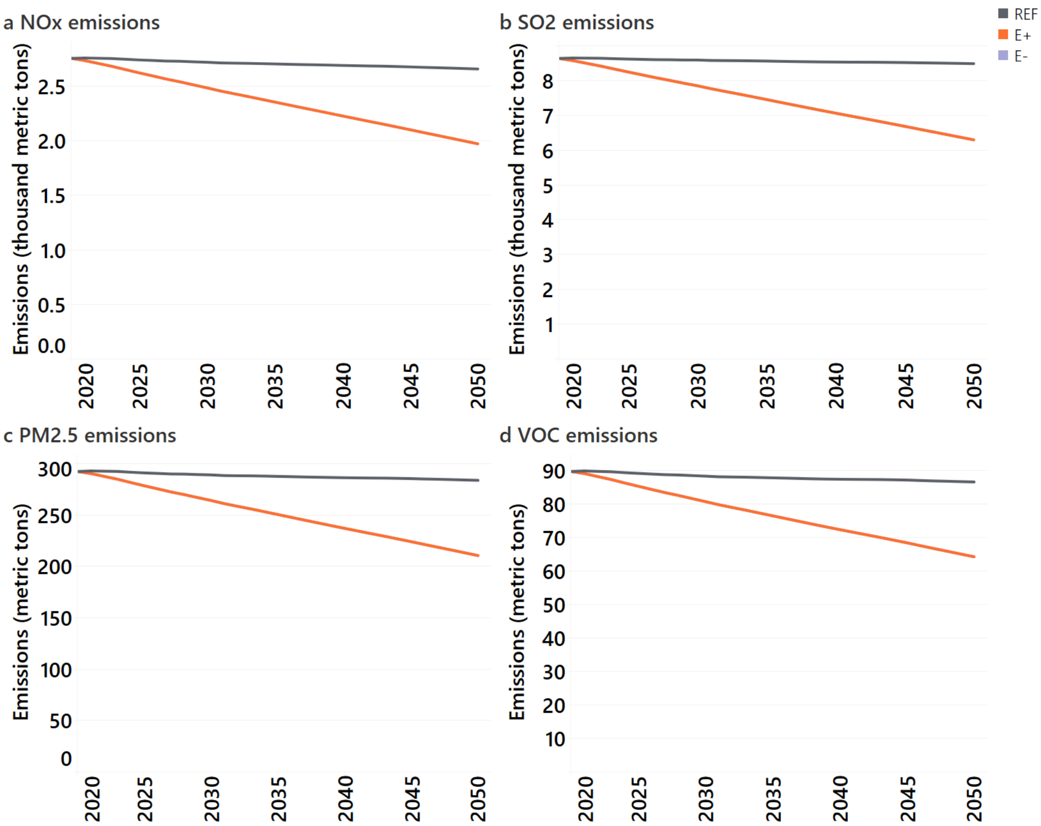


Figure 5. Annual emissions associated with coal combustion in the commercial sector by scenario.

Figure 6. Annual, county-level emissions associated with coal combustion in the commercial sector by scenario.

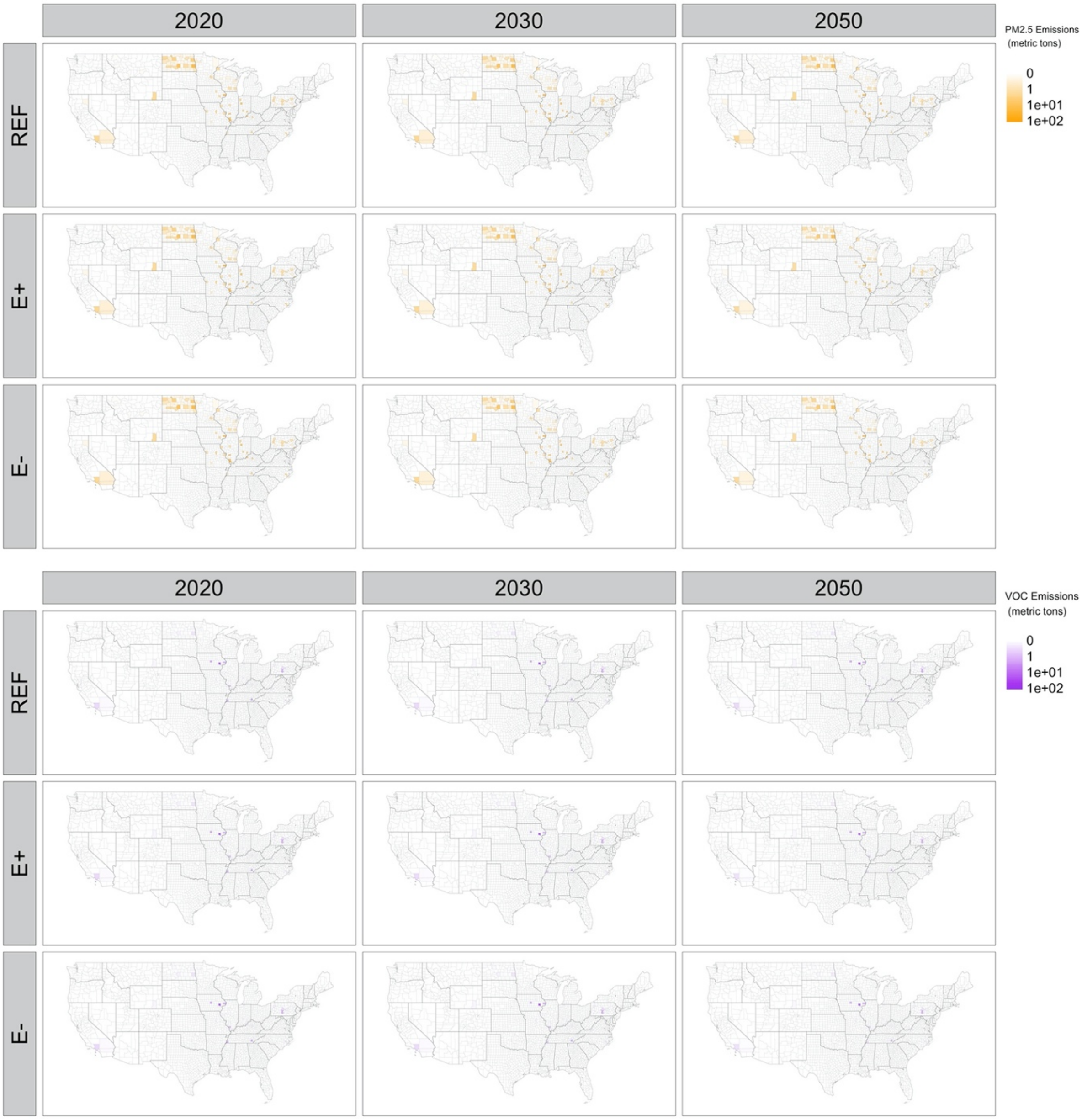


Figure 6. Annual, county-level emissions associated with coal combustion in the commercial sector by scenario. (continued)

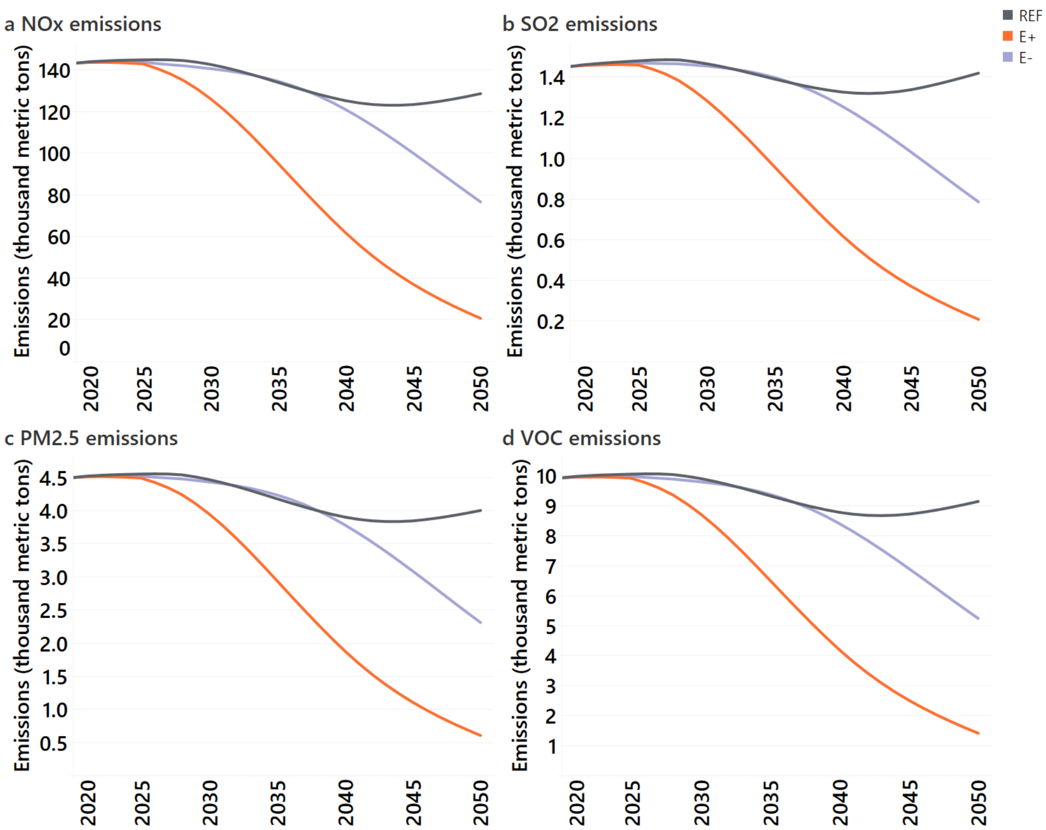


Figure 7. Annual emissions associated with natural gas combustion in the commercial sector by scenario.

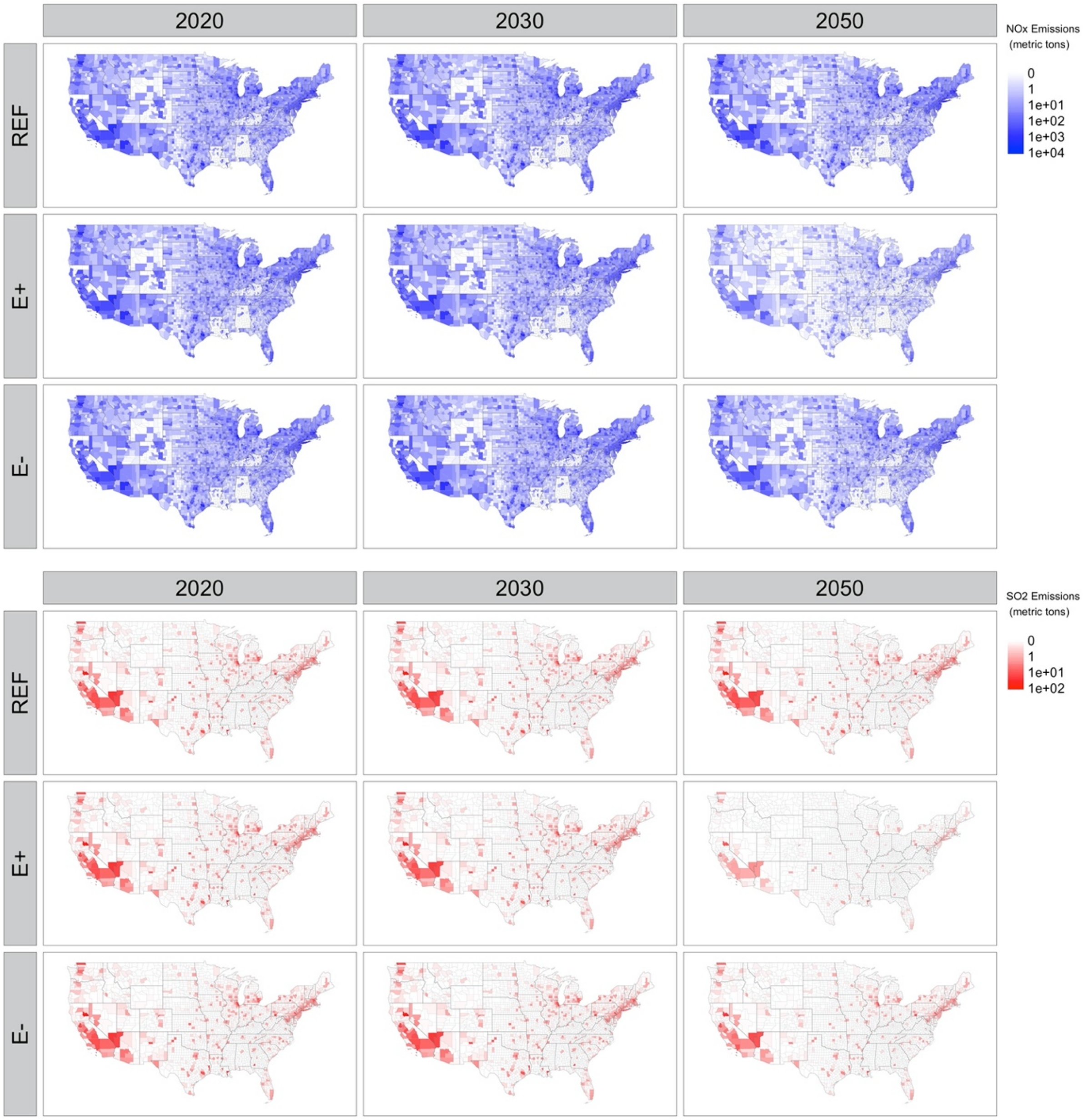


Figure 8. Annual, county-level emissions associated with natural gas combustion in the commercial sector by scenario.

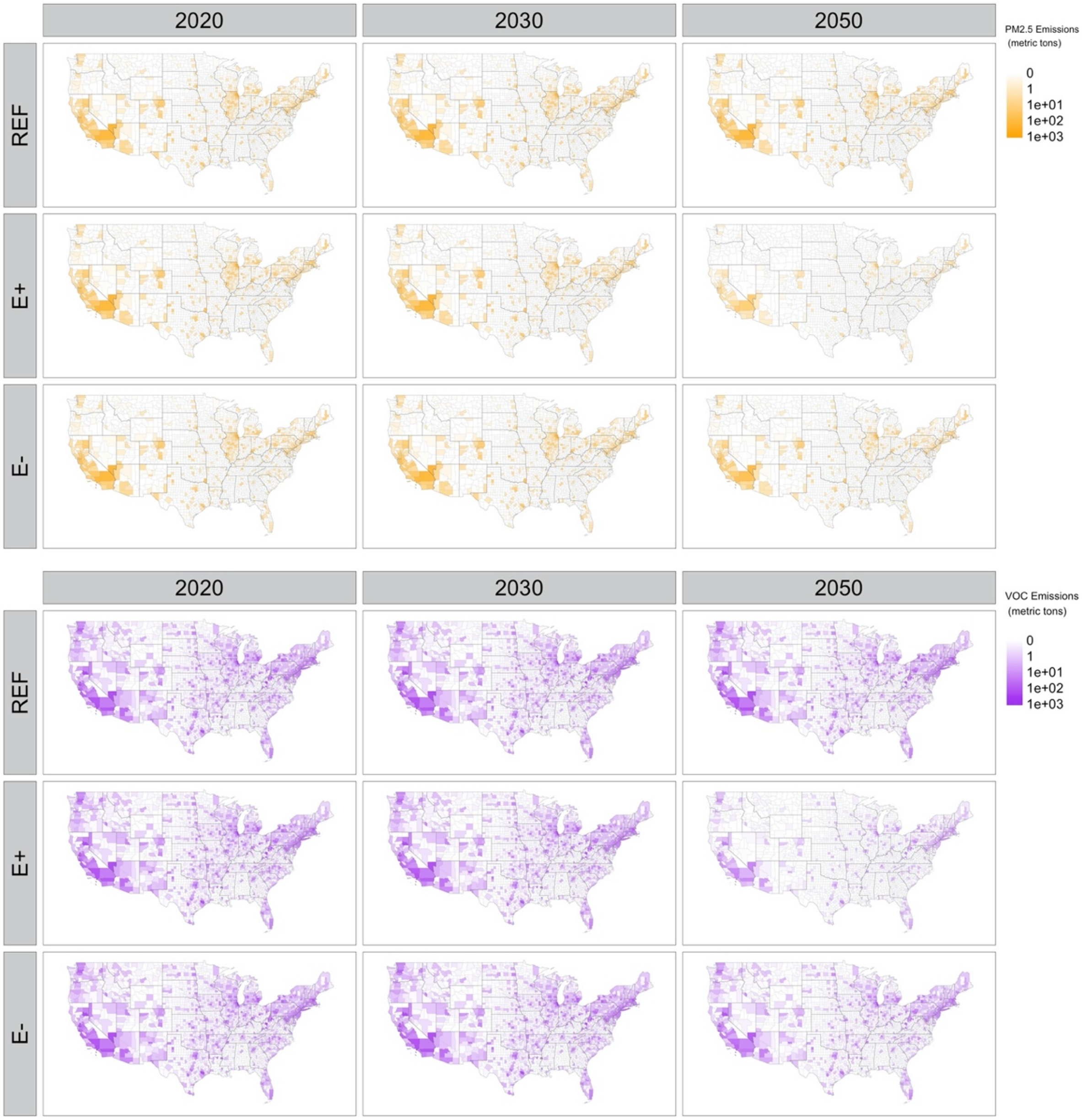


Figure 8. Annual, county-level emissions associated with natural gas combustion in the commercial sector by scenario. (continued)

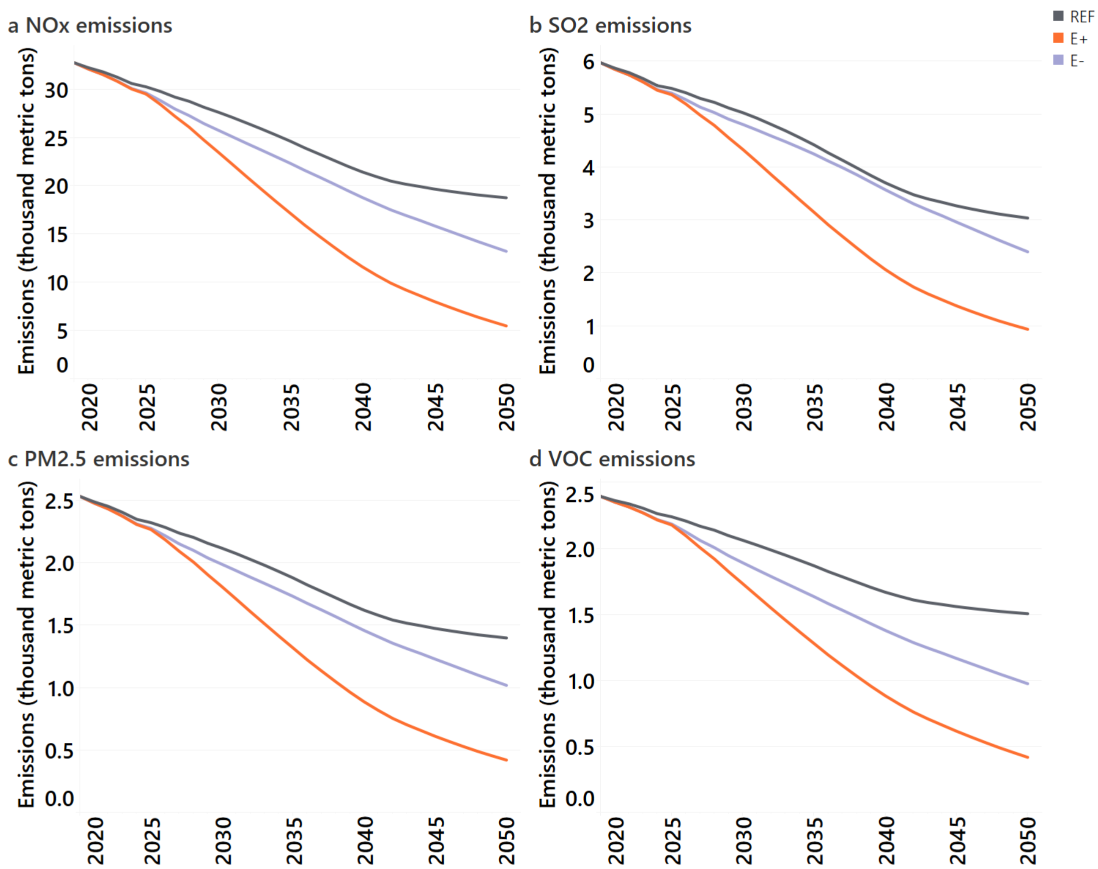


Figure 9. Annual emissions associated with oil combustion in the commercial sector by scenario.

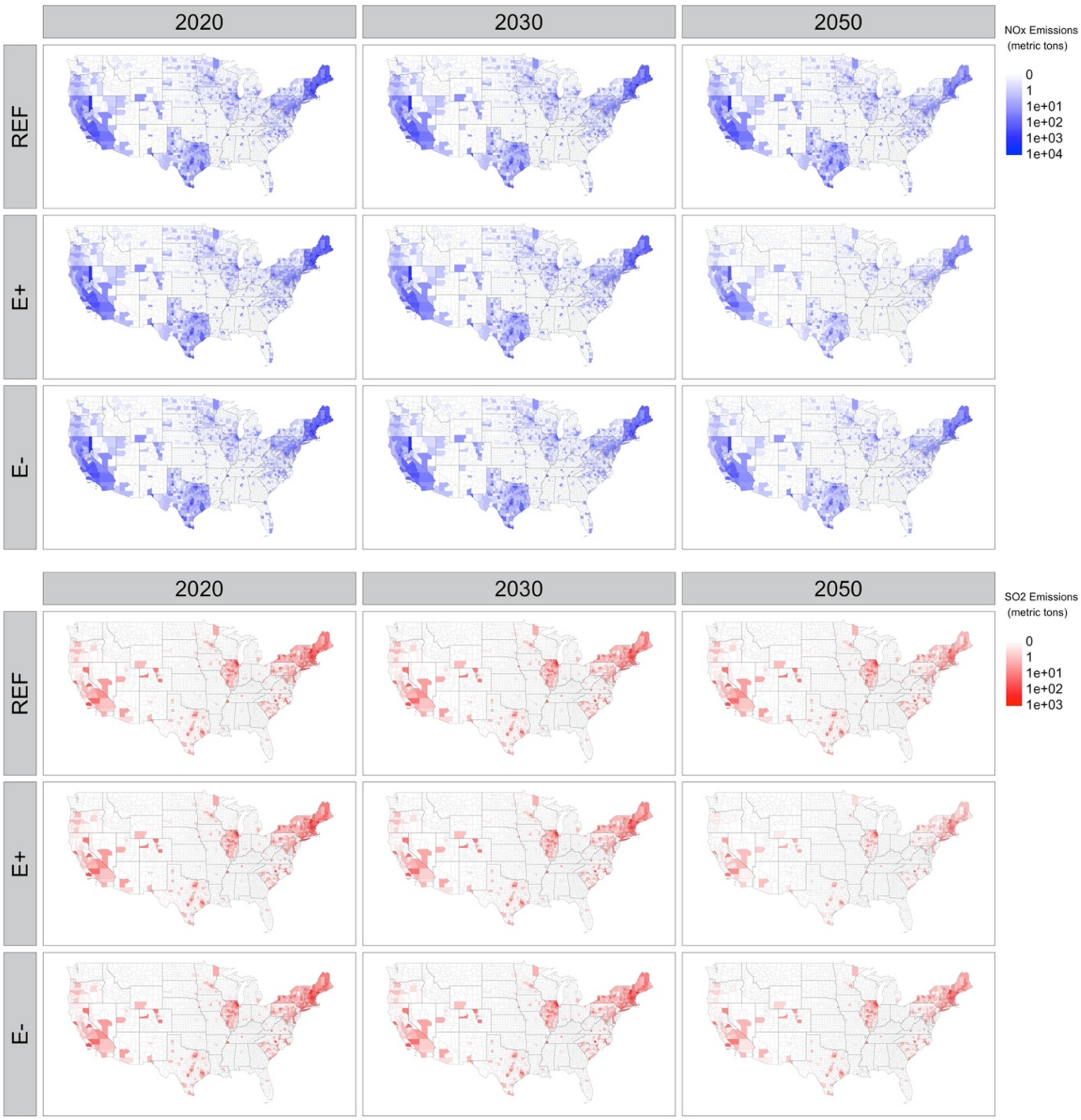


Figure 10. Annual, county-level emissions associated with oil combustion in the commercial sector by scenario.

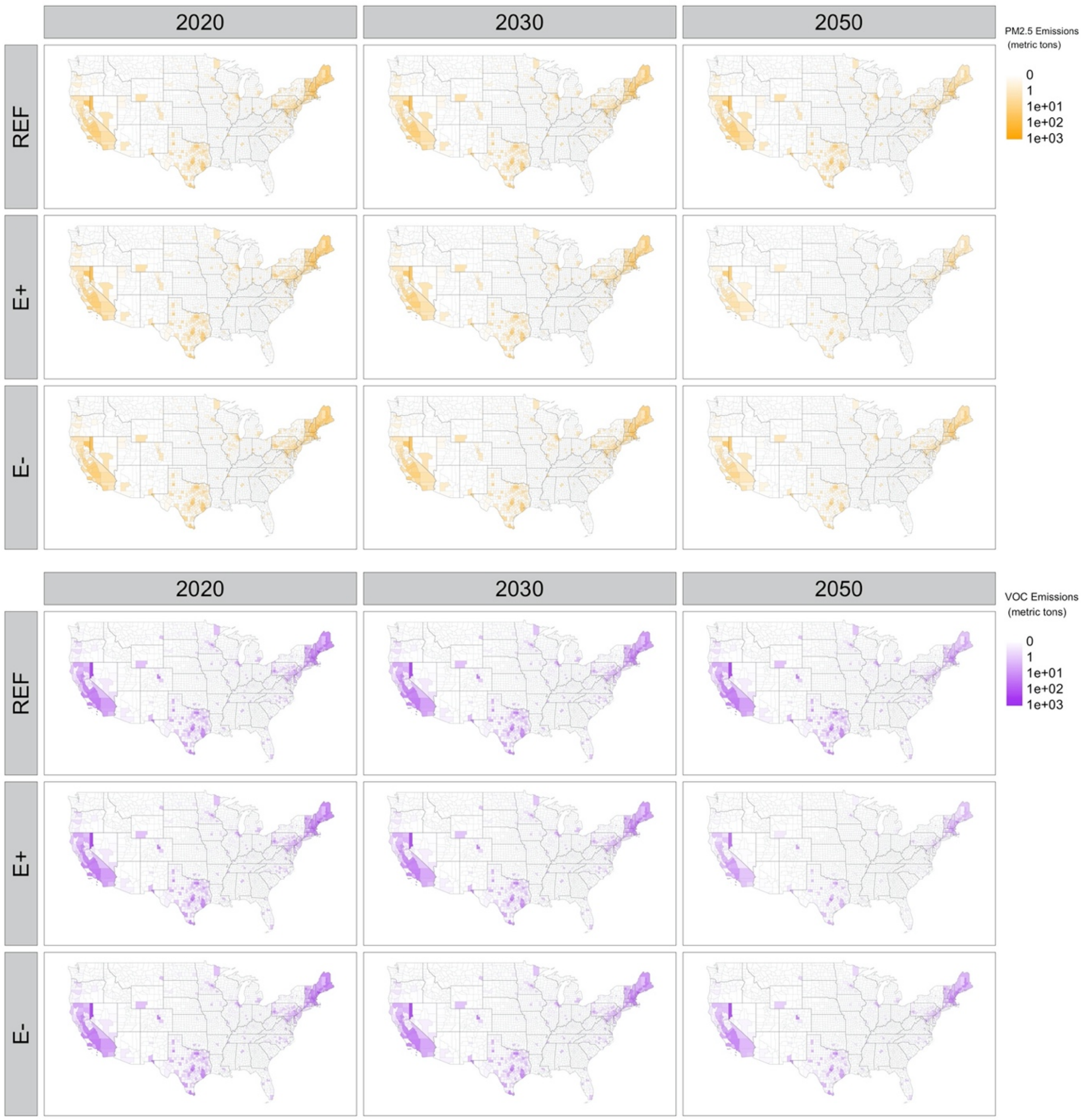


Figure 10. Annual, county-level emissions associated with oil combustion in the commercial sector by scenario. (continued)

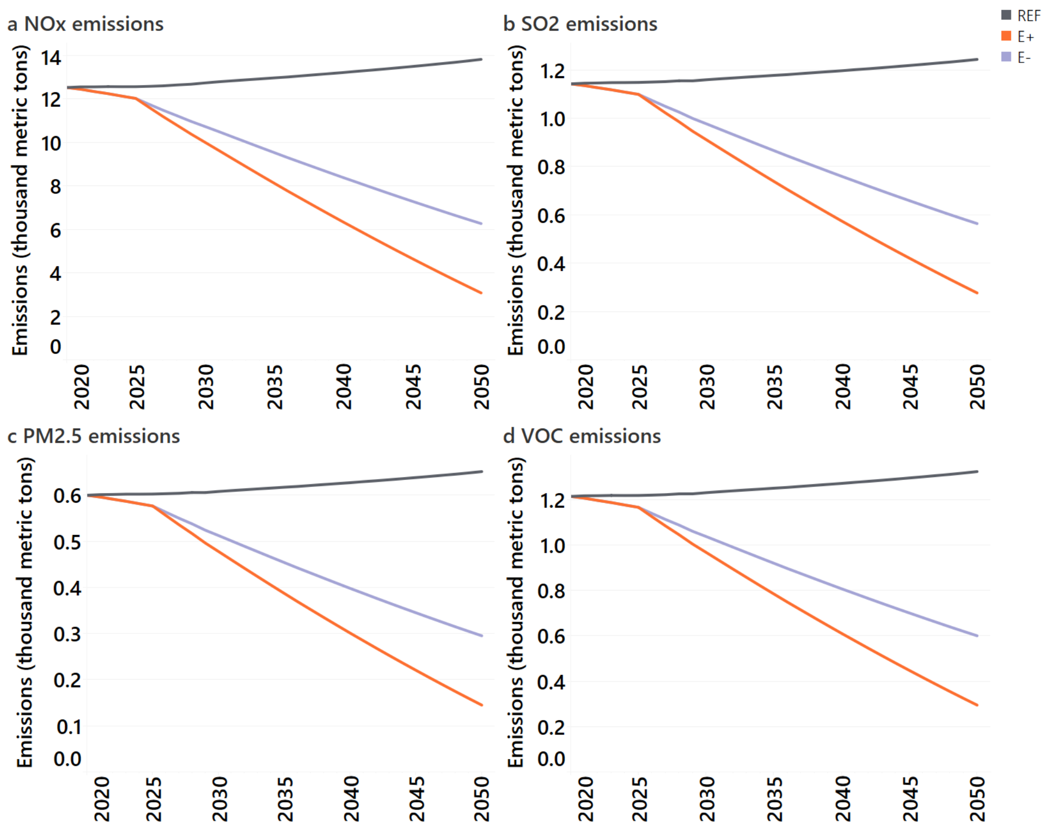


Figure 11. Annual emissions associated with fuel combustion (other than coal, natural gas, and oil) in the commercial sector by scenario.

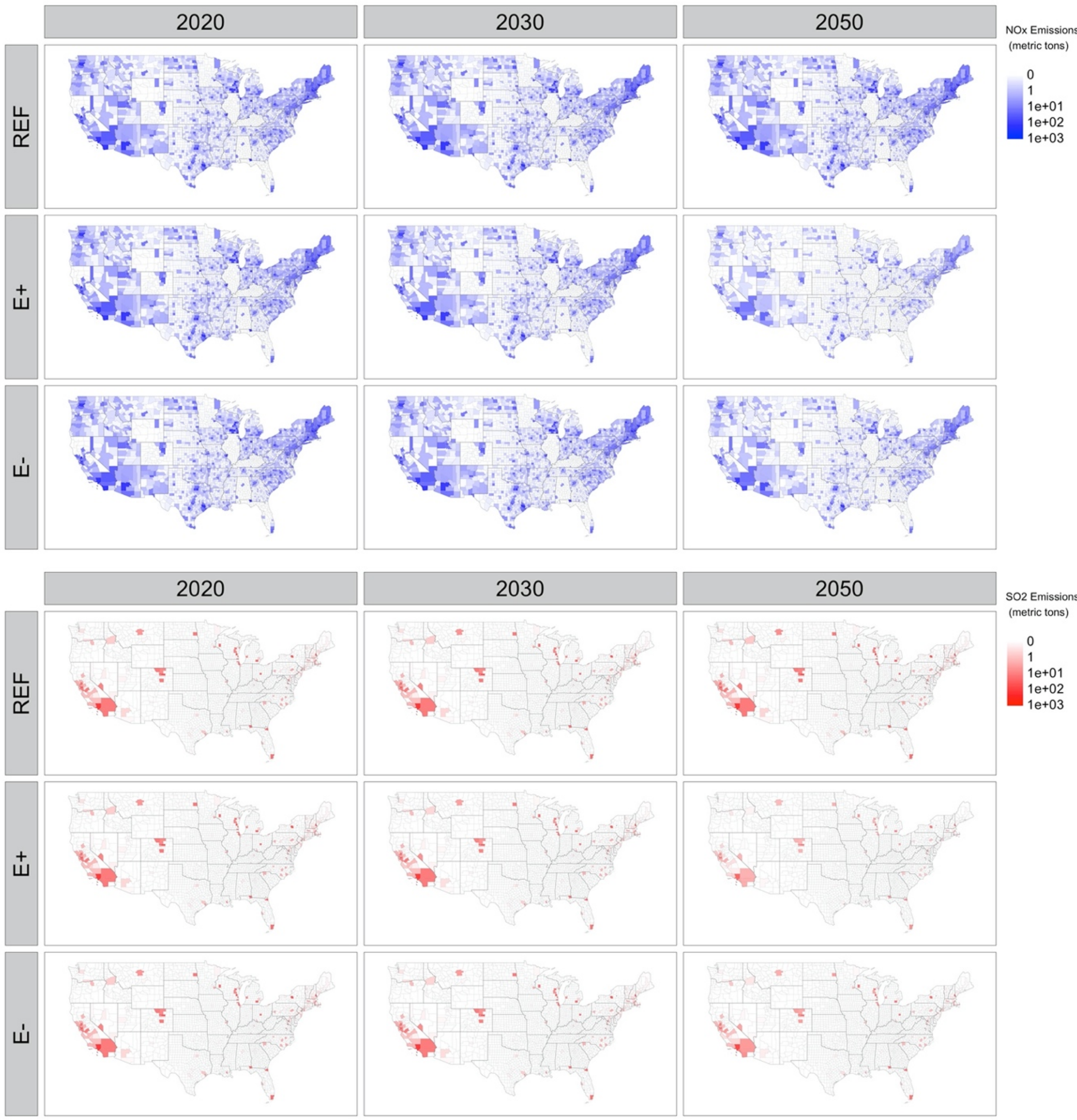


Figure 12. Annual, county-level emissions associated with fuel combustion (other than coal, natural gas, and oil) in the commercial sector by scenario.

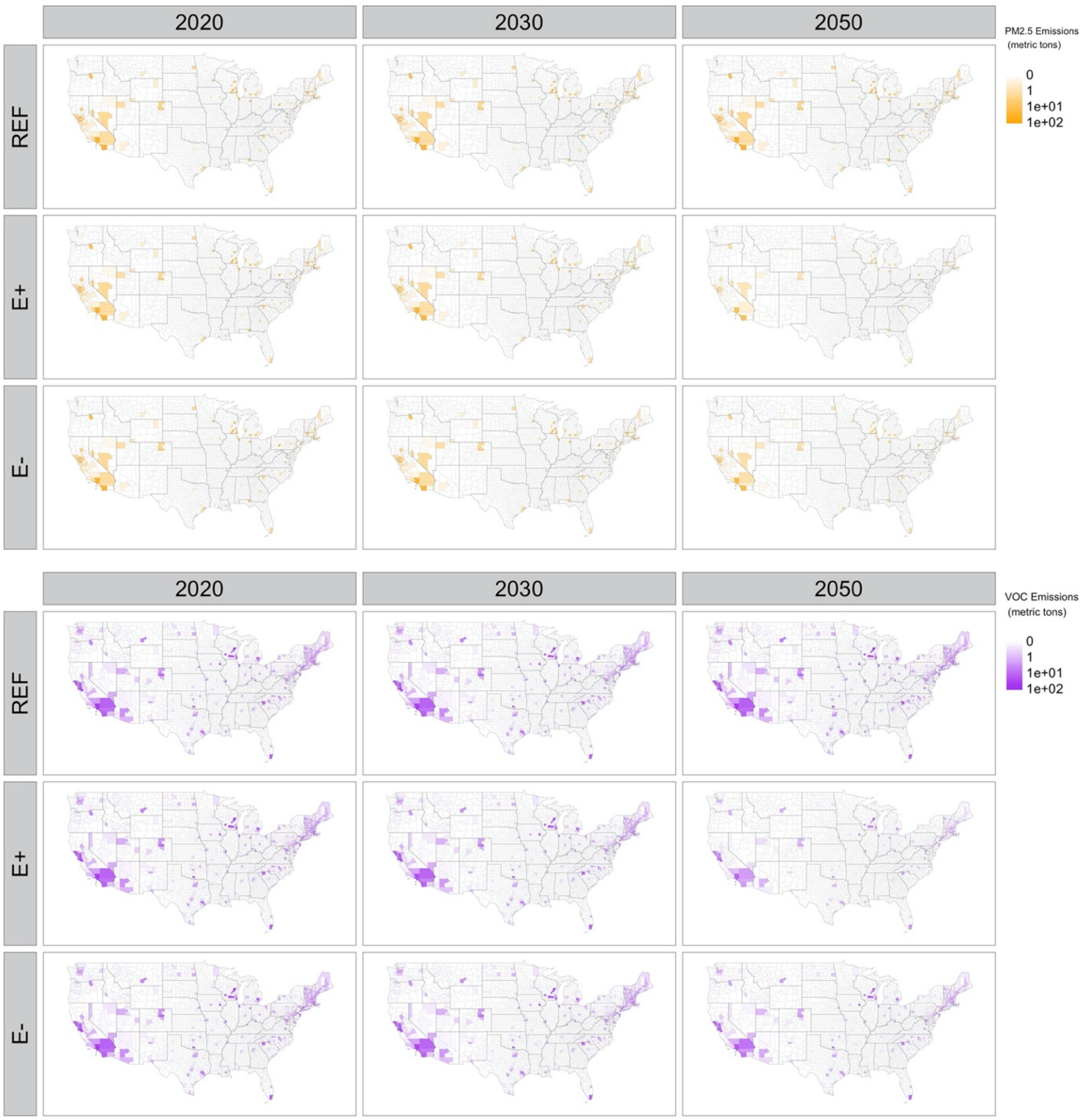


Figure 12. Annual, county-level emissions associated with fuel combustion (other than coal, natural gas, and oil) in the commercial sector by scenario. (continued)

1.5 Fuel combustion – residential

We model county-level emissions from 2020 to 2050 associated with fuel combustion in the residential sector. We use county-level emissions reported in the 2017 NEI associated with residential-sector combustion of wood, natural gas, oil (i.e., kerosene, distillate oil), and other fuels (i.e., coal, lpg) [2]. Using annual, state-level fuel consumption reported in SEDS, we scale the 2017 emissions to 2019 (the most recent consumption data) [4]. To project future emissions from 2020 to 2050, we scale 2019 emissions using state-level, residential-sector fuel demand projections, including wood, natural gas, oil (i.e., kerosene, diesel), and other fuel (i.e., lpg) consumption associated with heating, cooling, cooking, and other demands, from EnergyPathways for three demand scenarios. Emission projections are depicted in Figure 13 through Figure 20.

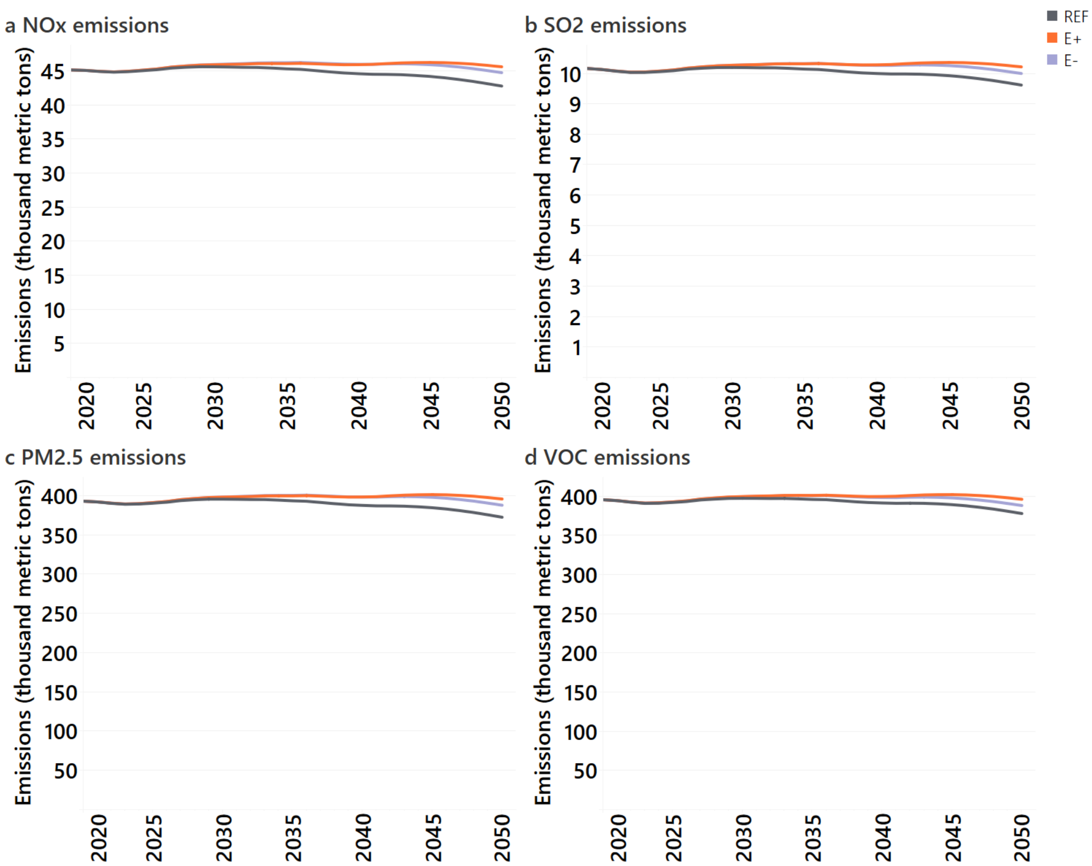


Figure 13. Annual emissions associated with wood combustion in the residential sector by scenario.

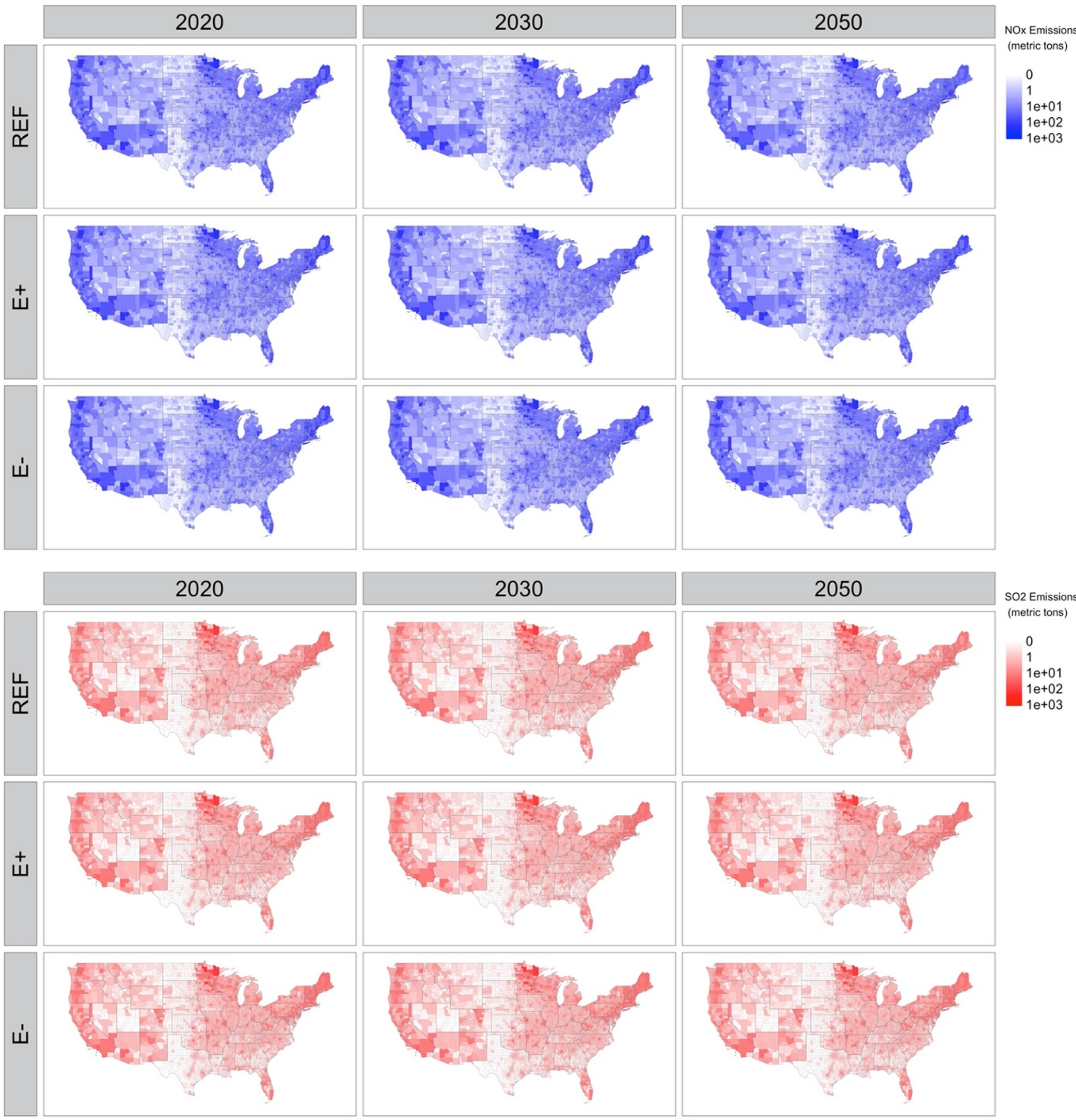


Figure 14. Annual, county-level emissions associated with wood combustion in the residential sector by scenario.

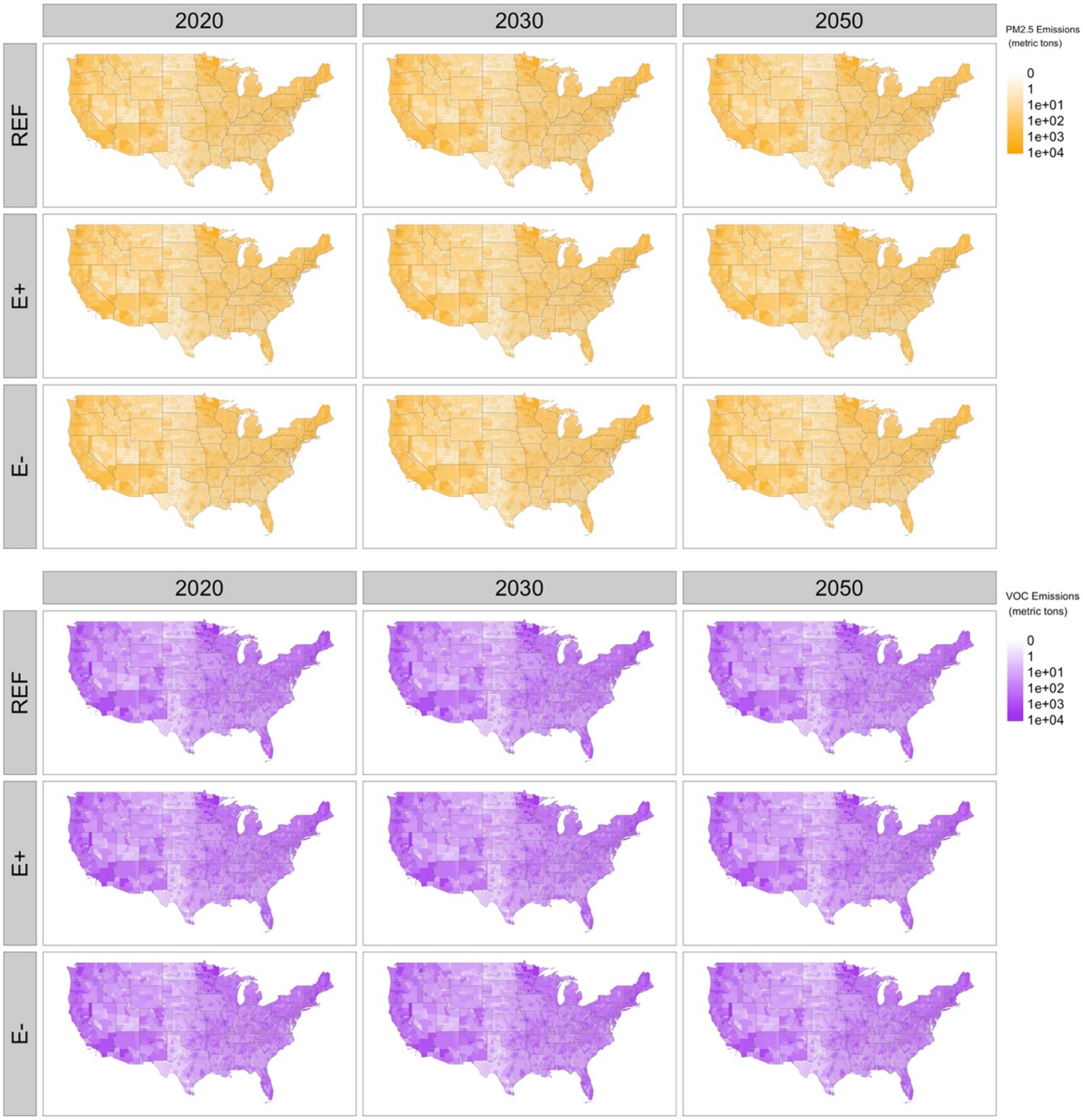


Figure 14. Annual, county-level emissions associated with wood combustion in the residential sector by scenario. (continued)

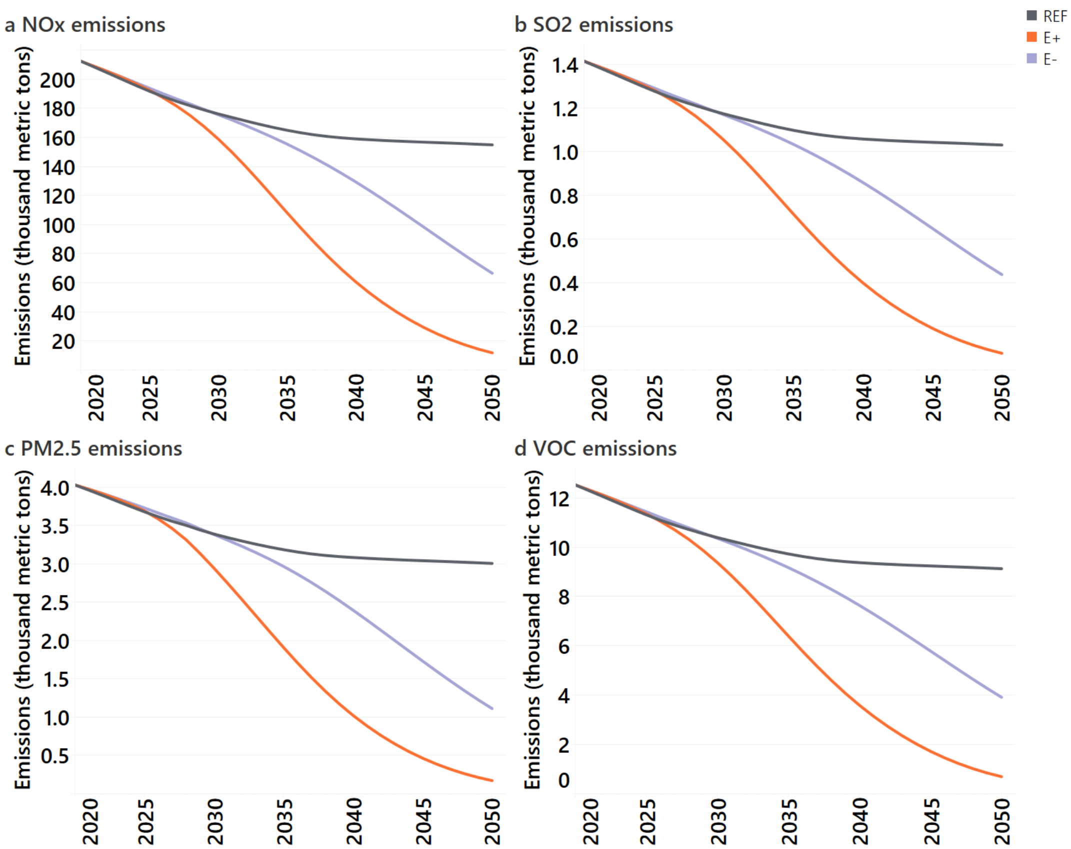


Figure 15. Annual emissions associated with natural gas combustion in the residential sector by scenario.

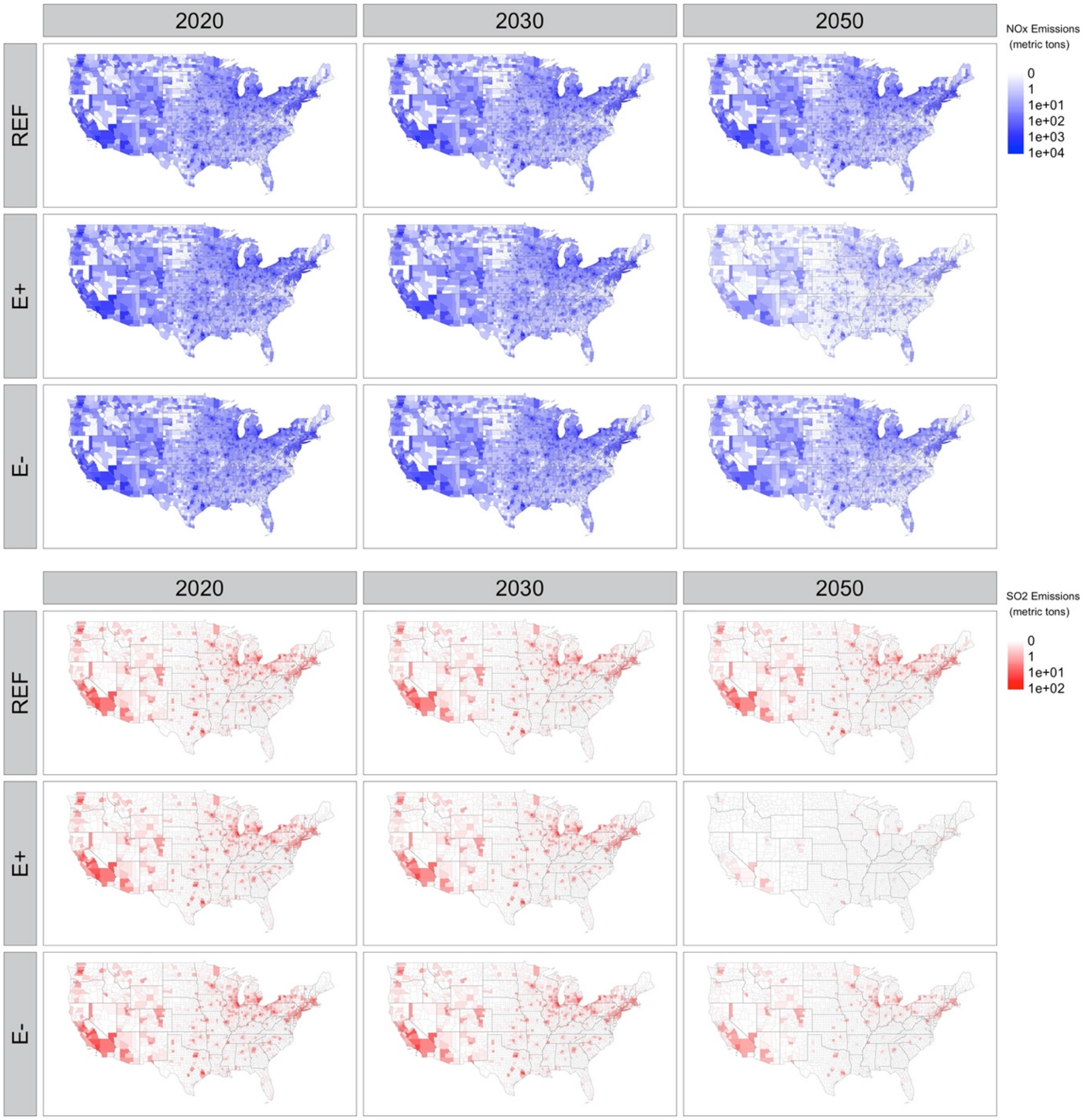


Figure 16. Annual, county-level emissions associated with natural gas combustion in the residential sector by scenario.

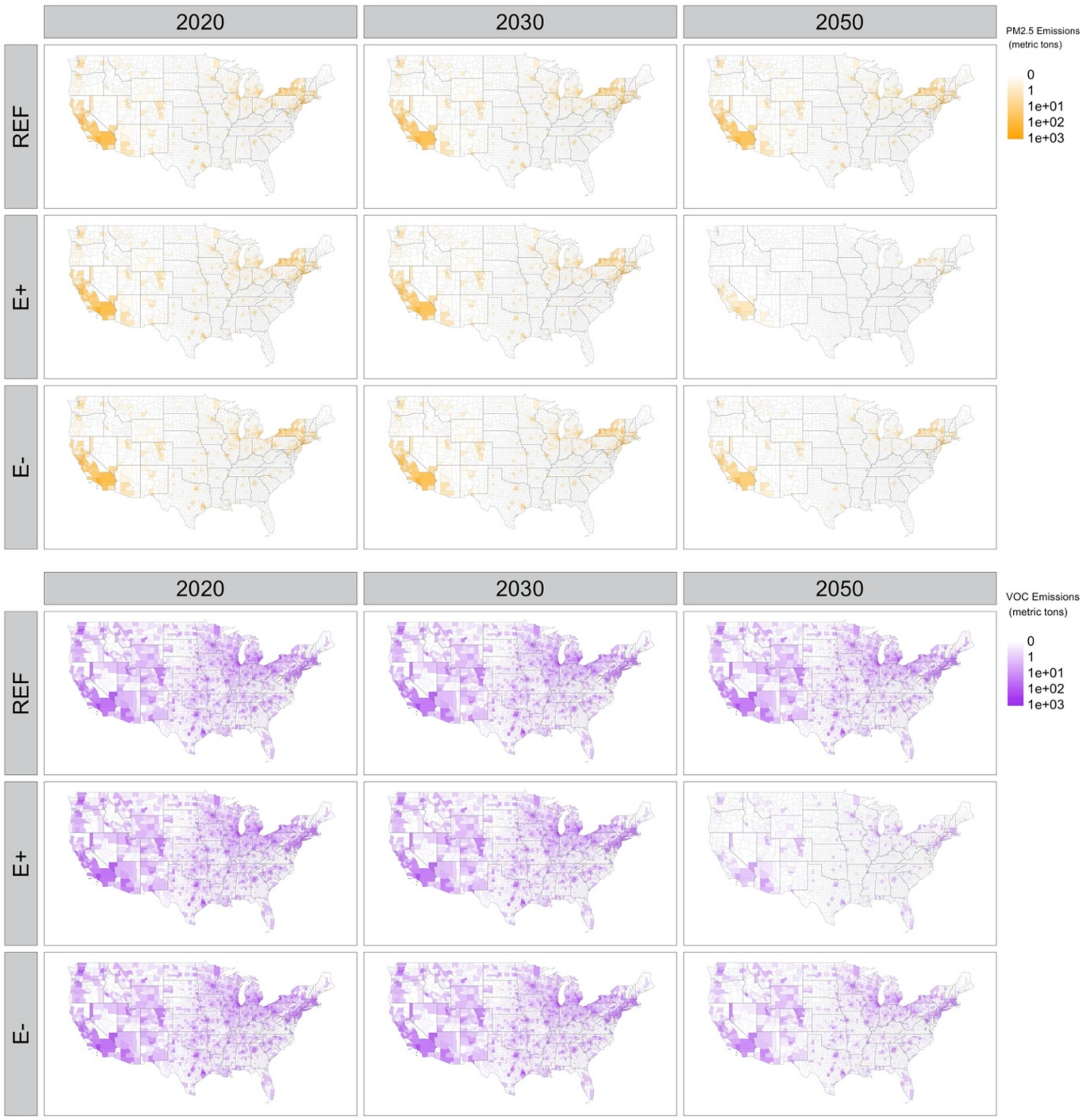


Figure 16. Annual, county-level emissions associated with natural gas combustion in the residential sector by scenario. (continued)

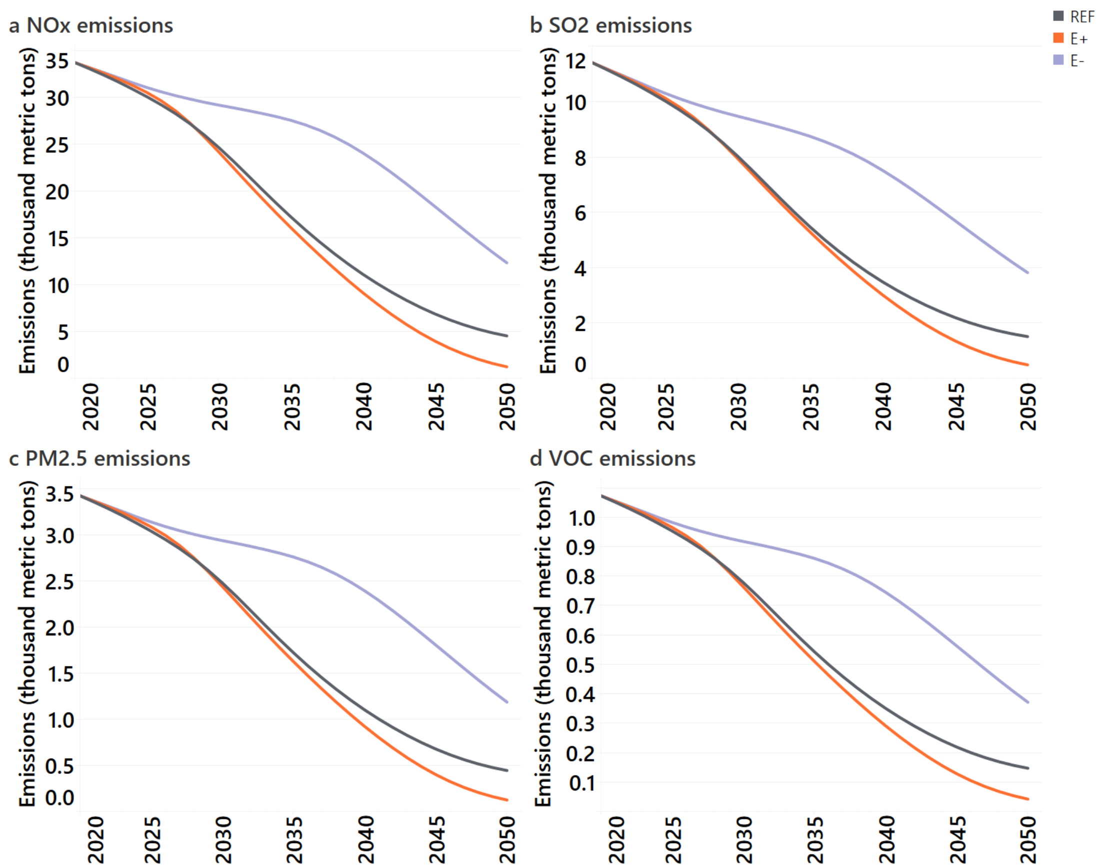


Figure 17. Annual emissions associated with oil combustion in the residential sector by scenario.

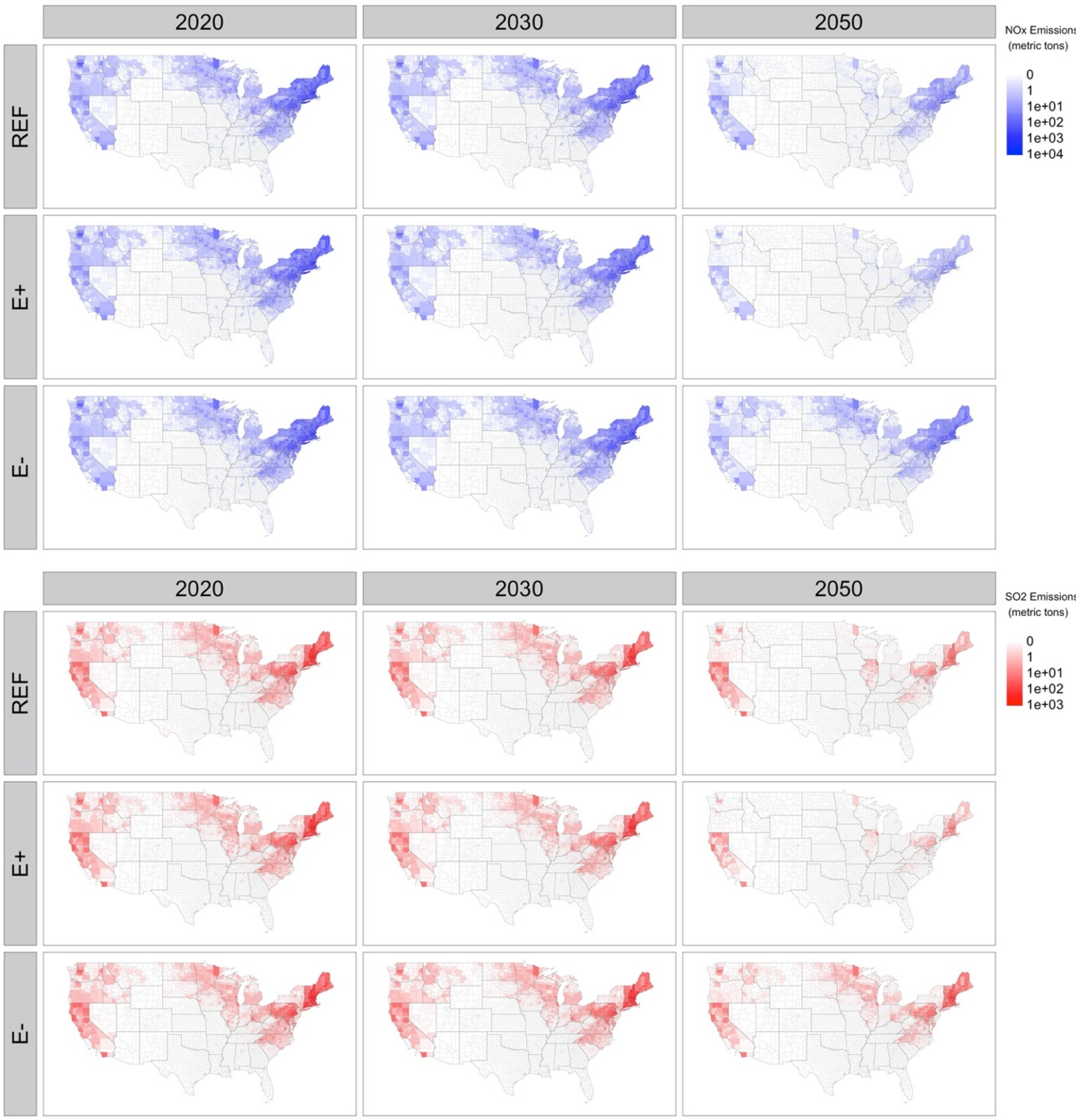


Figure 18. Annual, county-level emissions associated with oil combustion in the residential sector by scenario.

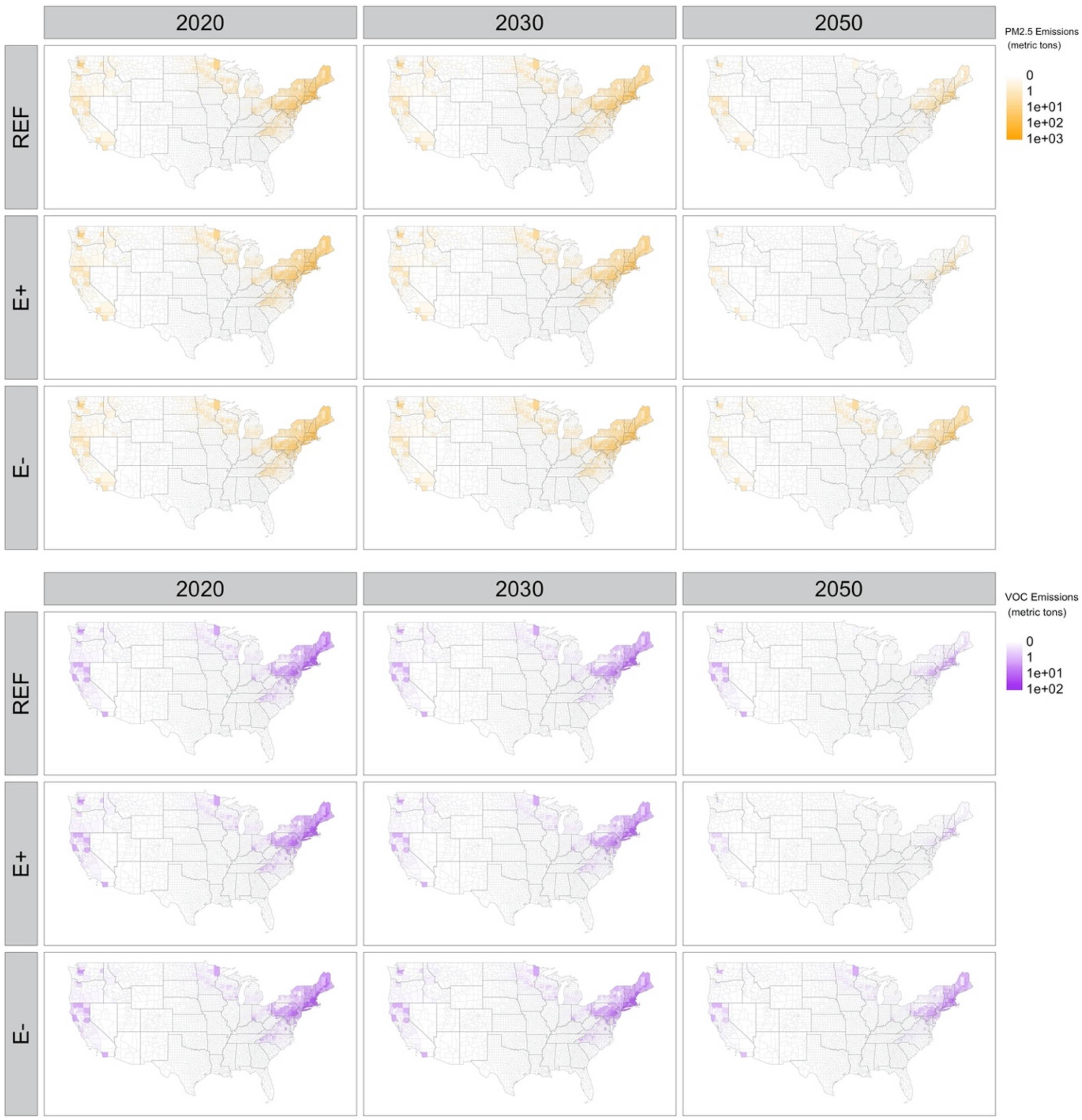


Figure 18. Annual, county-level emissions associated with oil combustion in the residential sector by scenario. (continued)

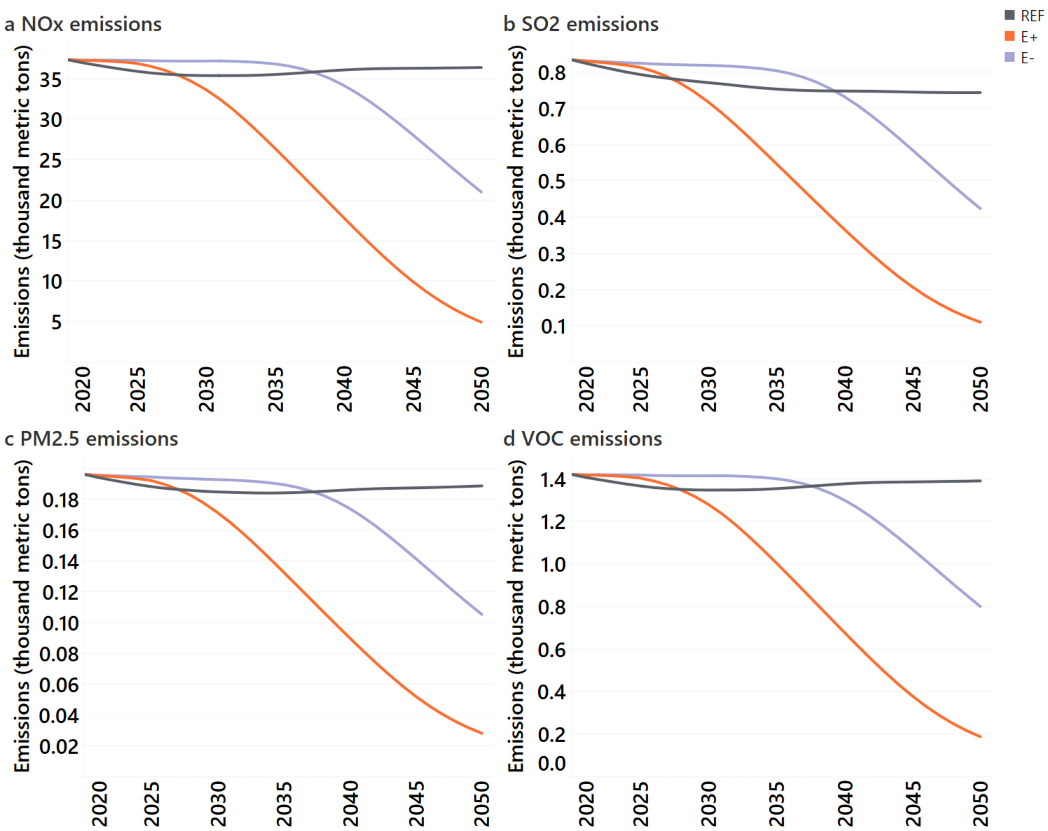


Figure 19. Annual emissions associated with fuel combustion (other than wood, natural gas, and oil) in the residential sector by scenario.

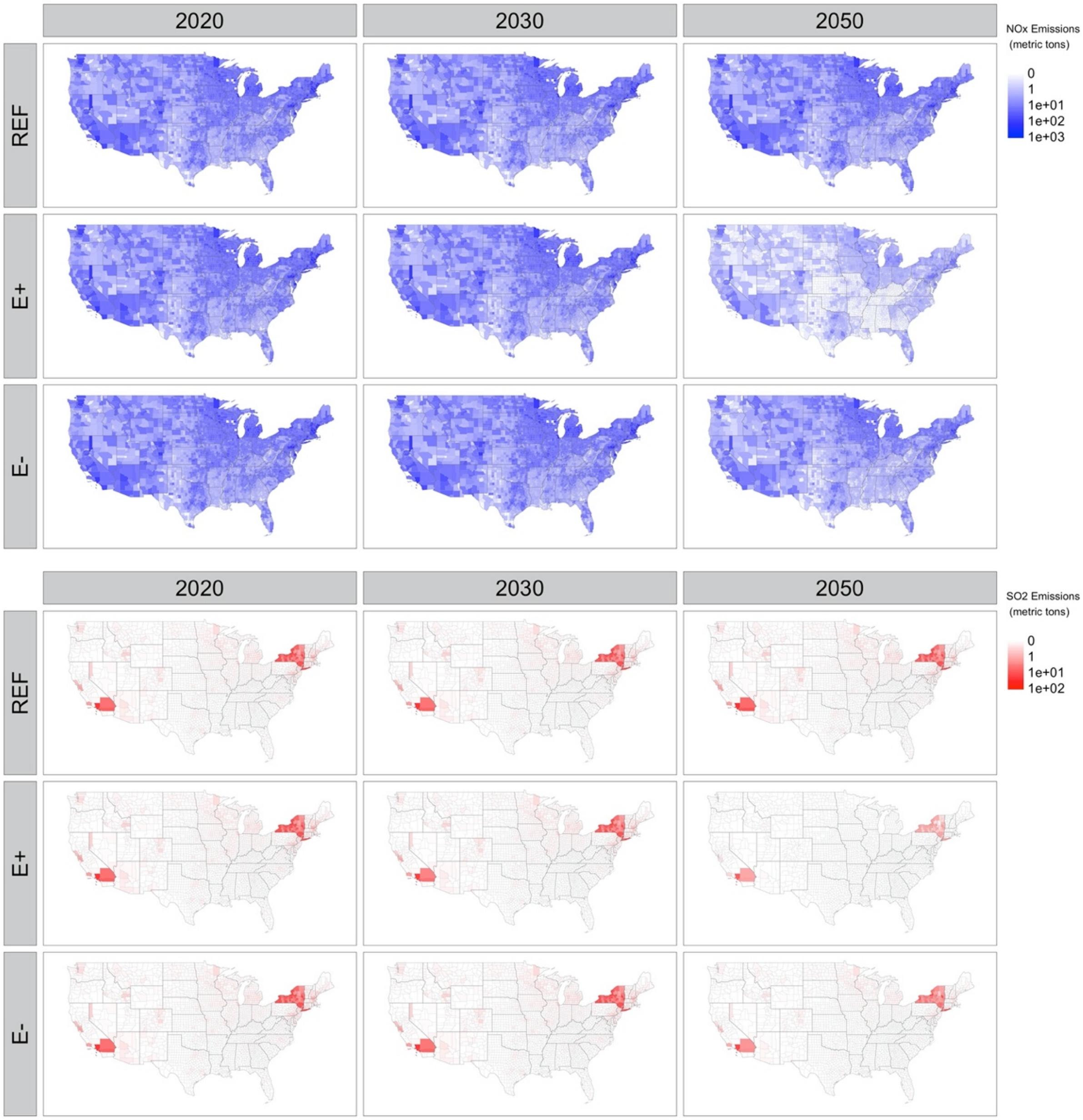


Figure 20. Annual, county-level emissions associated with fuel combustion (other than wood, natural gas, and oil) in the residential sector by scenario.

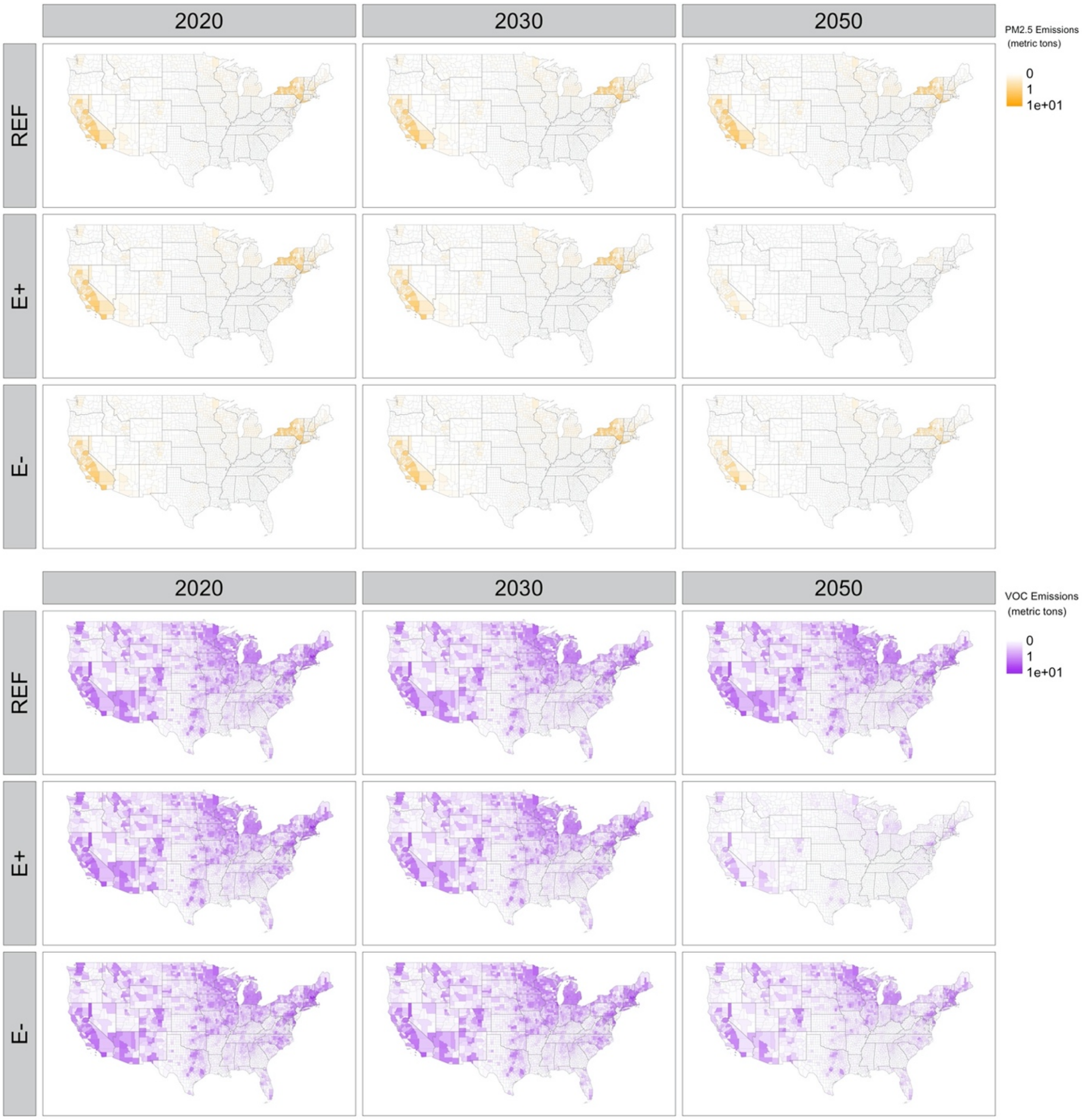


Figure 20. Annual, county-level emissions associated with fuel combustion (other than wood, natural gas, and oil) in the residential sector by scenario. (continued)

1.6 Industrial processes – coal mining

We model county-level emissions from 2020 to 2050 associated with coal mining. We first estimate annual, county-level coal production from underground and surface mines, as shown in Figure 21 and **Error! Reference source not found.**. We assume that the US continues to produce coal to meet domestic industrial and coking demand as reported in the NZA study as well as projected exports [5]. We assume that continued coal production to meet export demand occurs in states that have historically produced coal for export; we use the 2019 historical state origin of exports to spatially allocate future production at the state-level [6]. To spatially allocate underground and surface production to the county-level, we use mine-level data reported for 2017 and 2019 [7].

We model point and non-point emissions associated with coal mining, as shown in Figure 22 and Figure 23. We employ emissions reported in the 2017 NEI for coal point sources (NAICS 2121 coal mining, 212111 Bituminous Coal and Lignite Surface Mining, 212112 Bituminous Coal Underground Mining) [2]. We project county-level point source emissions from 2020 to 2050 for each scenario, using scaling factors based on future annual surface and underground production relative to 2017 production for each county. We also estimate nonpoint source industrial process emissions associated with coal mining operations, including fugitive emissions from overburden removal, drilling and blasting, loading and unloading and overburden replacement activities, assuming an emissions factor (0.064 pounds $PM_{2.5}$ per ton surface coal production) reported in the 2017 NEI [2].

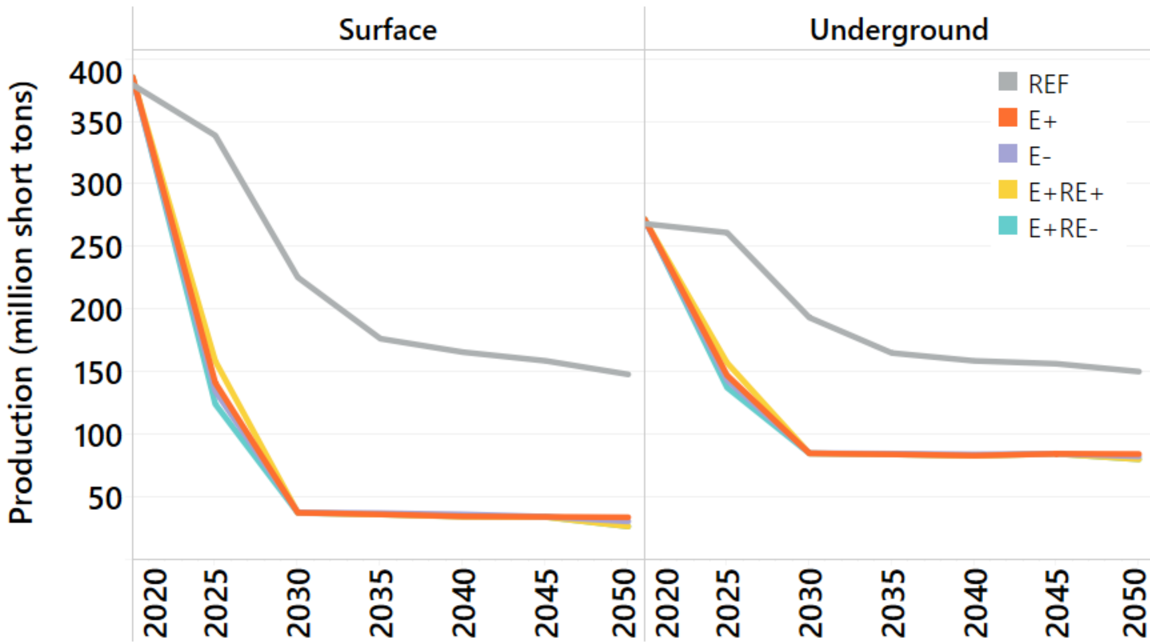


Figure 21. Annual coal production by scenario.

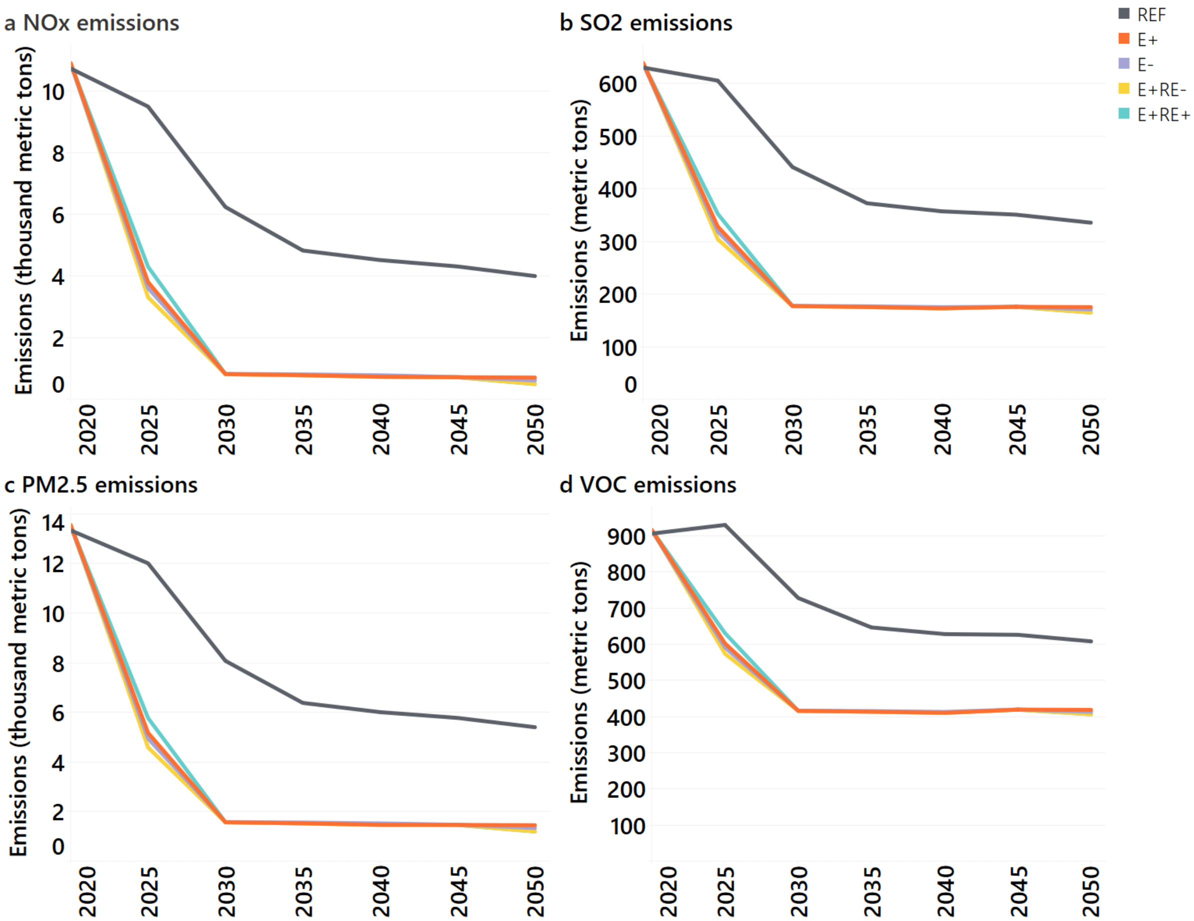


Figure 22. Annual emissions from coal mining by scenario.

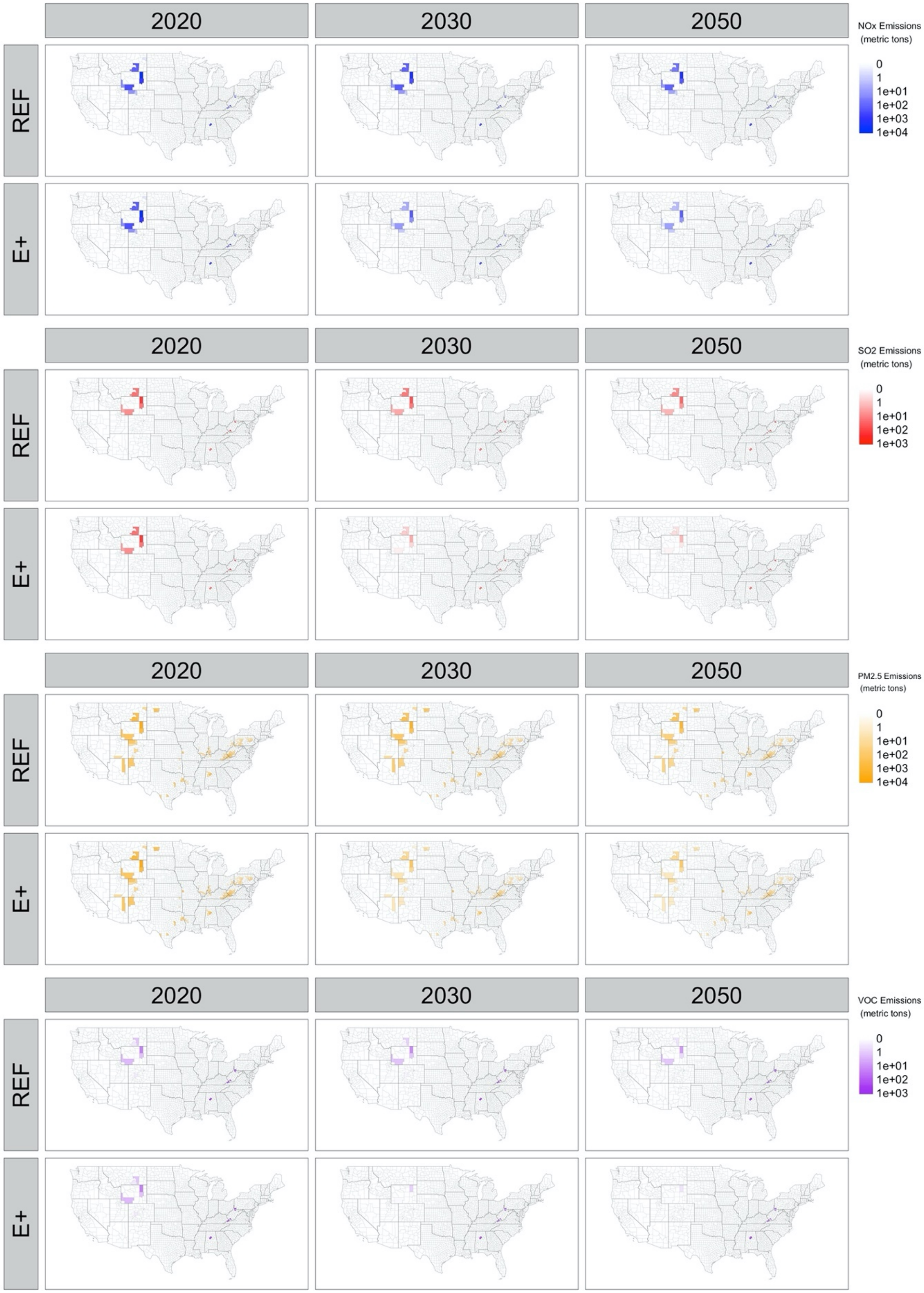
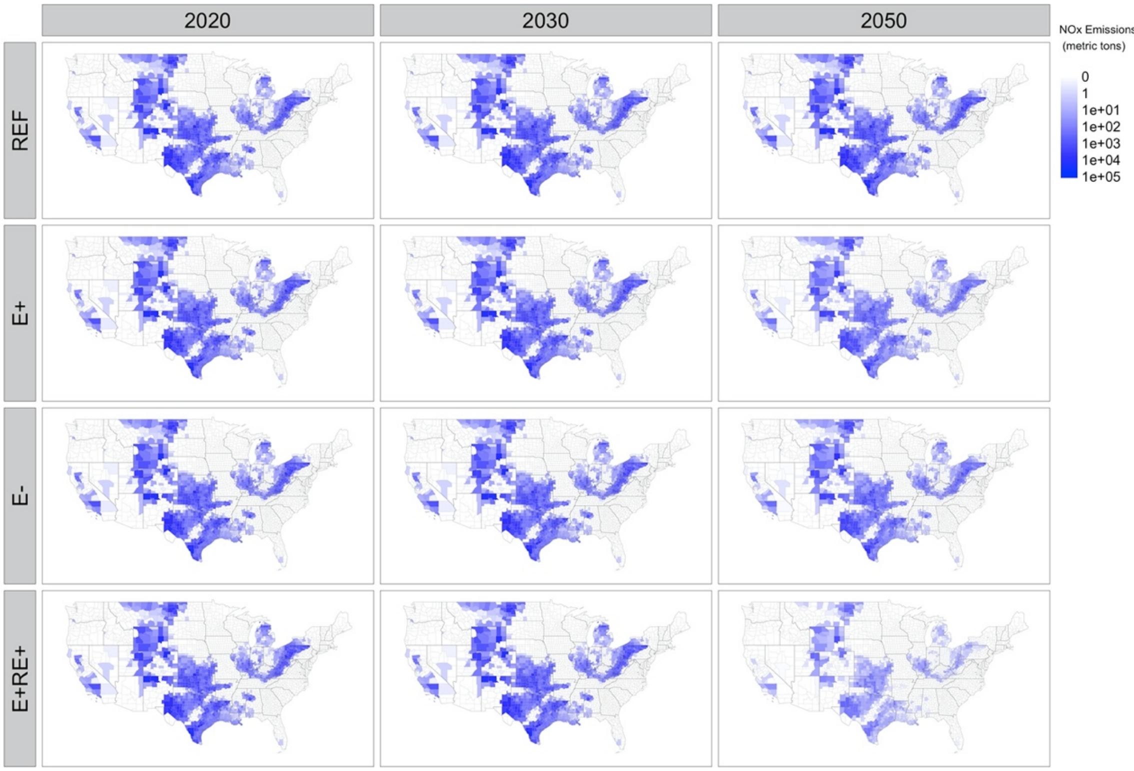


Figure 23. Annual, county-level emissions from coal mining by scenario.

1.7 Industrial processes – oil & gas production

We model county-level emissions from 2020 to 2050 associated with oil & gas production. We use county-level emissions (including venting, fugitive, flaring, other combustion, and other process emissions) reported in the 2017 NEI associated all upstream oil & gas exploration, extraction, and storage processes [2]. Using annual, state-level oil & gas production reported by the EIA, we scale the 2017 emissions to 2020 [8], [9]. To project future emissions from 2020 to 2050, we scale 2020 emissions using state-level, oil and gas production projections. We then convert projected US-wide oil & gas production, as reported in Annex N, to states based on the historical spatial distribution [8], [9]. We assume that the US will continue to export oil & gas at rates consistent with the EIA AEO reference case projection [5]. As domestic oil consumption declines, we assume that the US will import less oil and a higher share of oil will be produced domestically, but not in excess of projected domestic crude production [5]. We also assume that the US produces enough natural gas to meet domestic and export demand. Emission projections are

depicted in Figure 24 **through**



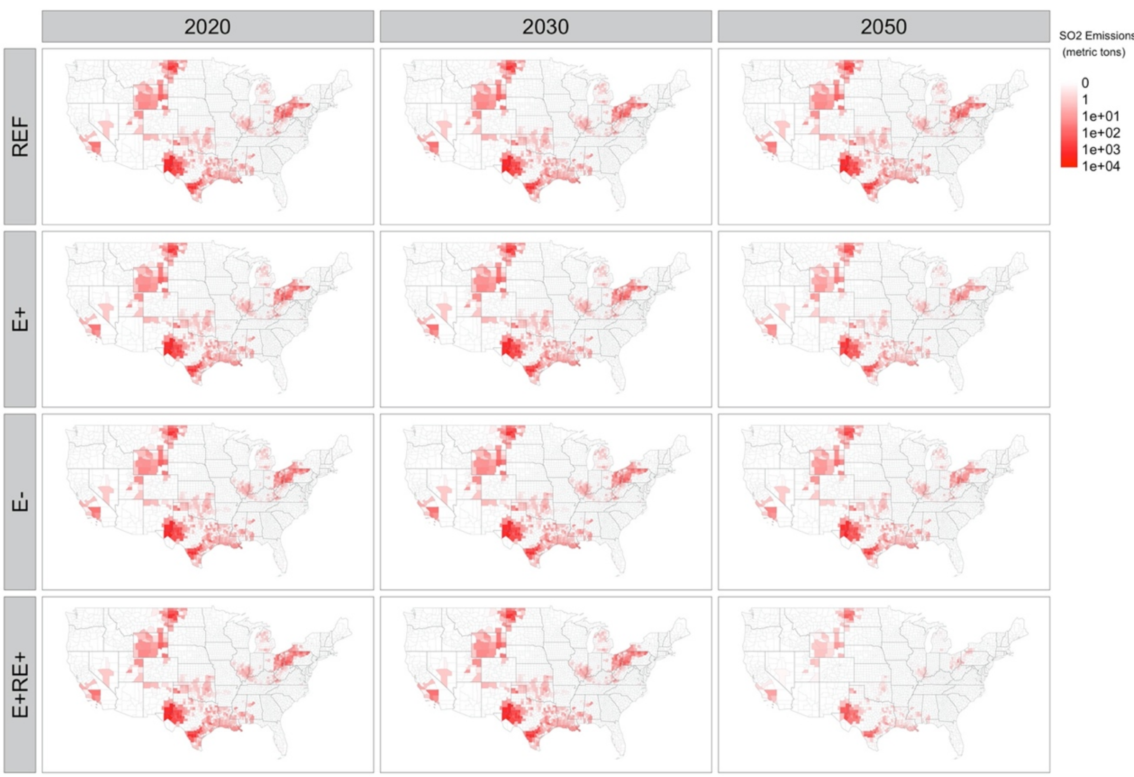


Figure 26.

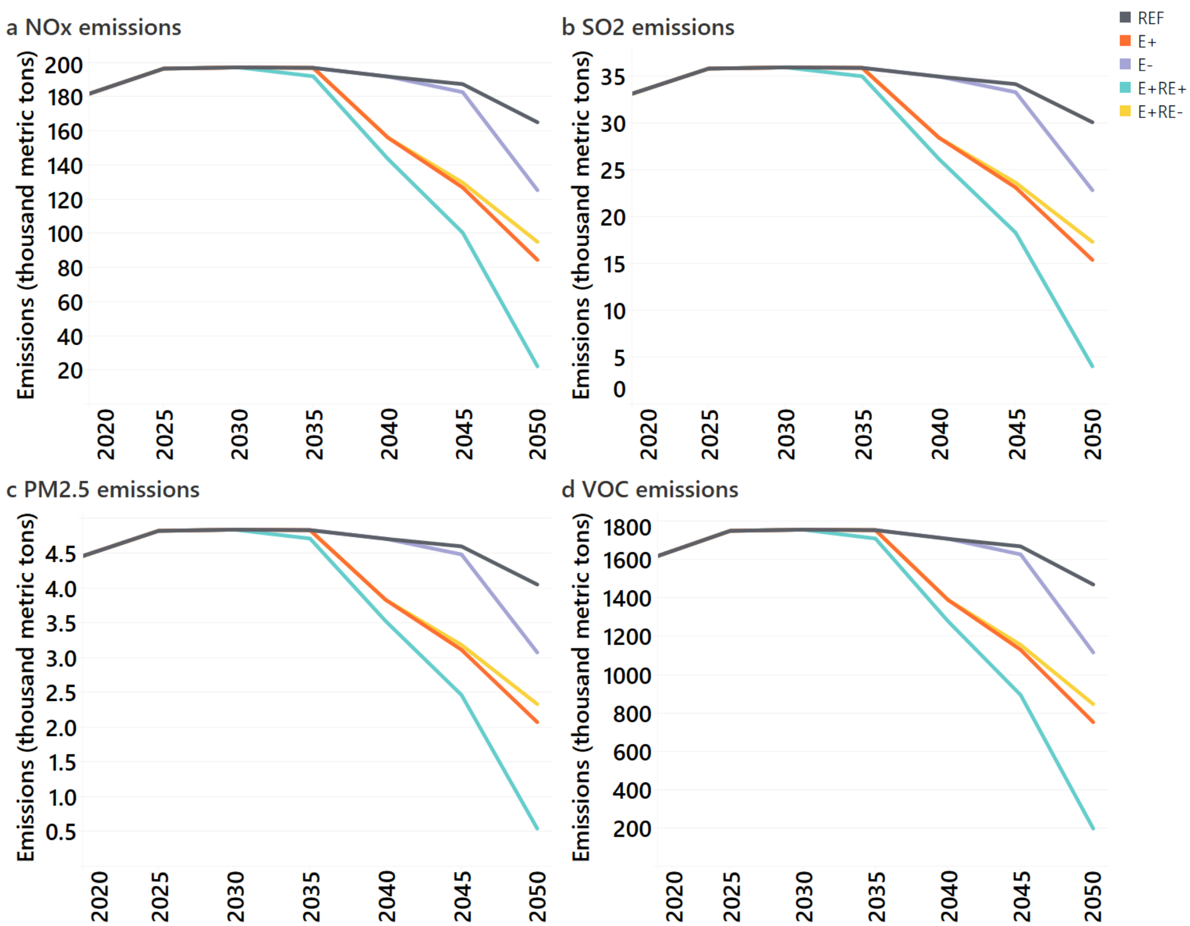


Figure 24. Annual emissions associated with oil production by scenario.

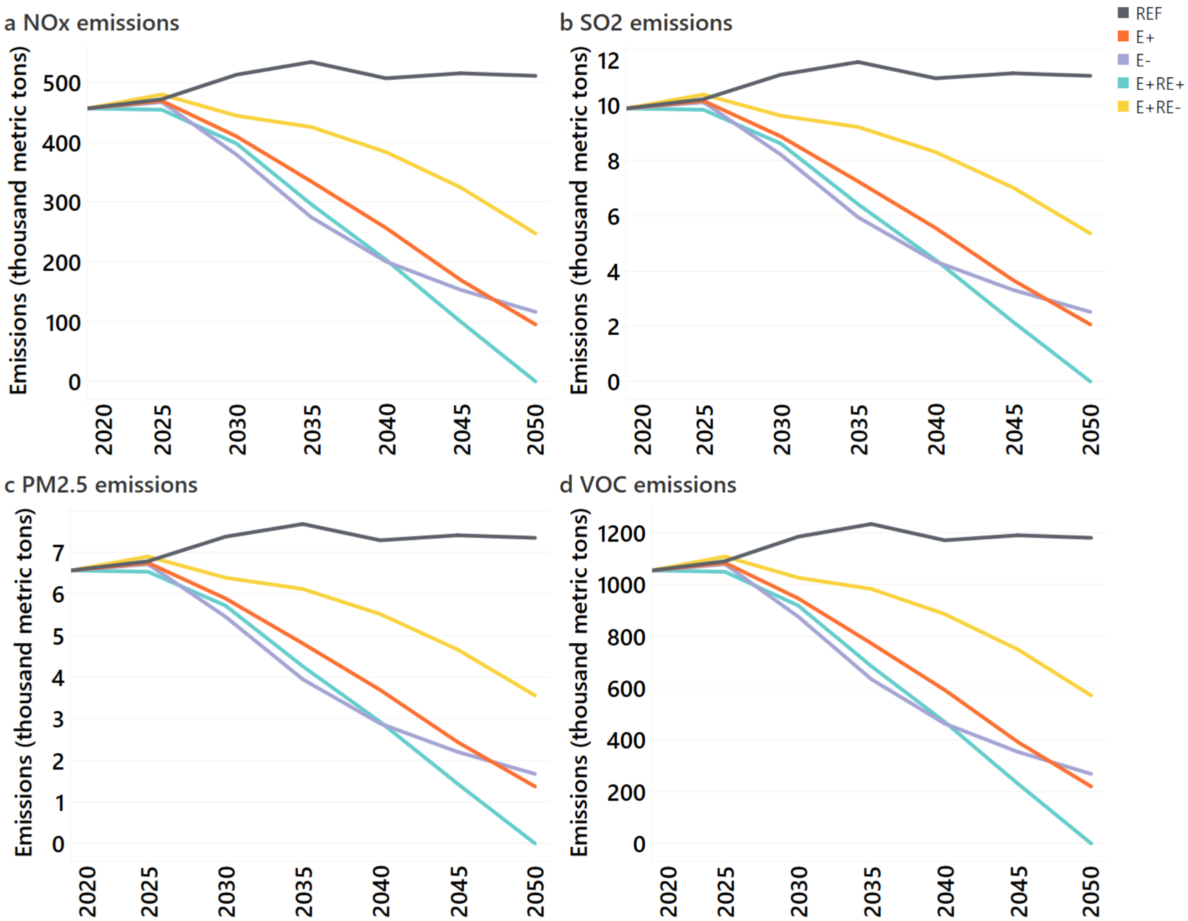
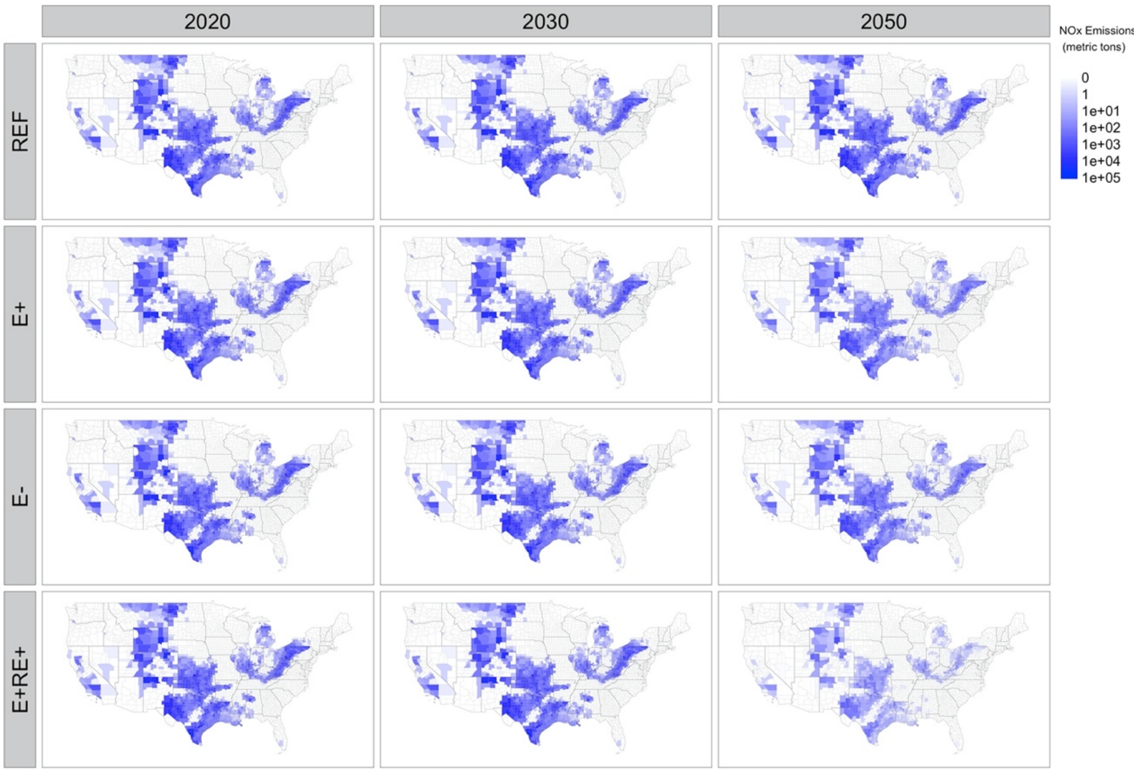


Figure 25. Annual emissions associated with natural gas production by scenario.



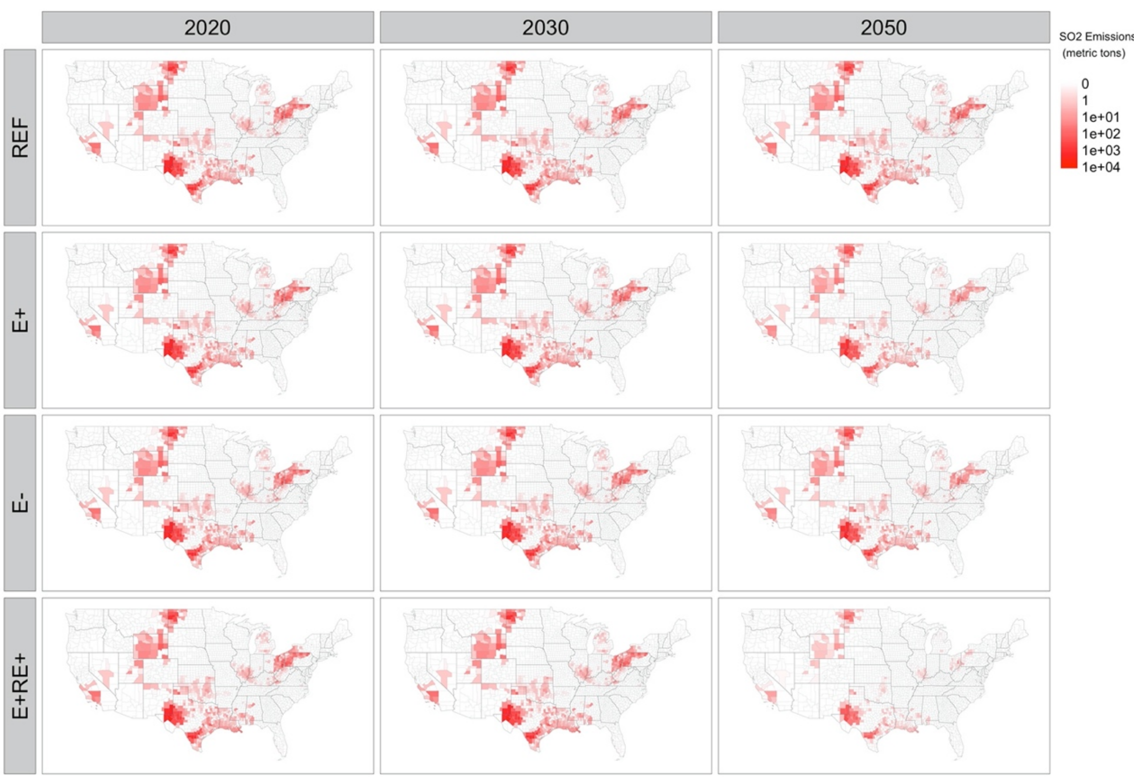
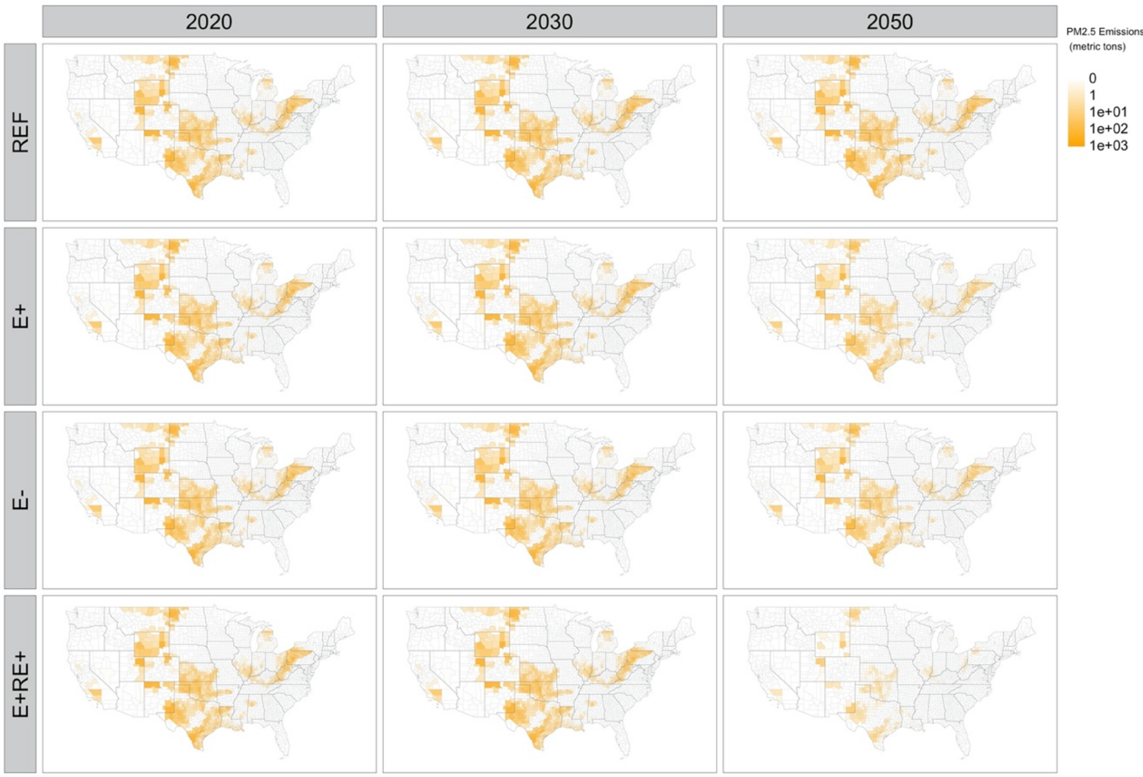


Figure 26. Annual, county-level emissions associated with oil and natural gas production by scenario.



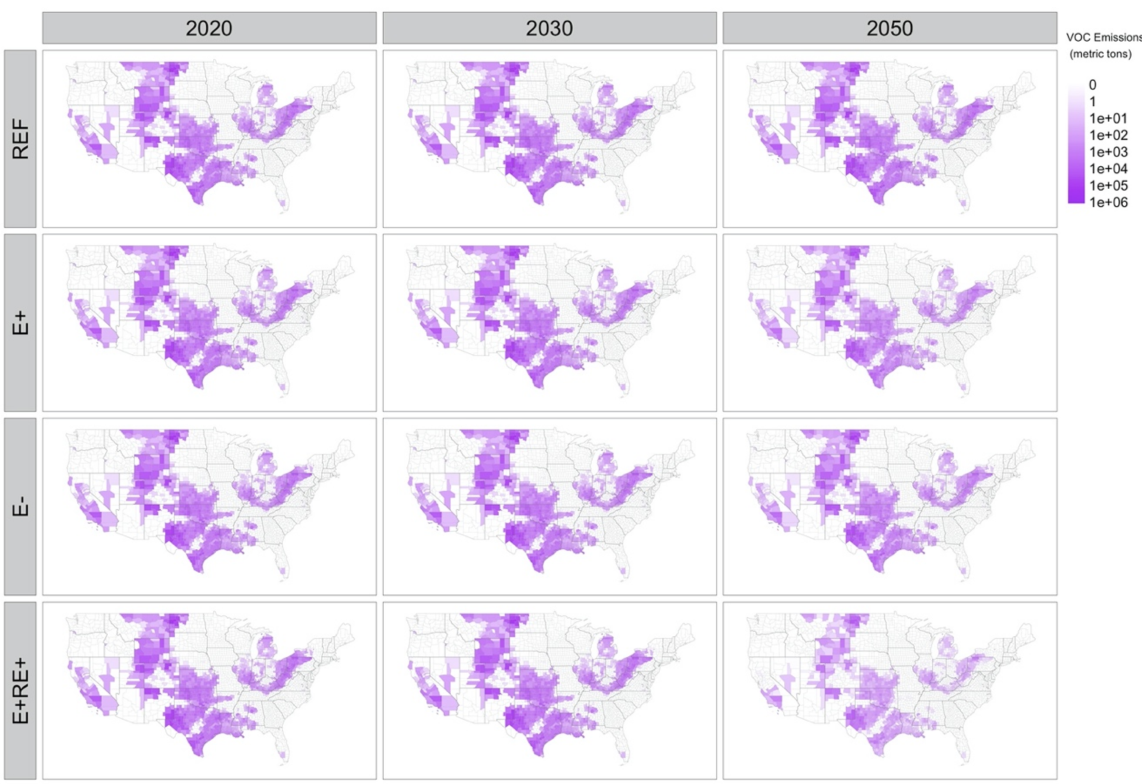


Figure 26. Annual, county-level emissions associated with oil and natural gas production by scenario. (continued)

1.8 Mobile – on-road vehicles

We model county-level emissions from 2020 to 2050 associated with on-road transportation including 6 vehicle classes (i.e., medium-duty, heavy-duty, transit bus, school & intercity bus, light-duty auto, light-duty truck) and 39 technologies (e.g., gasoline light-duty auto, electric long-range light-duty auto). We first model county-level vehicle miles traveled (VMT) by vehicle class and technology over time for three demand scenarios. We use state-level vehicle class and technology VMT projections from EnergyPathways, as shown in Figure 27 and Figure 28. To downscale activity to the county-level, we derive scaling factors based on county-level VMTs by vehicle class reported in the 2017 NEI [2]; examples for gasoline light duty vehicles are shown in Figure 29 and Figure 30. As shown in Figure 31 and Figure 32, we use emission factors by year, vehicle class, and fuel type reported in GREET v2020 combined with the demand projections to project county-level emissions over time [10].

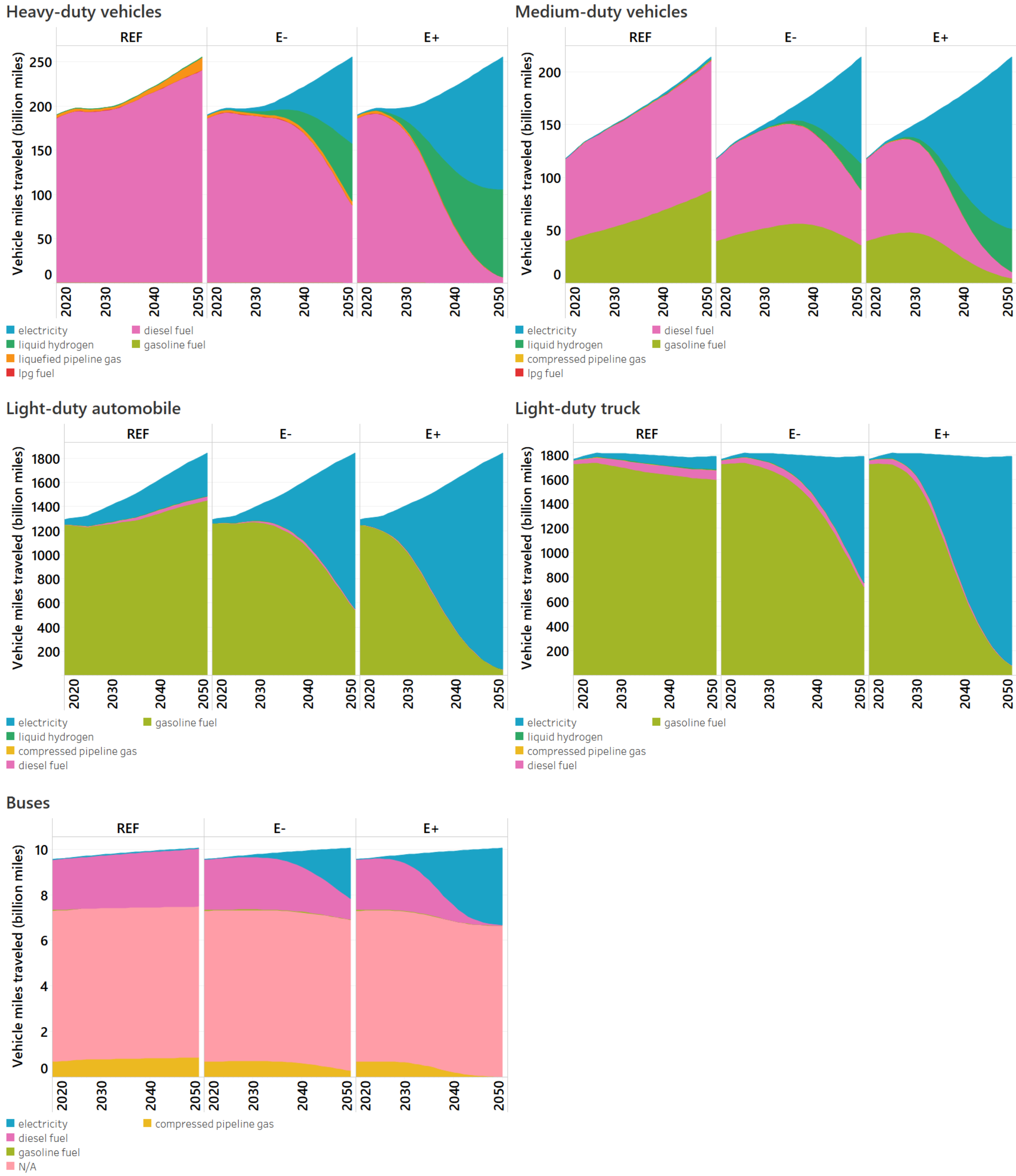


Figure 27. Vehicle miles traveled by fuel type, vehicle class, and demand scenario.

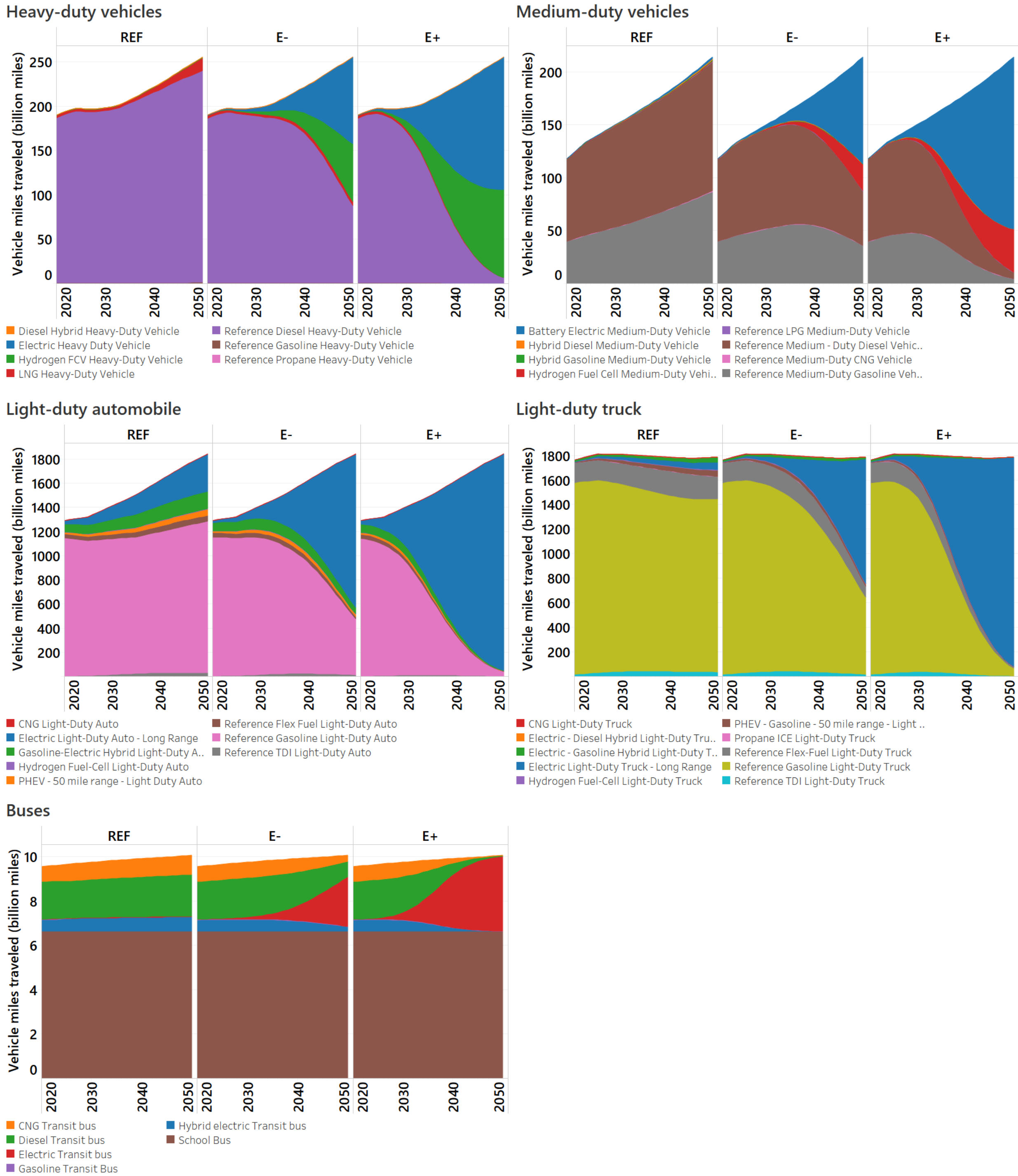


Figure 28. Vehicle miles traveled by demand technology, vehicle class, and demand scenario.

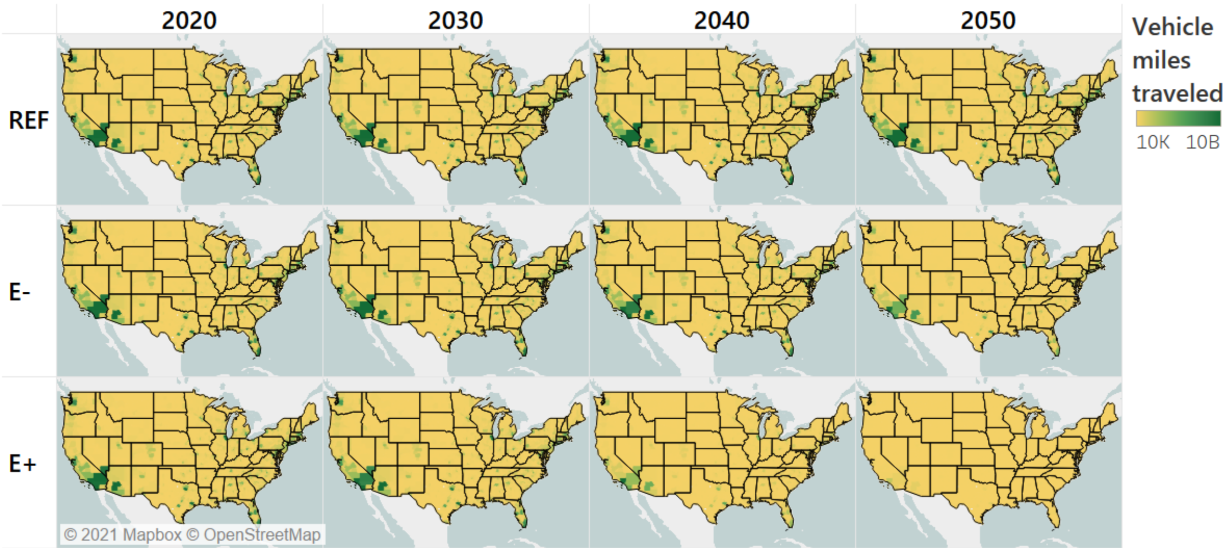


Figure 29. Sample of county-level demand projection for gasoline light duty automobiles by demand scenario.

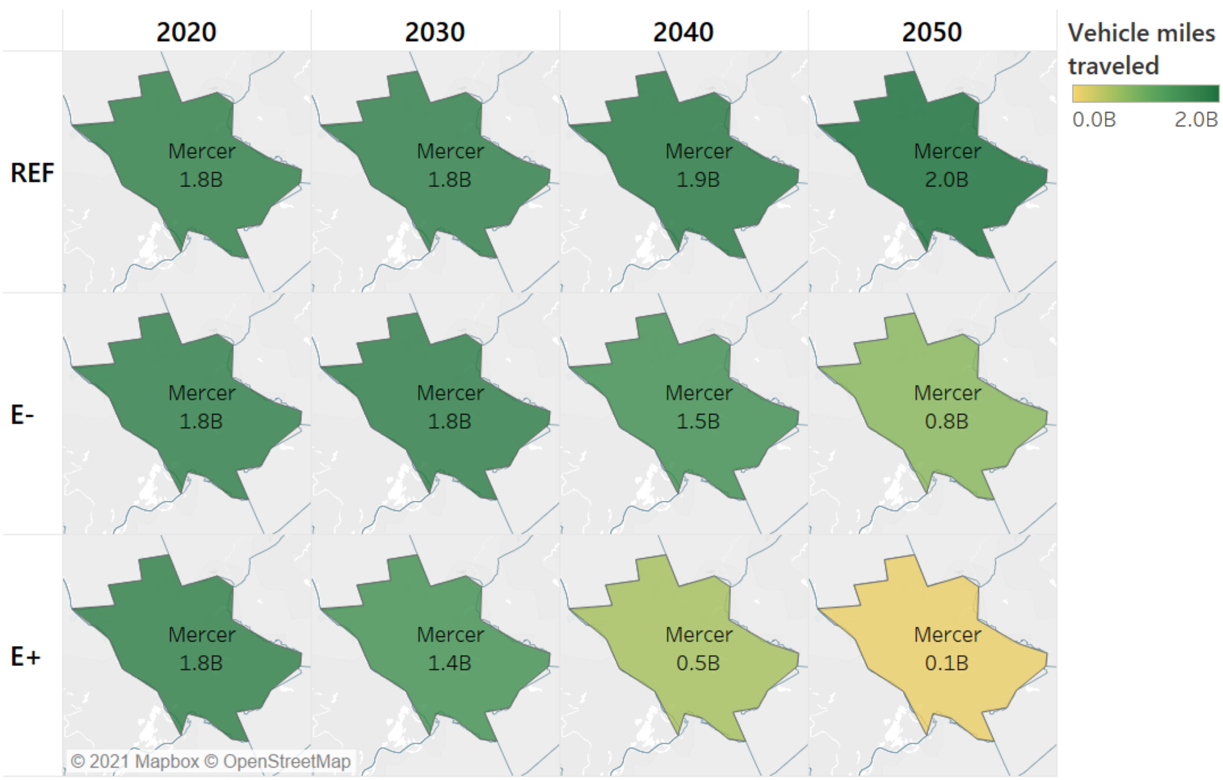


Figure 30. Sample of demand projection for gasoline light duty automobiles for Mercer County, New Jersey, by demand scenario.

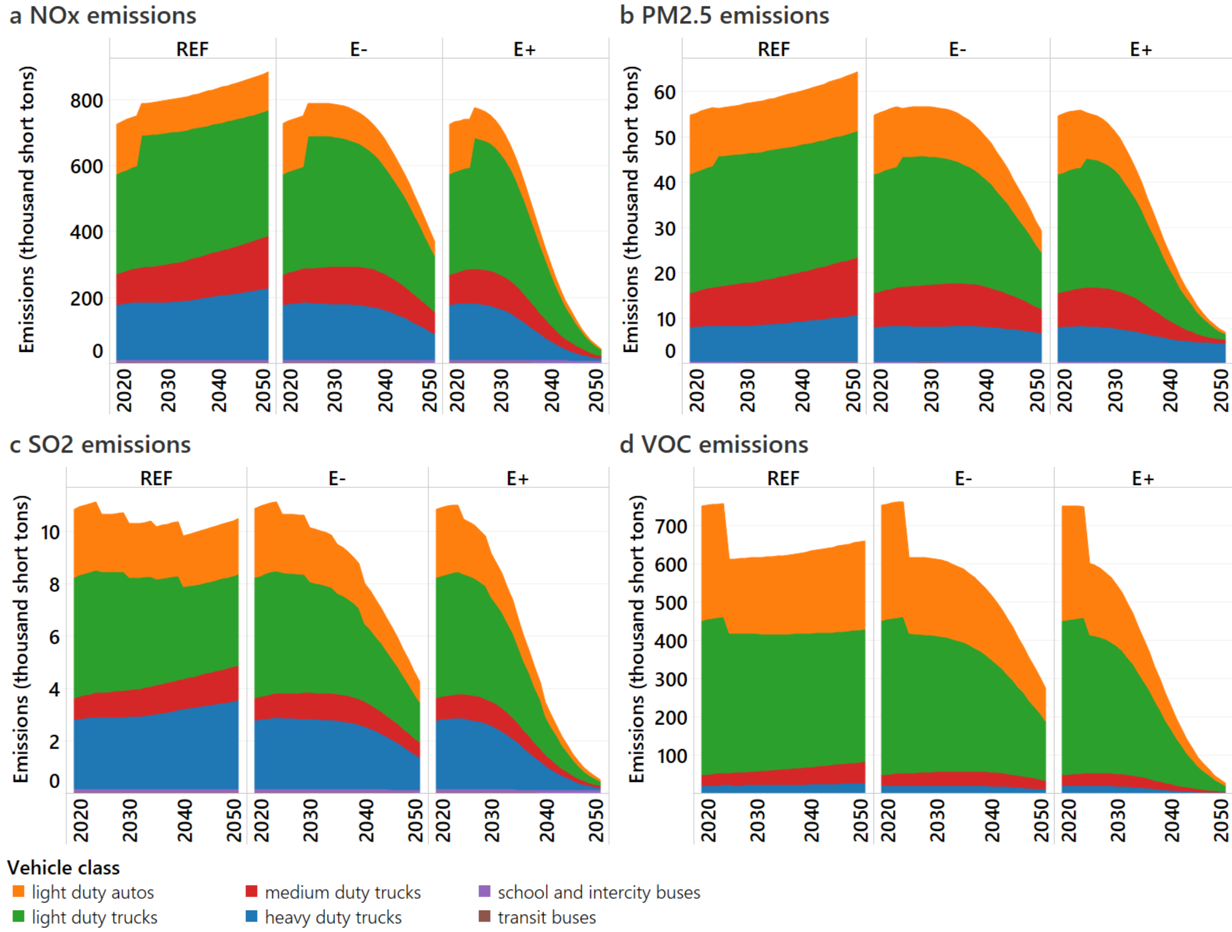


Figure 31. Annual emissions associated with on-road vehicles by scenario and vehicle class.

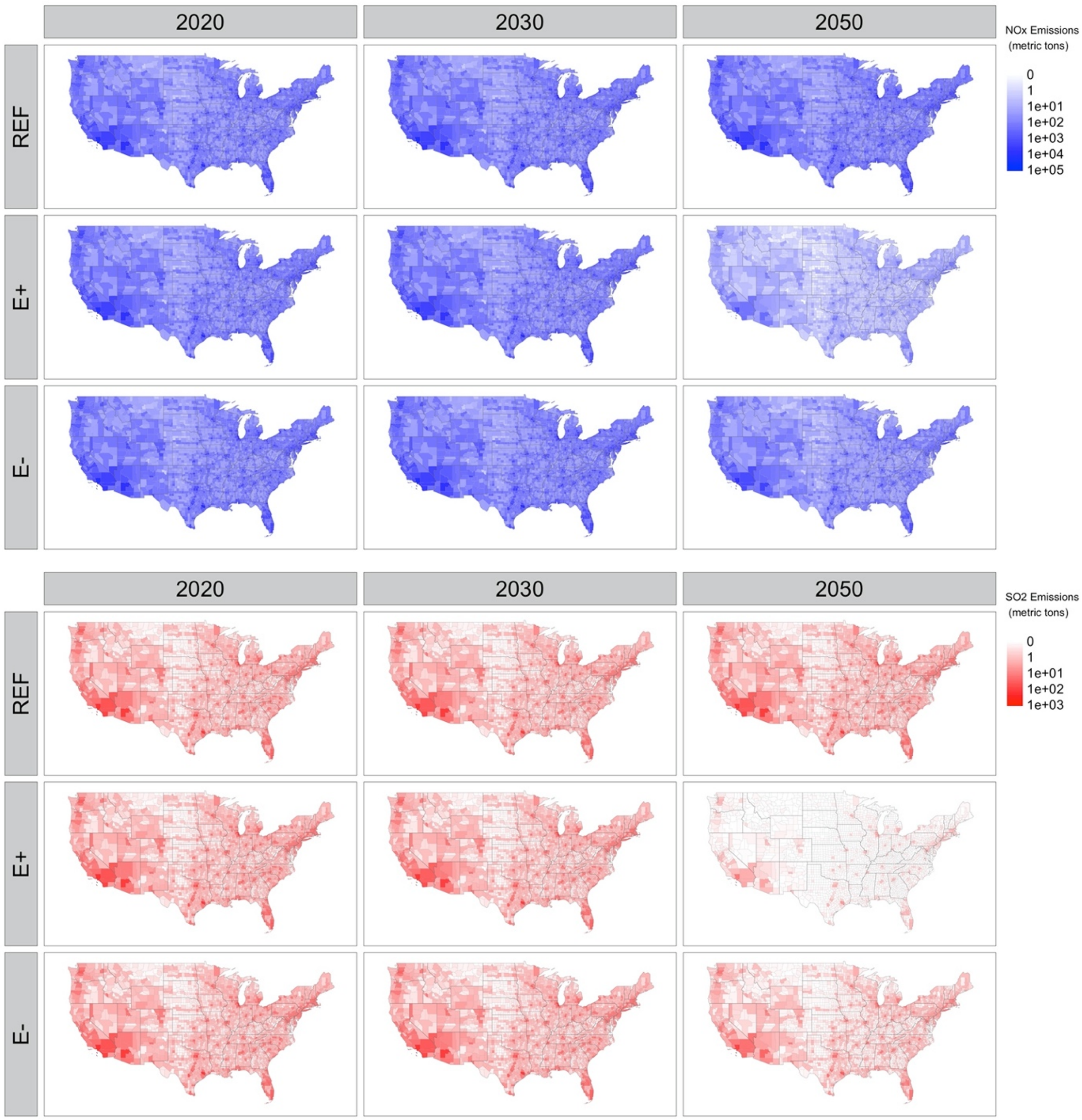
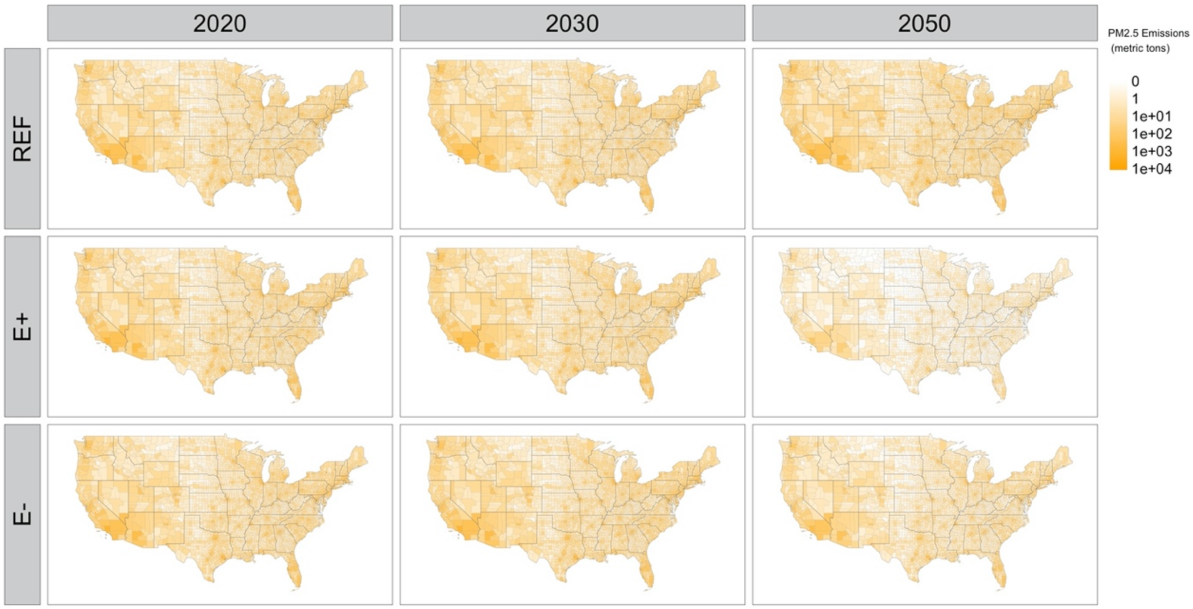


Figure 32. Annual, county-level emissions associated with on-road vehicles by scenario.



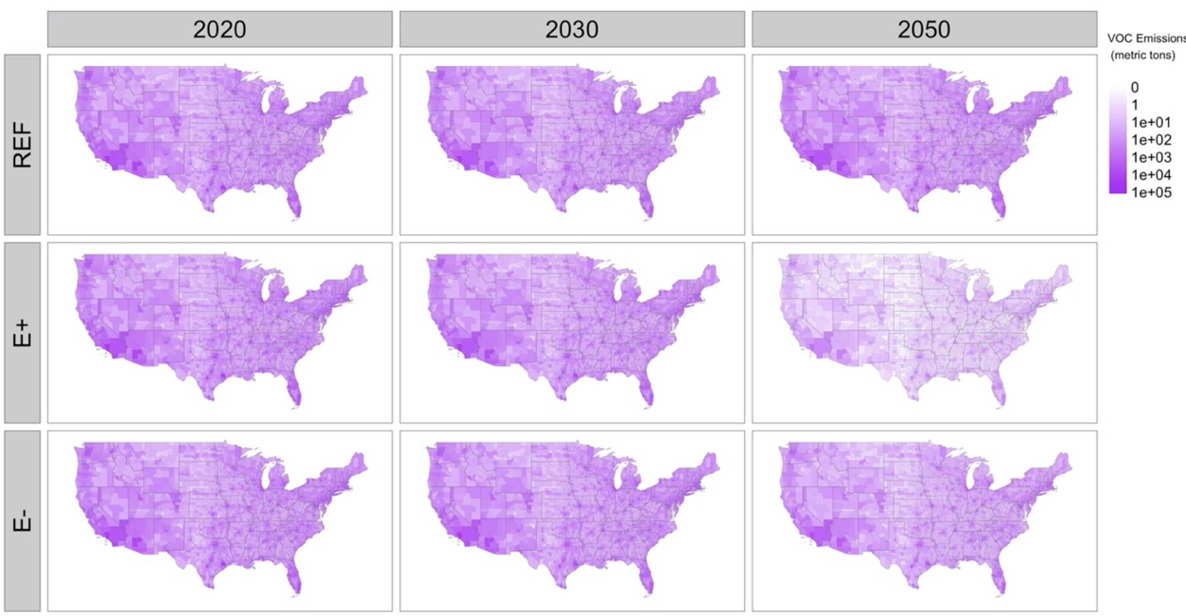


Figure 32. Annual, county-level emissions associated with on-road vehicles by scenario. (continued)

1.9 Miscellaneous source categories

We model county-level emissions from 2020 to 2050 associated with commercial cooking and gas stations. For both source categories, we use county-level emissions reported in the 2017 NEI [2]. To project future emissions associated with gas stations, we scale 2017 emissions using state-level VMT projections for on-road vehicles that use gasoline, diesel, lpg, and compressed petroleum gas and diesel from EnergyPathways for three demand scenarios. To project future emissions associated with commercial cooking, we scale 2017 emissions using state-level VMT projections for gas commercial cooking from EnergyPathways for three demand scenarios. Emission projections are depicted in Figure 33 through Figure 35.

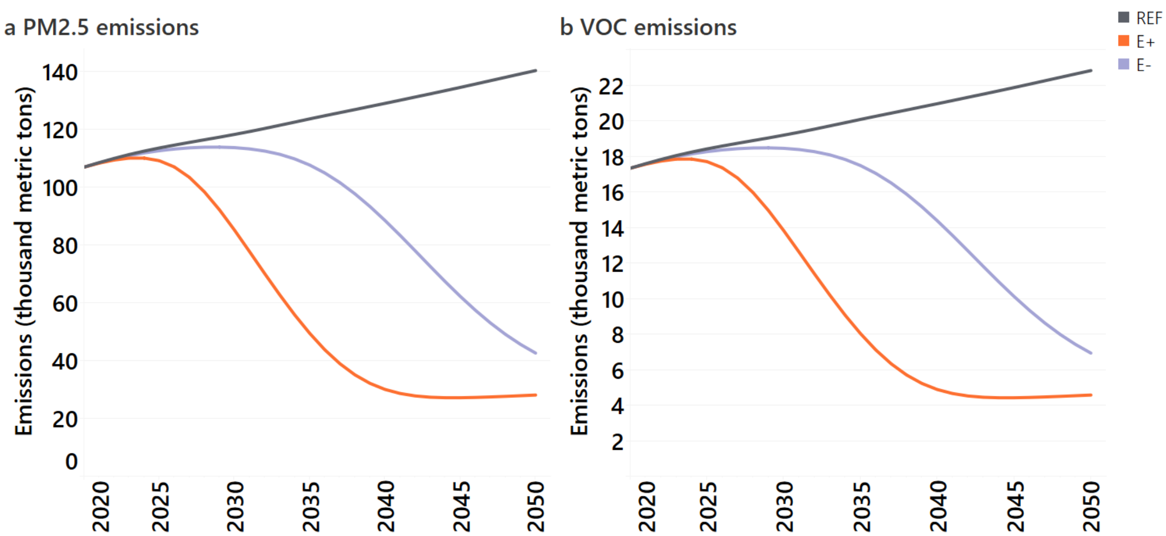


Figure 33. Annual emissions associated with commercial cooking by scenario.

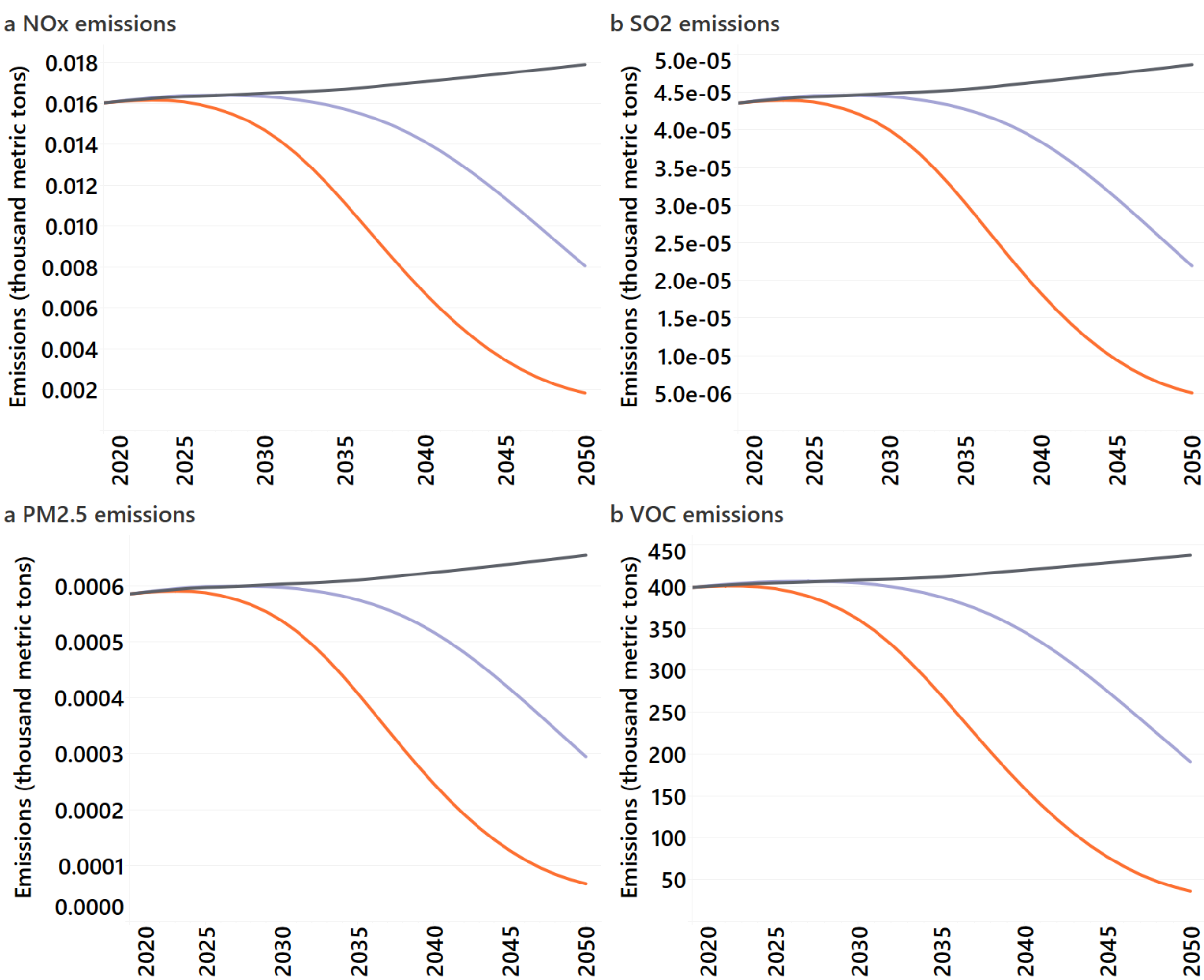


Figure 34. Annual emissions associated with gas stations by scenario.

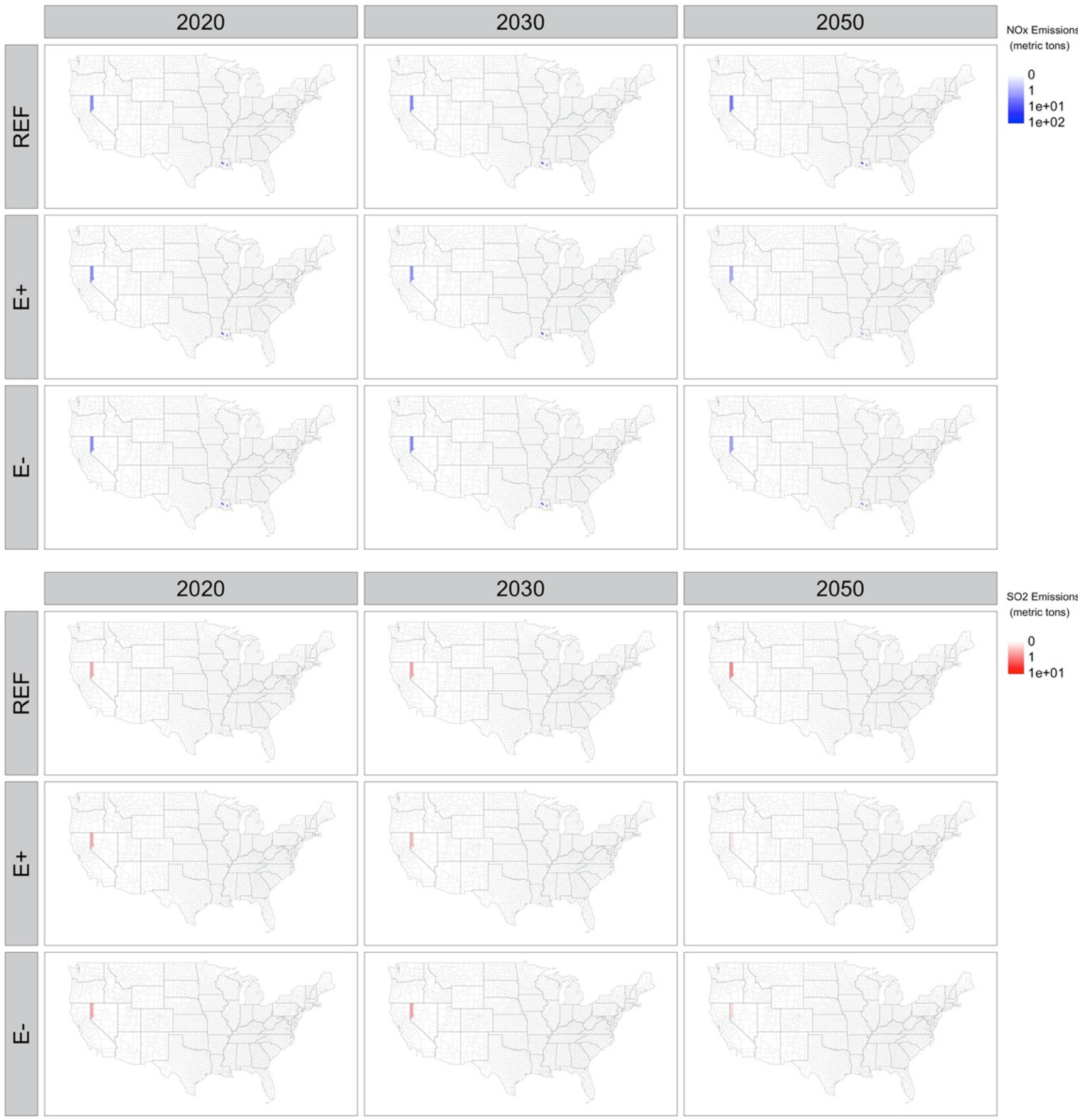


Figure 35. Annual, county-level emissions associated with miscellaneous source categories by scenario.

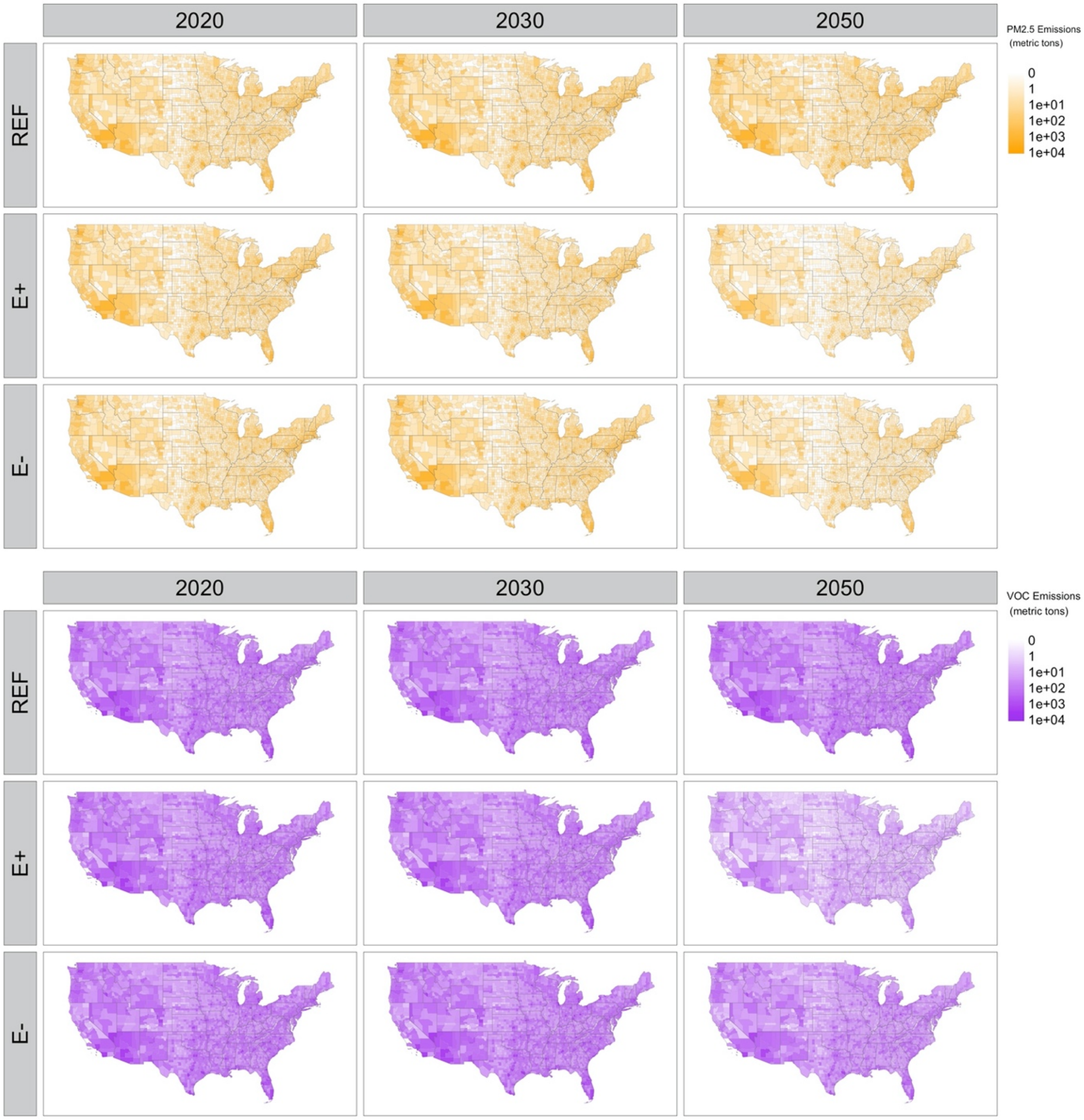


Figure 35. Annual, county-level emissions associated with miscellaneous source categories by scenario. (continued)

1.10 Air quality model

We estimate premature mortalities by combining the emissions simulation with the source-receptor reduced complexity model, the Air Pollution Emission Experiments and Policy Model (v.3, AP3) [11]. AP3 generates estimates of pollution-induced premature mortalities in downwind receptors associated with emissions from source locations and heights. We assume a concentration-response relationship consistent with the American Cancer Society study [12]. We modify marginal estimates based on county-level population projections from the EPA's Integrated Climate and Land Use Scenarios project [13].

To develop monetized impact estimates, we use the value of a statistical life (VSL), a commonly used measure of the willingness-to-pay for small changes in mortality risk. We assume a VSL of US$9.4 million (in 2019 US$) as reported by the US EPA [14].

2 Results

2.1 Summary

This section summarizes air quality impacts across all source categories modeled in this study. Figure 36 shows annual mortality associated with all modeled emissions categories, where current impacts are largely associated with coal electric power generation and on-road mobile emissions. Air pollution impacts across all net-zero scenarios decline substantially from 33,000 deaths ($290 billion in damages) in 2020, 20,000 to 22,000 deaths ($180-190 billion) in 2030, and 2,000 to 10,000 deaths ($20-90 billion) by 2050. Variation in the rate and extent of decline in air pollutant impacts is driven by electrification in the transport sector and declining domestic use of fossil fuels for electric power and heating. Figure 37 and Figure 38 show the spatial distribution of mortality and mortality rates. As depicted in Figure 40, approximately 40,000 to 45,000 deaths ($370-410 billion in damages) are avoided in the net-zero scenarios (relative to the reference scenario) in the first decade, and approximately 260,000 to 410,000 mortalities ($2.3-3.7 trillion in damages) are avoided from 2020 to 2050. Figure 39 shows the cumulative avoided mortalities from 2020 to 2050 by state, ranging from fewer than 1,000 mortalities avoided in Montana to upwards of approximately 30,000 to 70,000 mortalities avoided in California.

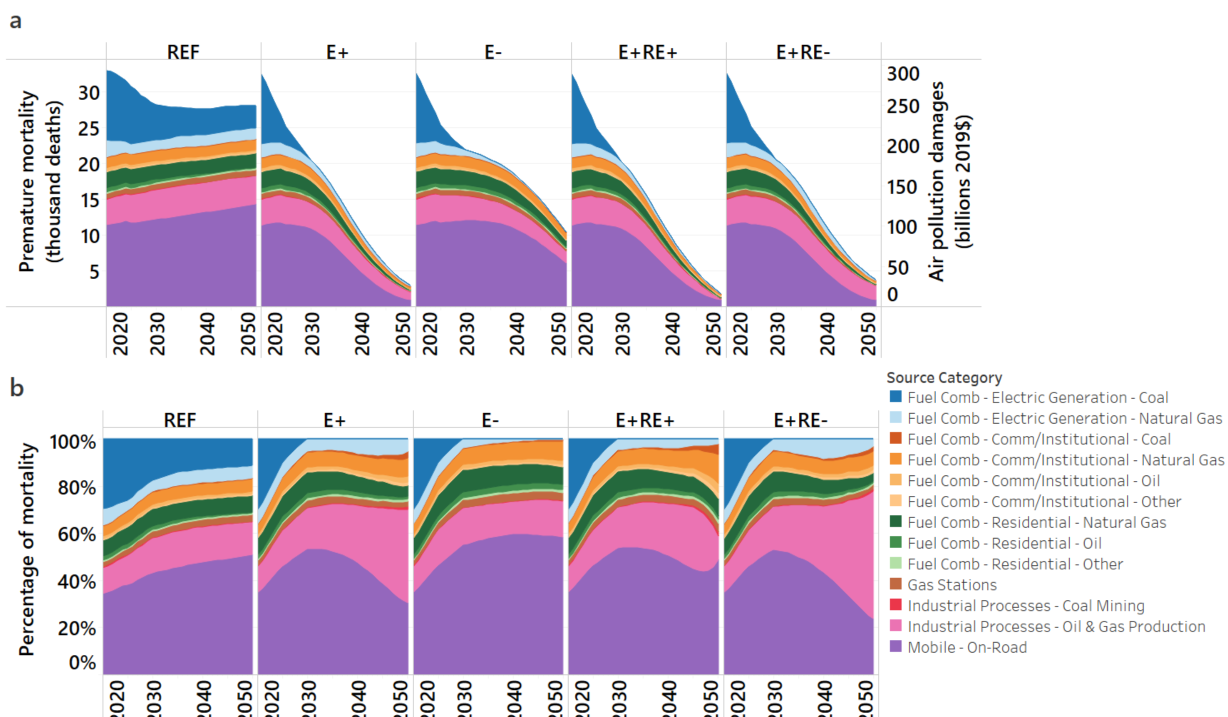


Figure 36. Annual criteria air pollutant emissions and air quality impacts associated with all modeled source emissions categories by scenario and source.

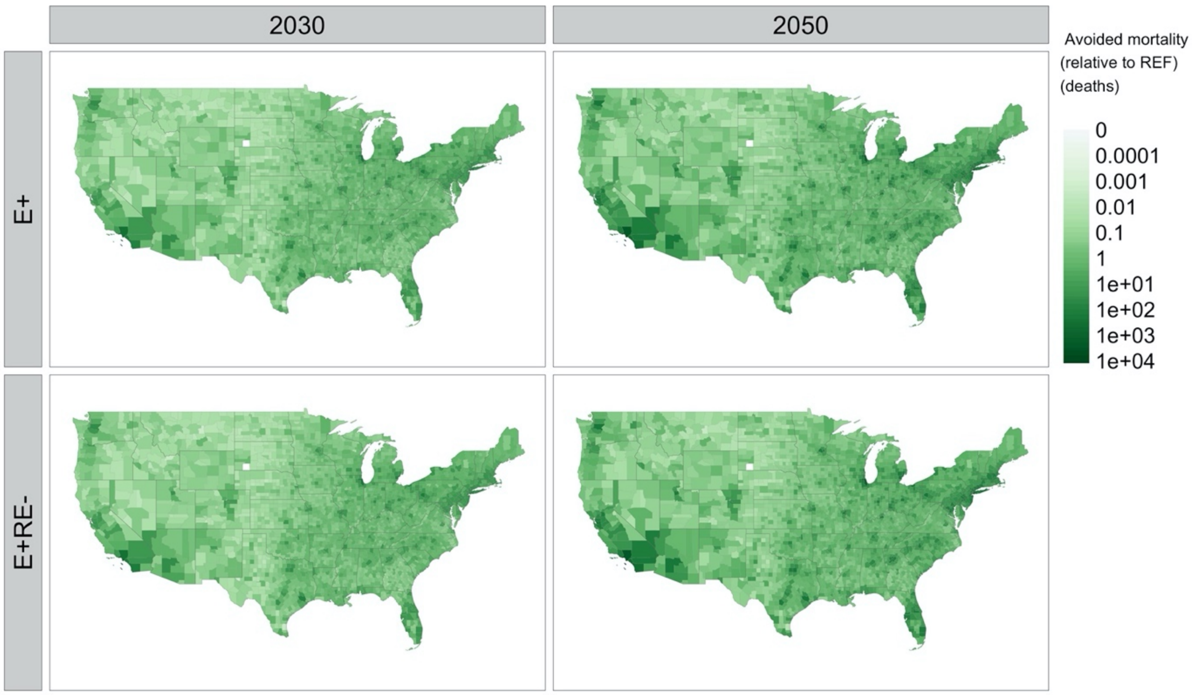


Figure 37. Annual, county-level avoided premature mortality (log scale) associated all modeled source emissions categories by scenario and source.

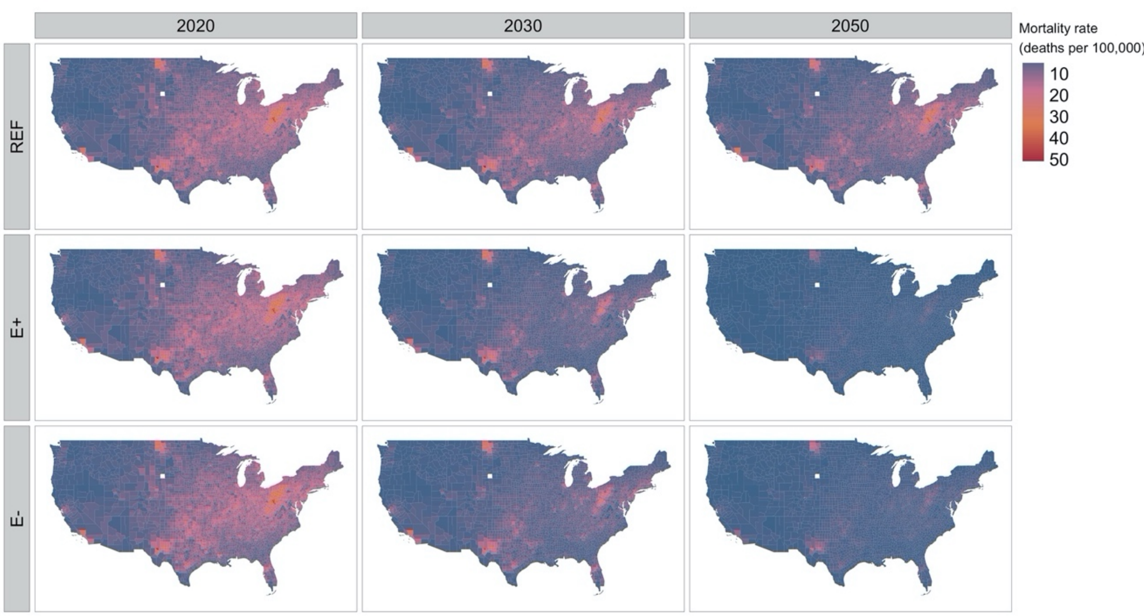


Figure 38. Annual, county-level mortality rates associated all modeled source emissions categories by scenario and source.

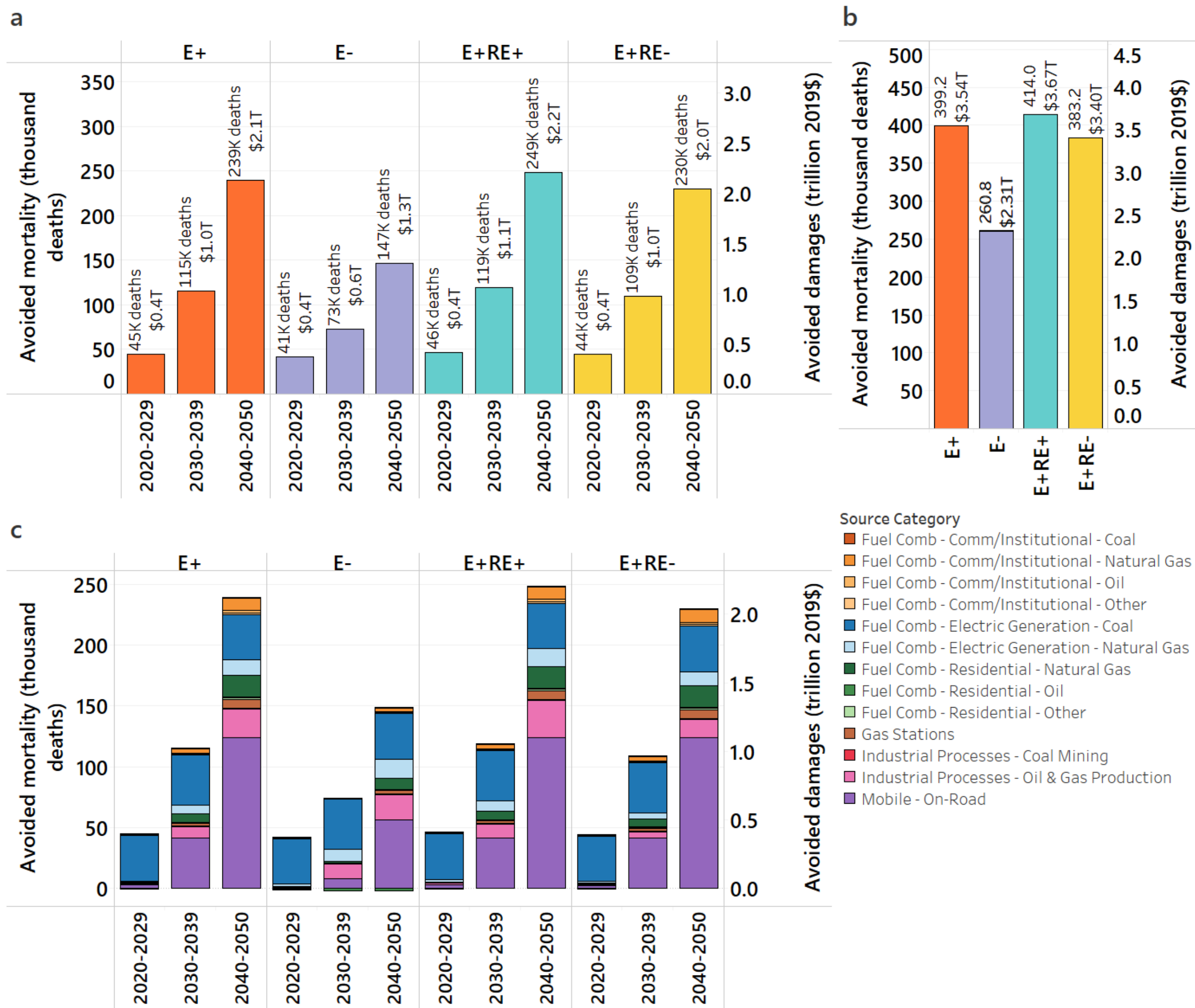


Figure 39. Avoided air quality impacts associated with all modeled source emissions categories by scenario, decade, and source. Avoided air quality impacts are estimated as the air pollution impacts in the reference scenario minus the net-zero scenario.

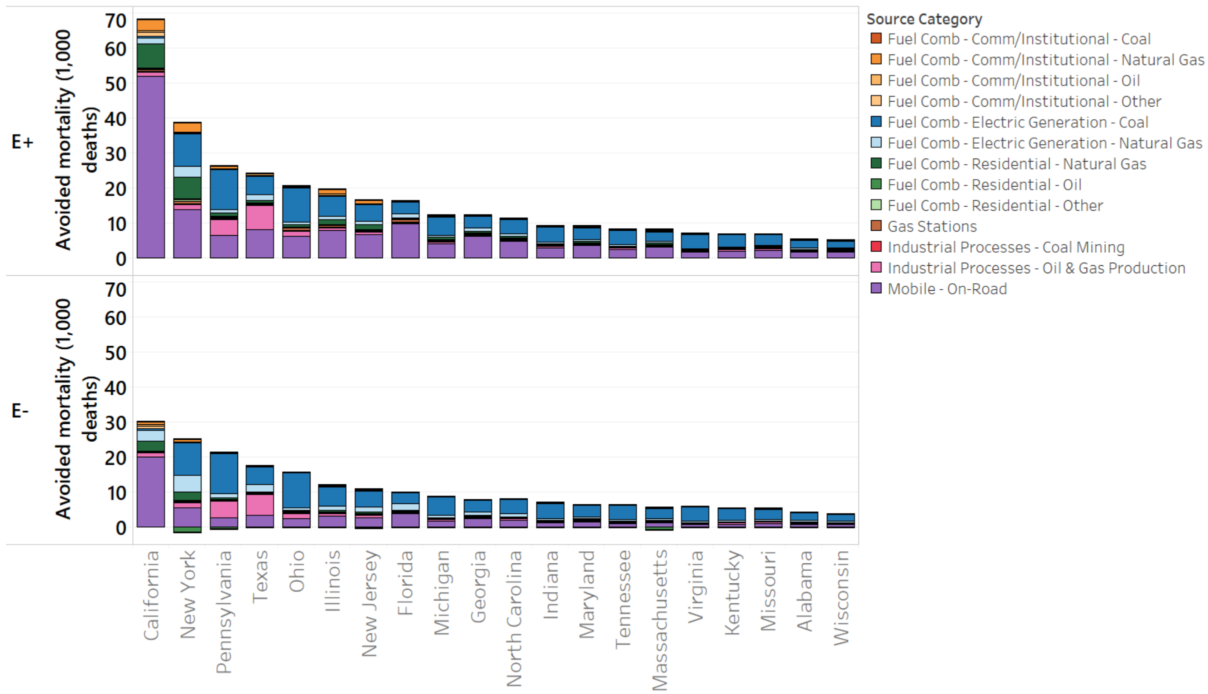


Figure 40. State-level criteria air pollutant emissions and air quality impacts associated all modeled source emissions categories by scenario and source.

2.2 Fuel combustion – electric generation – coal

Figure 41 shows annual mortality associated with coal electric power generation, which ceases by 2030 across all net-zero scenarios and significantly decreases over time in the reference scenario. Figure 42 and Figure 43 show the spatial distribution of mortality and avoided mortality. Total mortality is concentrated in more urban areas in the Eastern half of the US, and the highest mortality rates are observed in the Appalachian and Powder River basins where there is substantial coal electric power and proximate coal supplies. As depicted in Figure 44, approximately 37,000 mortalities ($340 billion in damages) are avoided in the net-zero scenarios (relative to the reference scenario) in the first decade (2020-2029), and approximately 117,000 mortalities ($1.0 trillion in damages) are avoided from 2020 to 2050. Figure 45 shows the cumulative avoided mortalities from 2020 to 2050 by state, where upwards of approximately 12,000 mortalities are avoided in Pennsylvania.

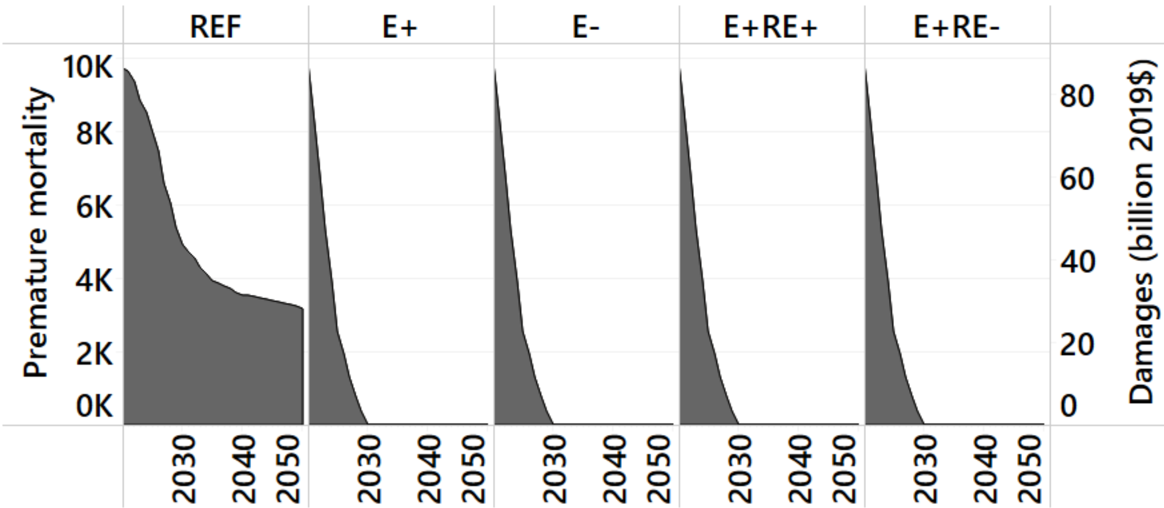


Figure 41. Annual air quality impacts associated with coal electric power generation by scenario.

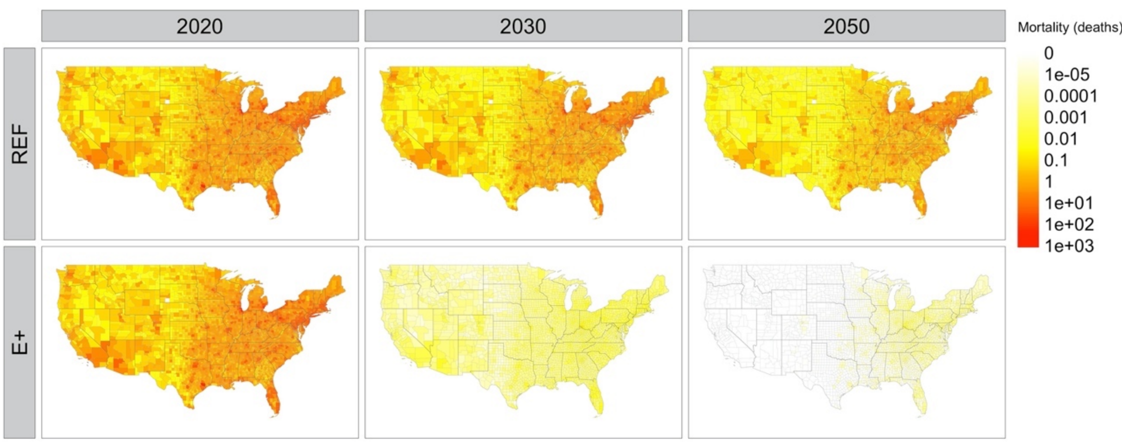


Figure 42. Annual, county-level premature mortality associated with coal electric power generation by scenario.

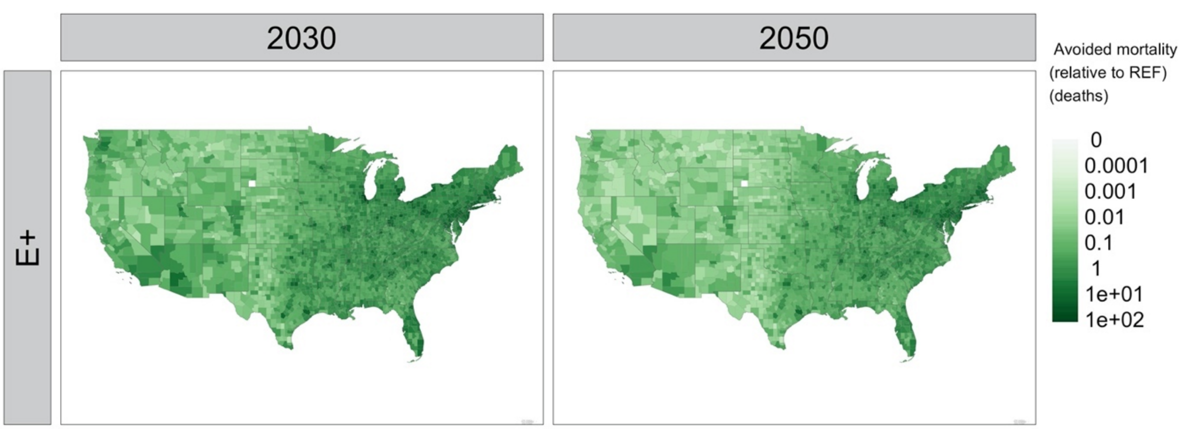


Figure 43. Annual, county-level avoided premature mortality associated with coal electric power generation by scenario. Avoided premature mortality is estimated as premature mortality in the reference scenario minus the net-zero scenario.

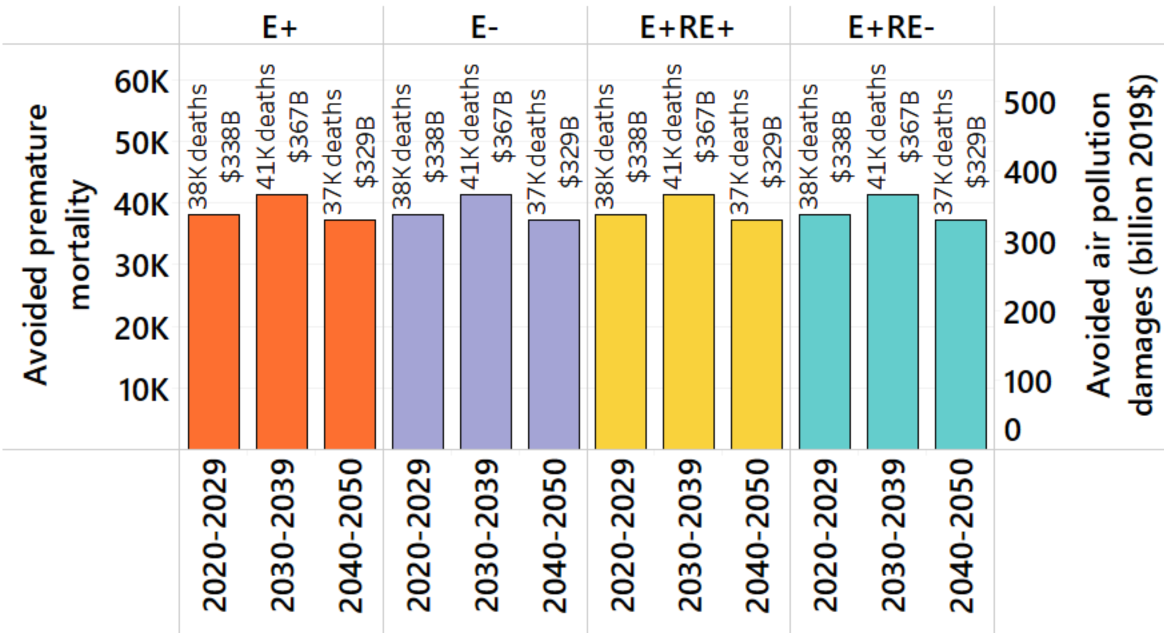


Figure 44. Avoided air quality impacts associated with coal electric power generation by scenario and decade. Avoided air quality impacts are estimated as the air pollution impacts in the reference scenario minus the net-zero scenario.

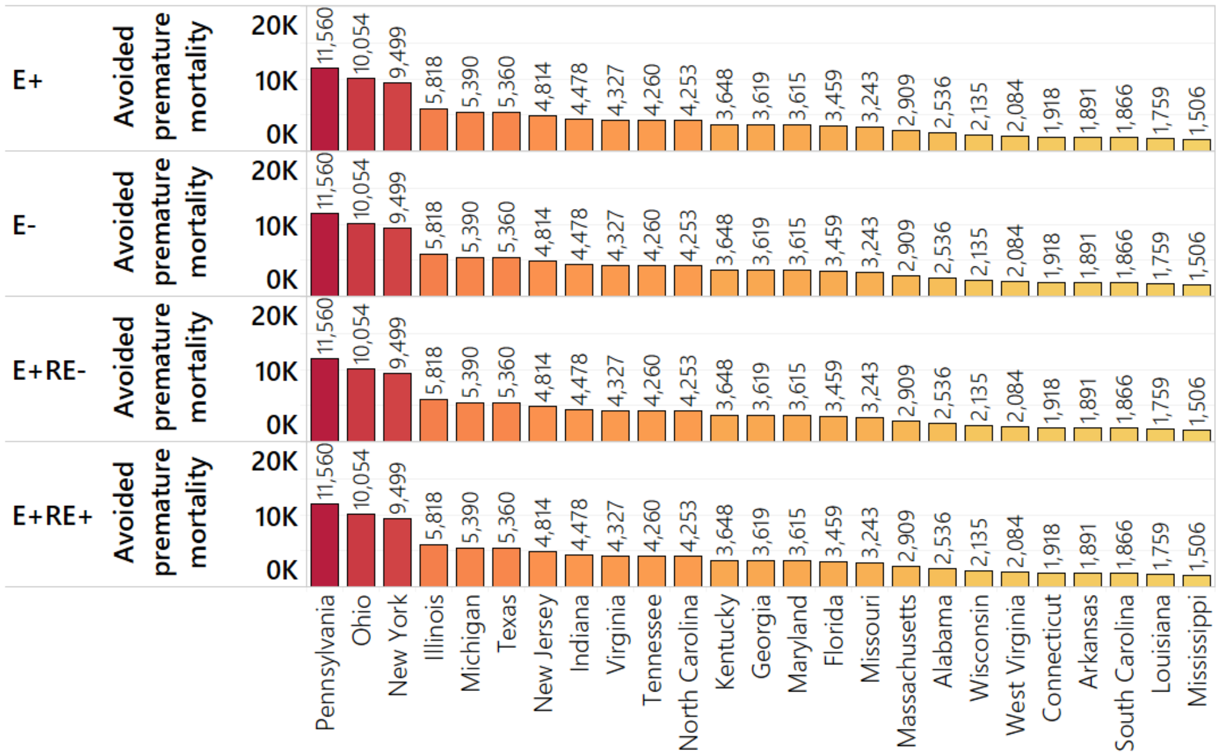


Figure 45. Cumulative avoided premature mortality associated with coal electric power generation by state from 2020 to 2050. Includes top 25 states in terms of cumulative avoided premature mortalities.

2.3 Fuel combustion – electric generation – natural gas

Figure 46 shows annual mortality associated with gas electric power generation, with variation across net-zero scenarios driven by the rate of electrification and constraints on renewables deployment. Air pollution impacts decline substantially across all net-zero scenarios, as newer gas-powered generation without carbon capture (with lower emissions rates) are deployed in the first decade, and Allam cycle gas-powered generation with carbon capture (with near zero emissions rates) is deployed in the 2030s and 2040s in most of the scenarios. Figure 47 and Figure 48 show the spatial distribution of mortality and avoided mortality, which are distributed across the US at present. As depicted in Figure 49, approximately 1,000 to 2,100 mortalities ($10-19 billion in damages) are avoided in the net-zero scenarios (relative to the reference scenario) in the first decade, and approximately 17,900 to 27,500 mortalities ($159-244 billion in damages) are avoided from 2020 to 2050. Figure 50 shows the cumulative avoided mortalities from 2020 to 2050 by state, where upwards of approximately 2,900 to 4,600 mortalities are avoided in New York.

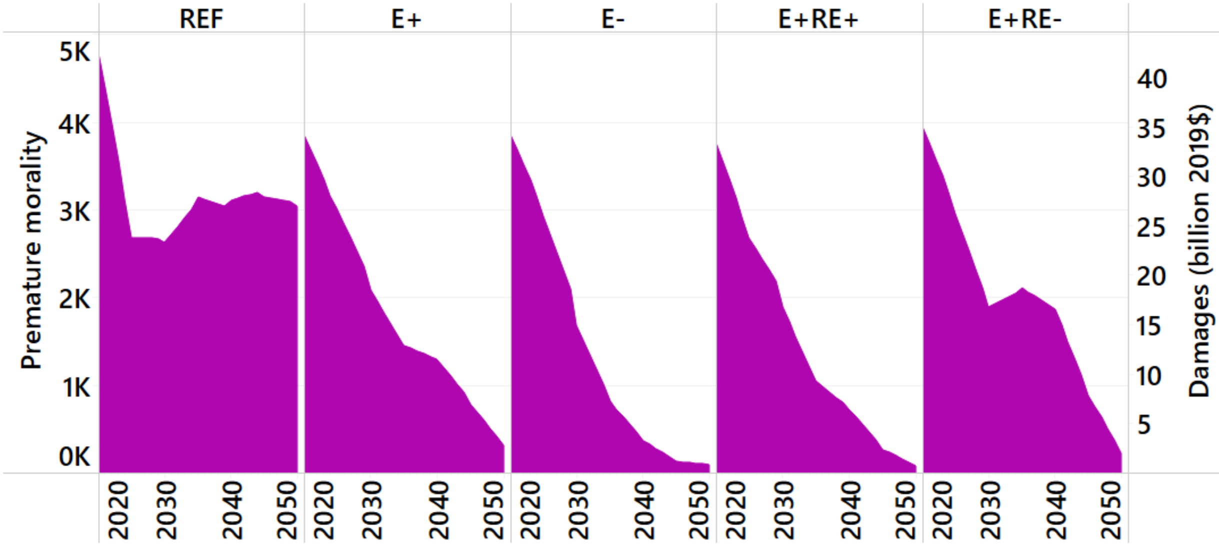


Figure 46. Annual air quality impacts associated with natural gas electric power generation by scenario.

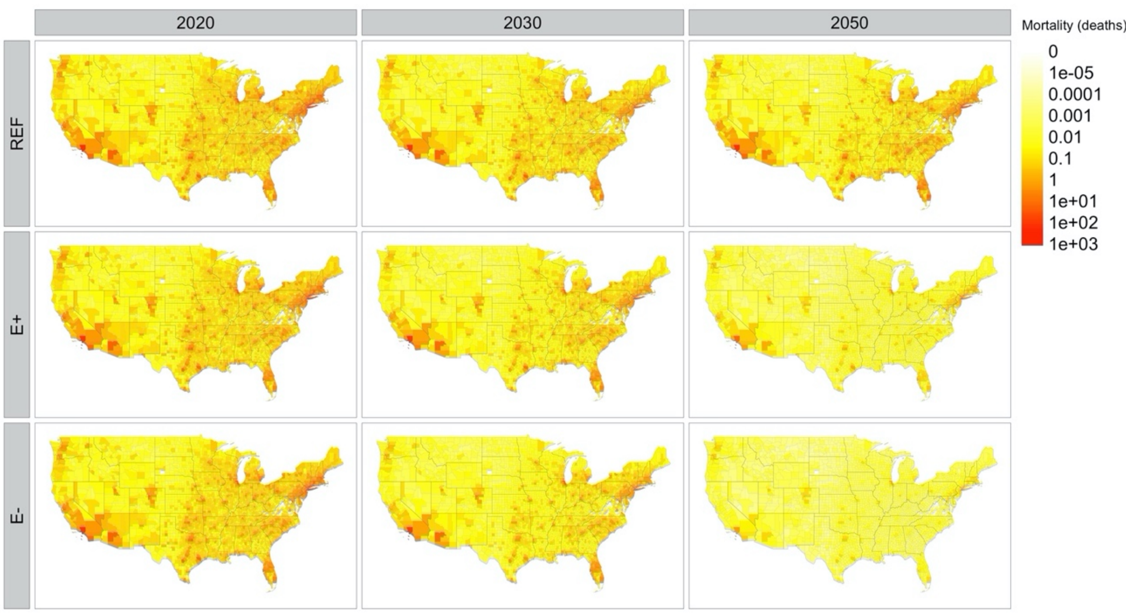


Figure 47. Annual, county-level premature mortality associated with natural gas electric power generation by scenario.

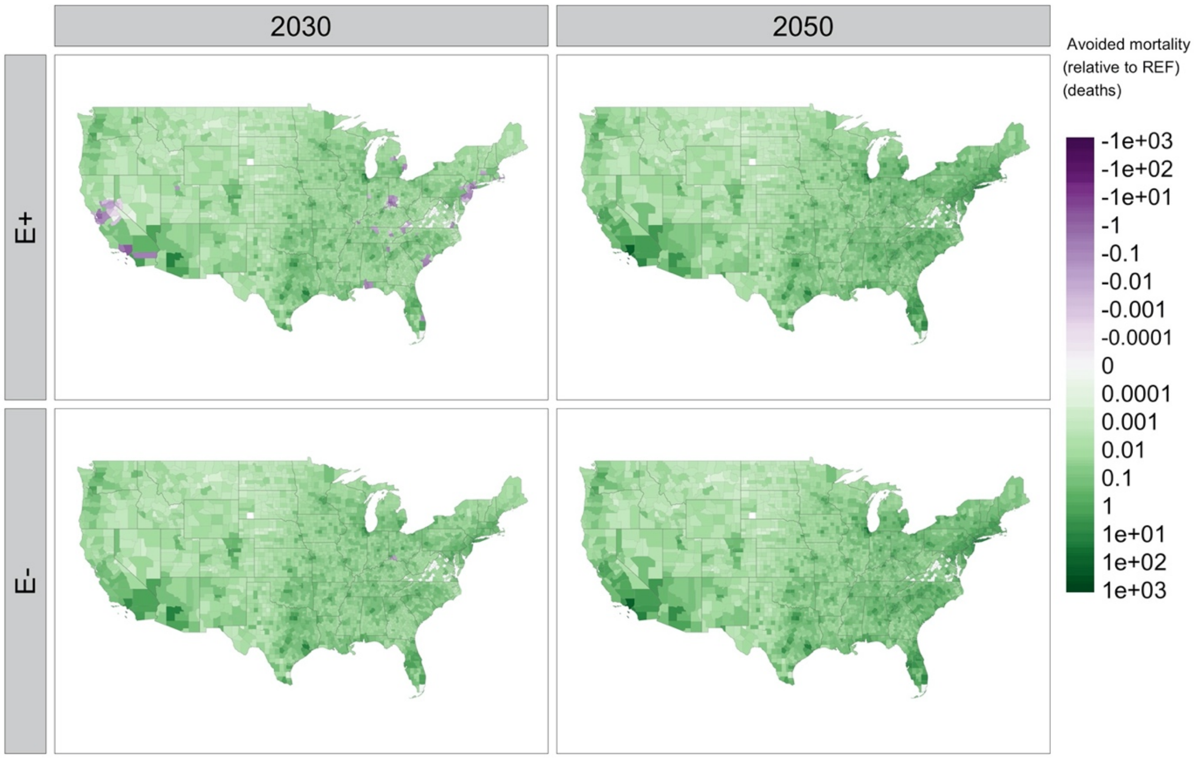


Figure 48. Annual, county-level avoided premature mortality associated with natural gas electric power generation by scenario. Avoided premature mortality is estimated as premature mortality in the reference scenario minus the net-zero scenario.

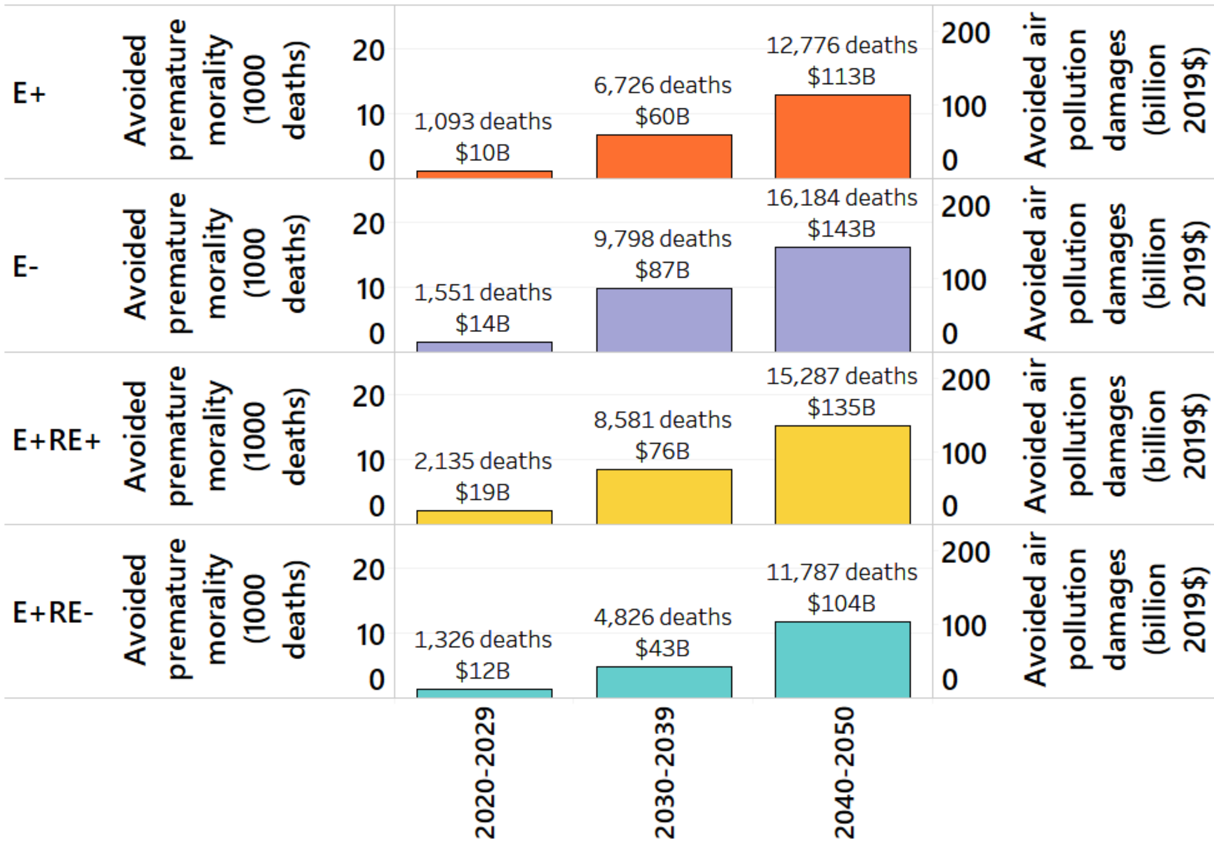


Figure 49. Avoided air quality impacts associated with natural gas electric power generation by scenario and decade. Avoided air quality impacts are estimated as the air pollution impacts in the reference scenario minus the net-zero scenario.

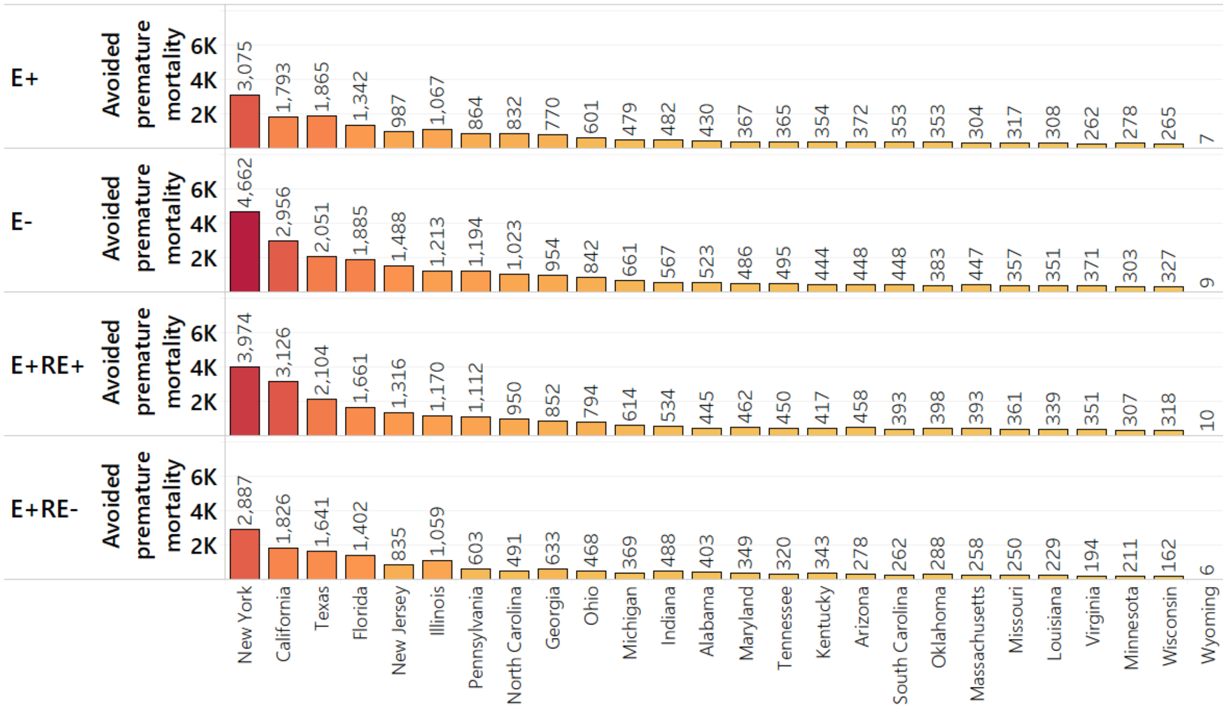


Figure 50. Cumulative avoided premature mortality associated with natural gas electric power generation by state from 2020 to 2050. Includes top 25 states in terms of cumulative avoided premature mortalities.

2.4 Fuel combustion – commercial/institutional

Figure 51 shows annual mortality associated with fuel combustion in the commercial sector, with variation across net-zero scenarios driven by the rate of electrification of heating and cooling demands. Figure 52 and Figure 53 show the spatial distribution of mortality and avoided mortality, with a concentration of impacts in the Northeast and Southwest. As depicted in Figure 54, approximately 350 to 700 mortalities ($3-6 billion in damages) are avoided in the net-zero scenarios (relative to the reference scenario) in the first decade, and approximately 6,600 to 20,700 mortalities ($58-183 billion in damages) are avoided from 2020 to 2050. Figure 55 shows the cumulative avoided mortalities from 2020 to 2050 by state, where upwards of approximately 2,200 to 5,000 mortalities are avoided in California.

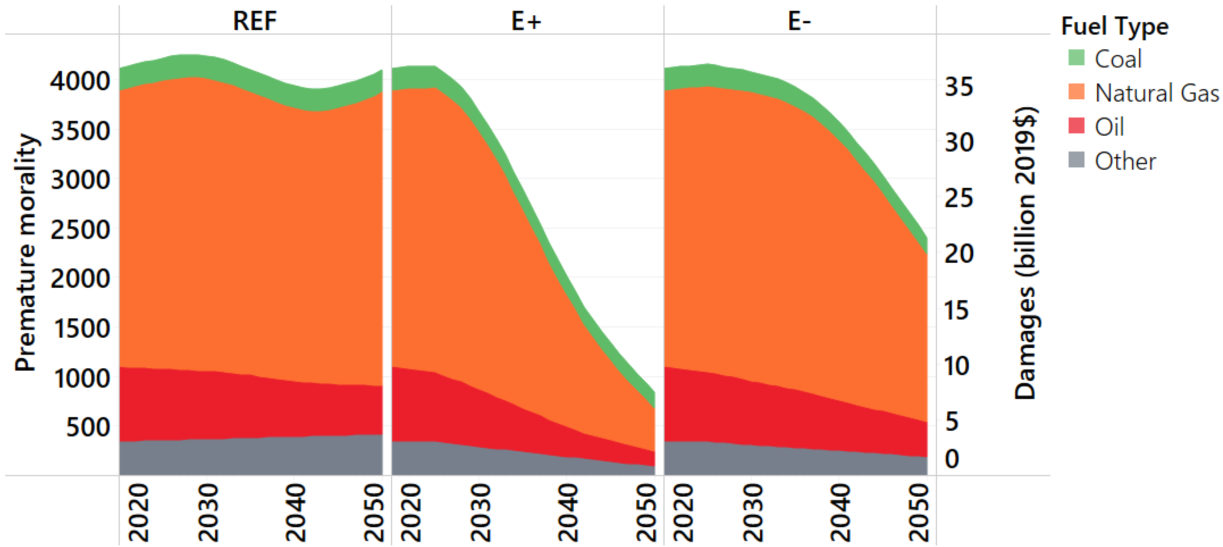


Figure 51. Annual air quality impacts associated with fuel combustion in the commercial sector by scenario and fuel type.

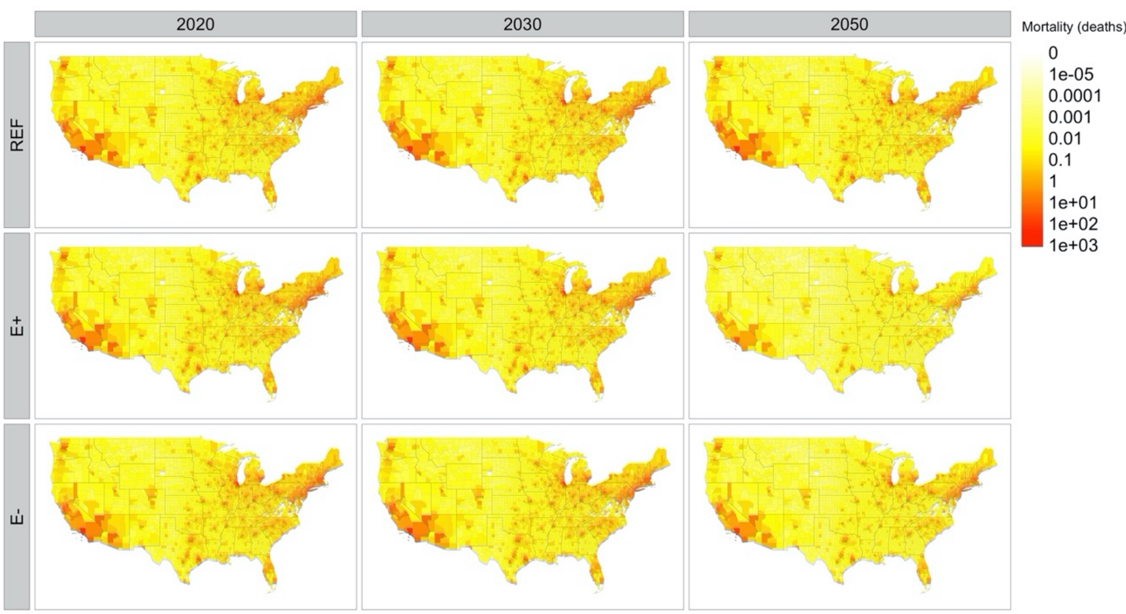


Figure 52. Annual, county-level mortality associated with fuel combustion in the commercial sector by scenario.

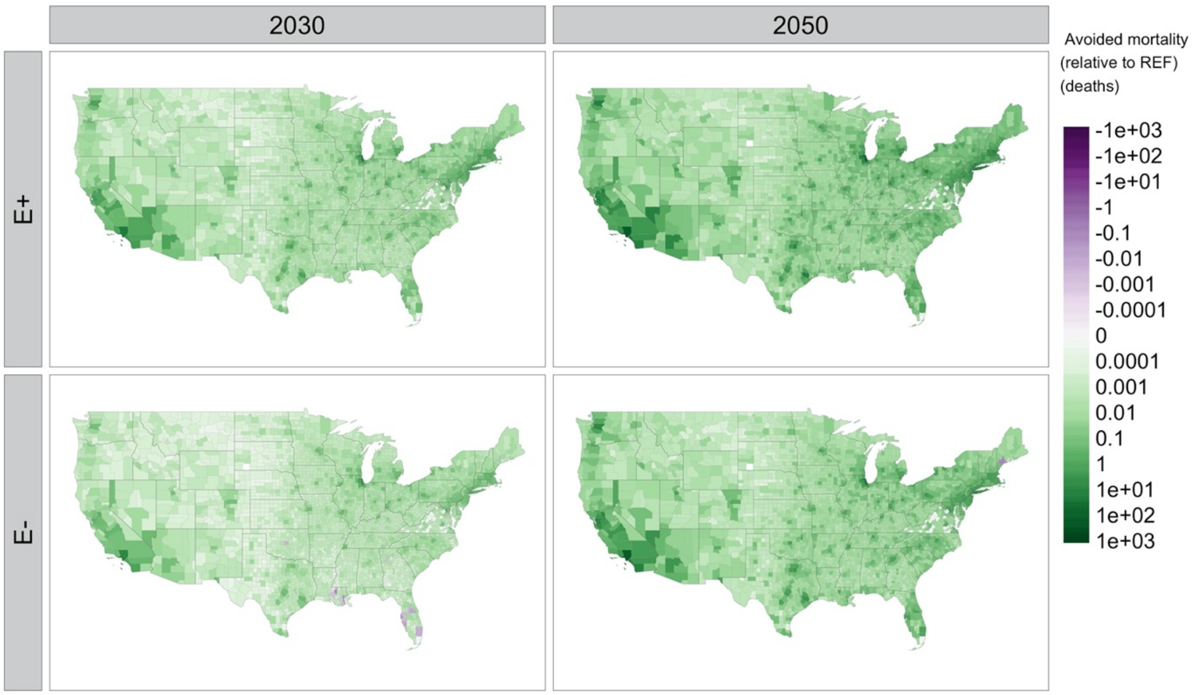


Figure 53. Annual, county-level avoided premature mortality associated with fuel combustion in the commercial sector by scenario. Avoided premature mortality is estimated as premature mortality in the reference scenario minus the net-zero scenario.

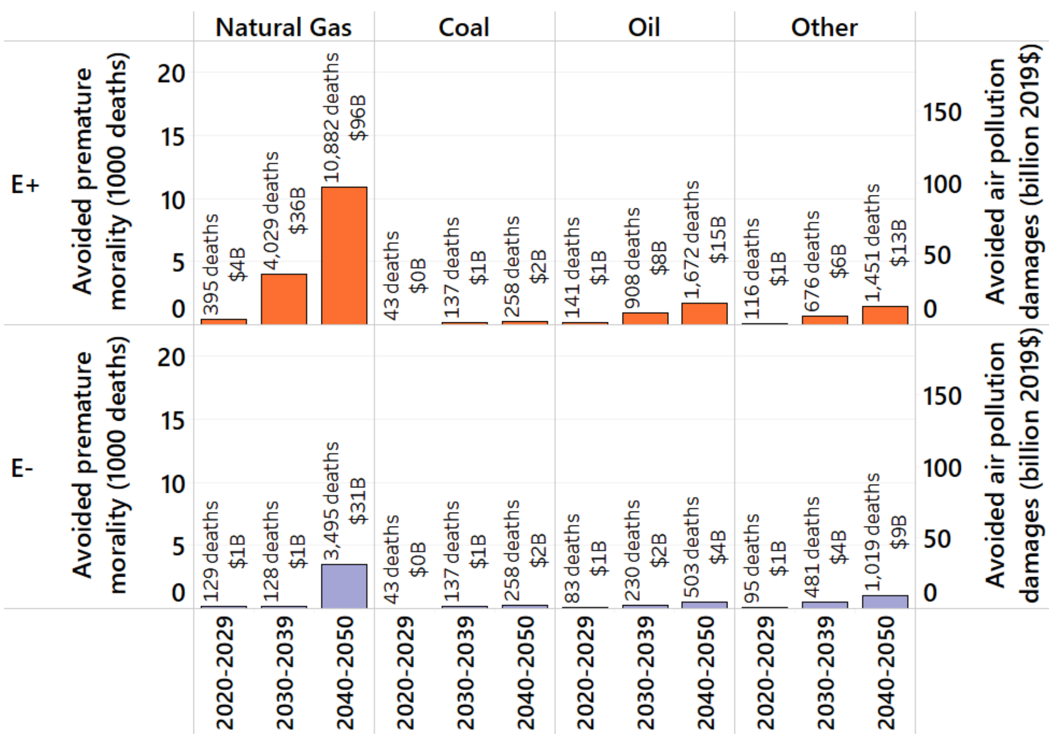


Figure 54. Avoided air quality impacts associated with fuel combustion in the commercial sector by scenario, decade, and fuel type. Avoided air quality impacts are estimated as the air pollution impacts in the reference scenario minus the net-zero scenario.

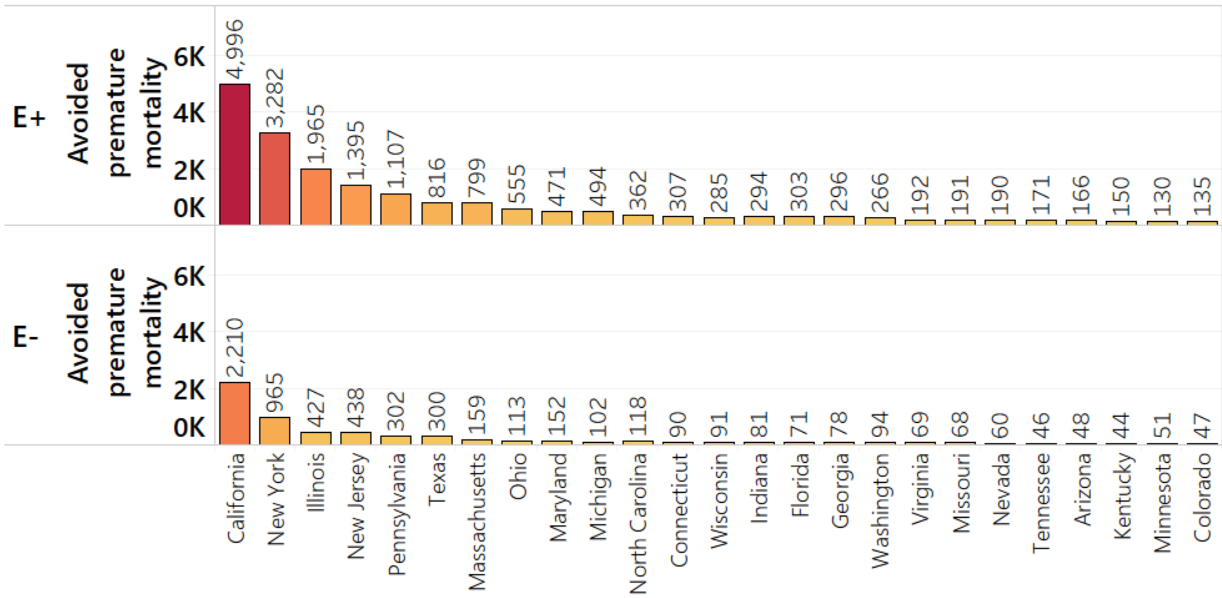


Figure 55. Cumulative avoided premature mortality associated with fuel combustion in the commercial sector by state from 2020 to 2050. Includes top 25 states in terms of cumulative avoided premature mortalities.

2.5 Fuel combustion – residential

Figure 56 shows annual mortality associated with fuel combustion in the residential sector, with variation across net-zero scenarios driven by the rate of electrification of heating and cooling demands that are currently met through gas and oil. Note that we exclude air pollution from wood consumption for residential heating. Figure 57 and Figure 58 show the spatial distribution of mortality and avoided mortality. As depicted in Figure 59, there is no net benefit in the net-zero scenarios (relative to the reference scenario) in the first decade, and approximately 6,200 to 27,700 mortalities ($55-246 billion in damages) are avoided from 2020 to 2050. Figure 60 shows the cumulative avoided mortalities from 2020 to 2050 by state, where upwards of approximately 3,100 to 7,300 mortalities are avoided in California, with a potential net increase in mortalities in some East coast states due to increases in oil consumption.

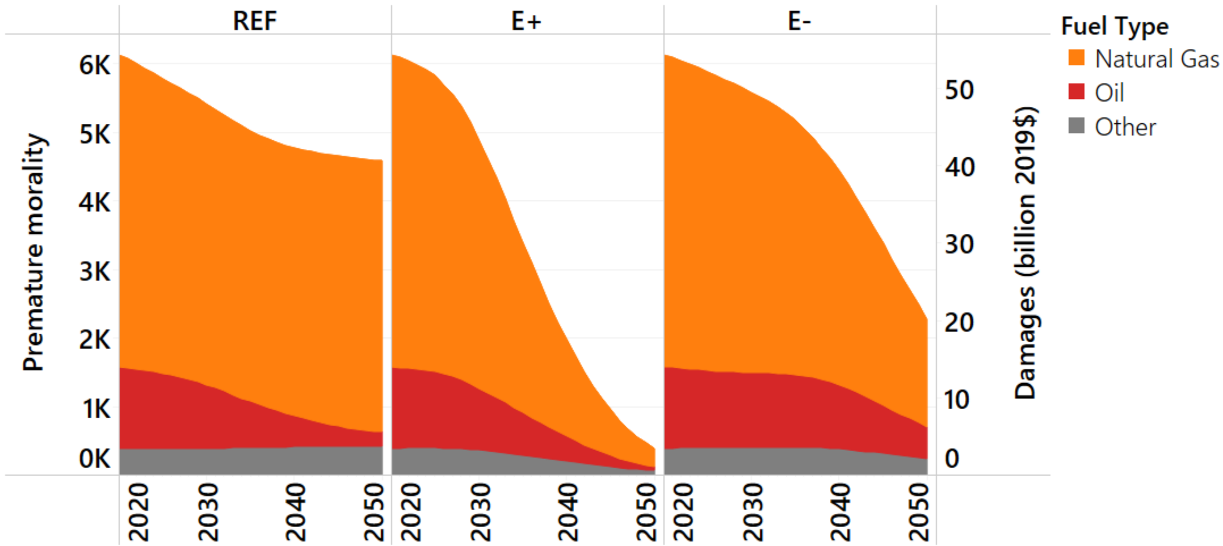


Figure 56. Annual air quality impacts associated with fuel combustion in the residential sector by scenario and fuel type.

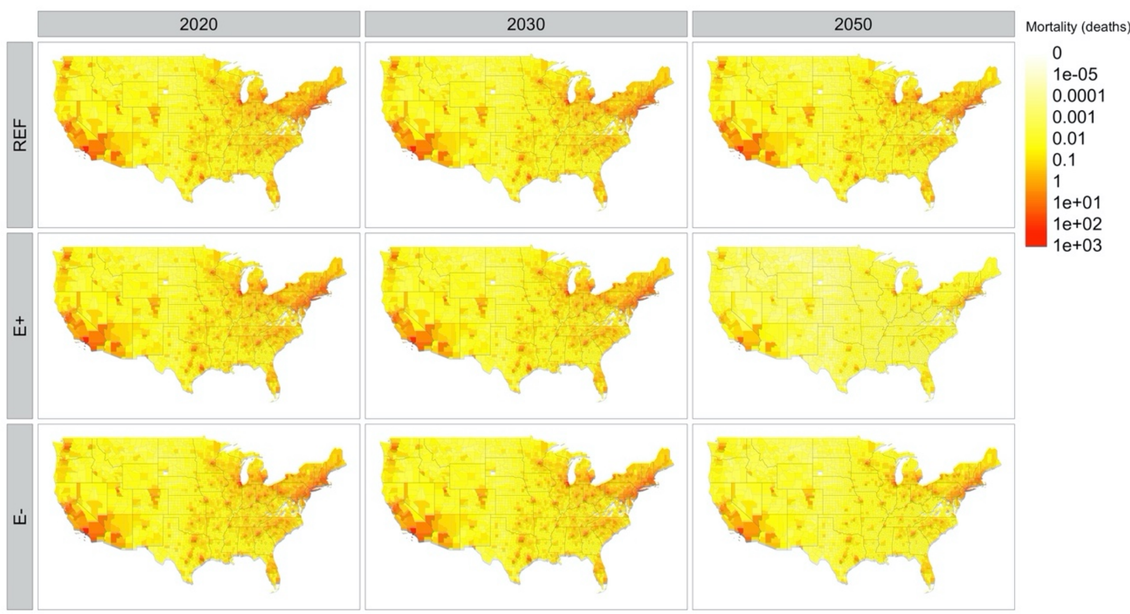


Figure 57. Annual, county-level mortality associated with fuel combustion in the residential sector by scenario.

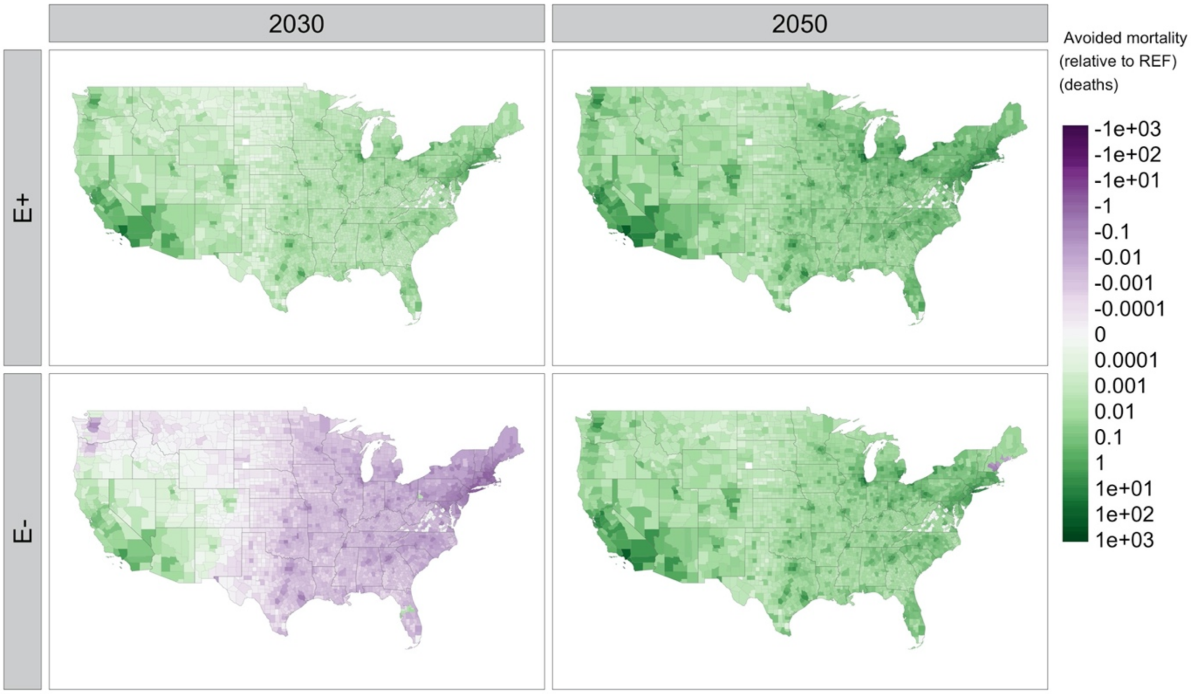


Figure 58. Annual, county-level avoided premature mortality associated with fuel combustion in the residential sector by scenario. Avoided premature mortality is estimated as premature mortality in the reference scenario minus the net-zero scenario.

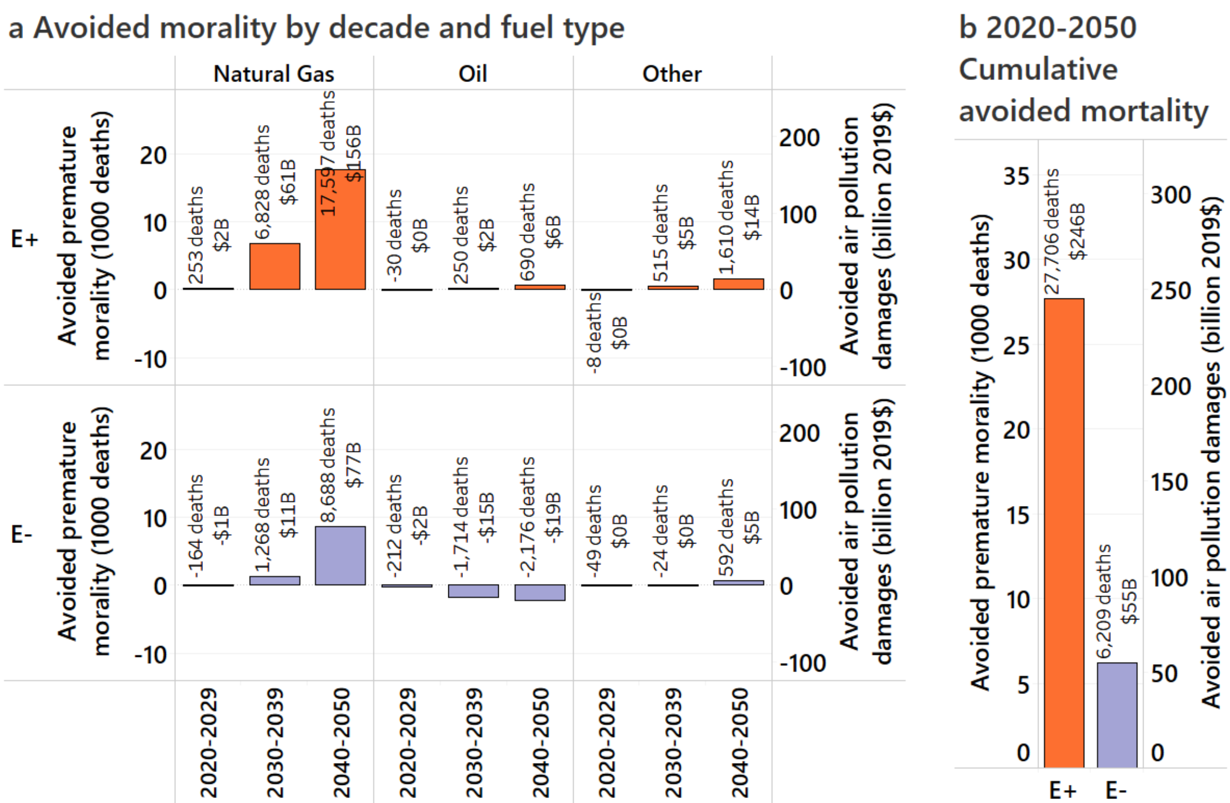


Figure 59. Avoided air quality impacts associated with fuel combustion in the residential sector by scenario, decade, and fuel type. Avoided air quality impacts are estimated as the air pollution impacts in the reference scenario minus the net-zero scenario.

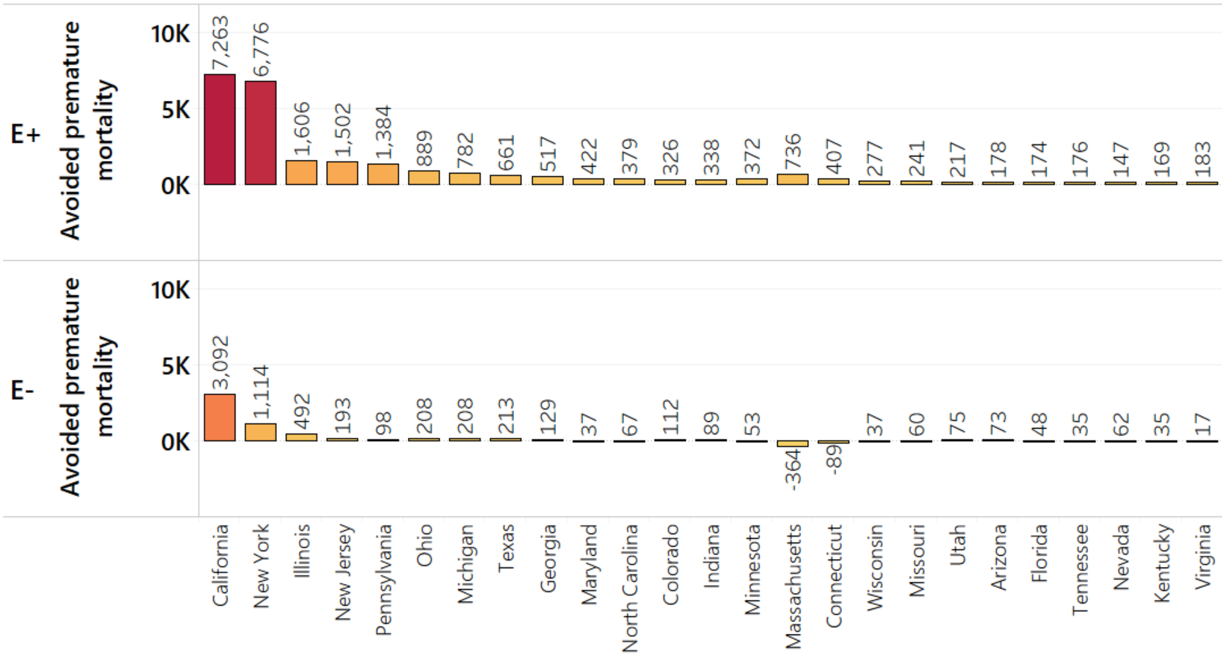


Figure 60. Cumulative avoided premature mortality associated with fuel combustion in the residential sector by state from 2020 to 2050.

2.6 Industrial processes – coal mining

Figure 61 shows annual mortality associated with coal mining, which declines substantially in both the reference and net-zero scenarios. Figure 62 and Figure 63 show the spatial distribution of mortality and avoided mortality, with a concentration of residual impacts by 2050 in the Appalachian basin where there is continued mining of metallurgical coal to meet domestic and export demand. As depicted in Figure 64, approximately 500 mortalities ($4 billion in damages) are avoided in the net-zero scenarios (relative to the reference scenario) in the first decade, and approximately 1,500 mortalities ($14 billion in damages) are avoided from 2020 to 2050. Figure 65 shows the cumulative avoided mortalities from 2020 to 2050 by state, where upwards of approximately 190 mortalities are avoided in California.

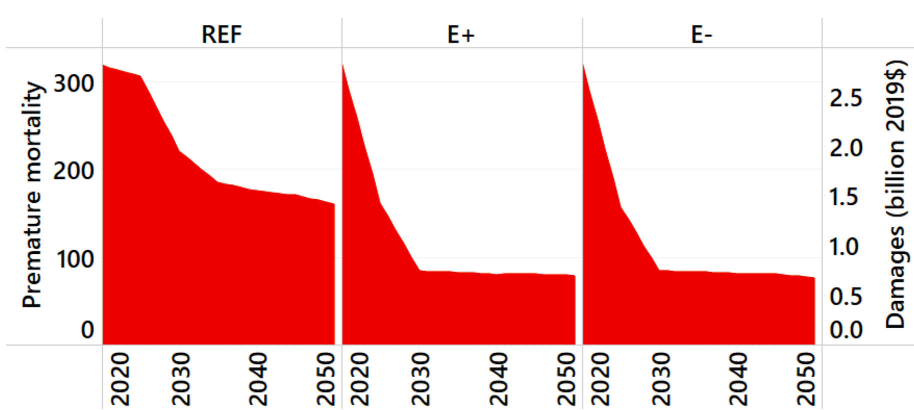


Figure 61. Annual air quality impacts associated with coal mining by scenario.

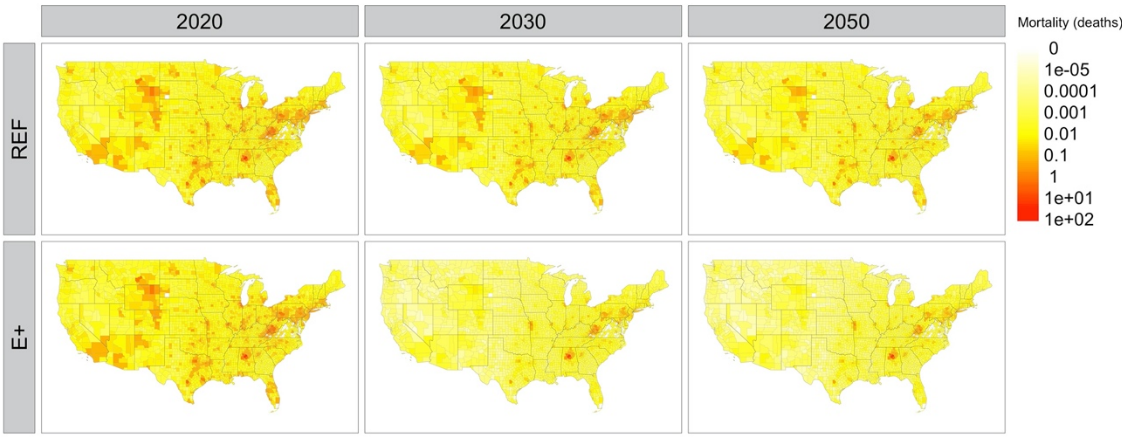


Figure 62. Annual, county-level air quality mortality associated with coal mining by scenario.

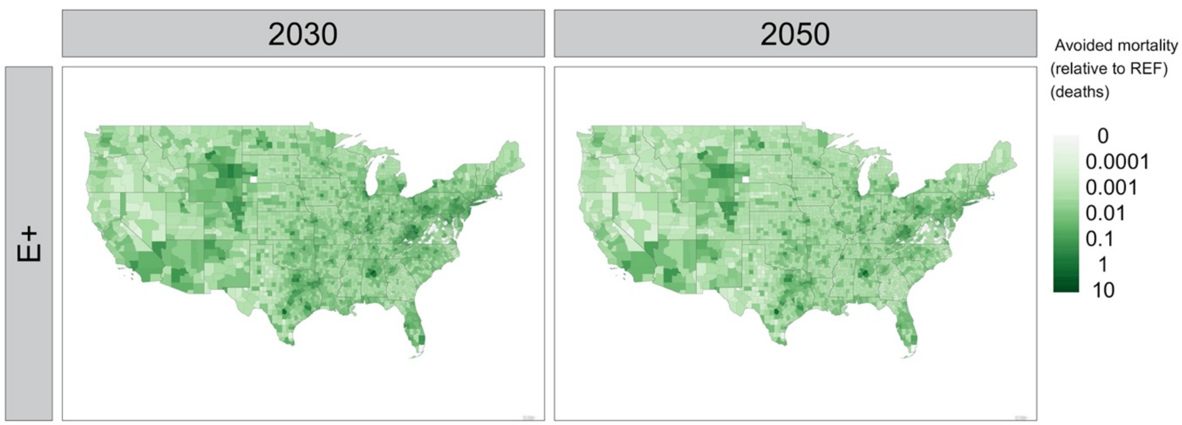


Figure 63. Annual, county-level air quality avoided premature mortality associated with coal mining by scenario. Avoided premature mortality is estimated as premature mortality in the reference scenario minus the net-zero scenario.

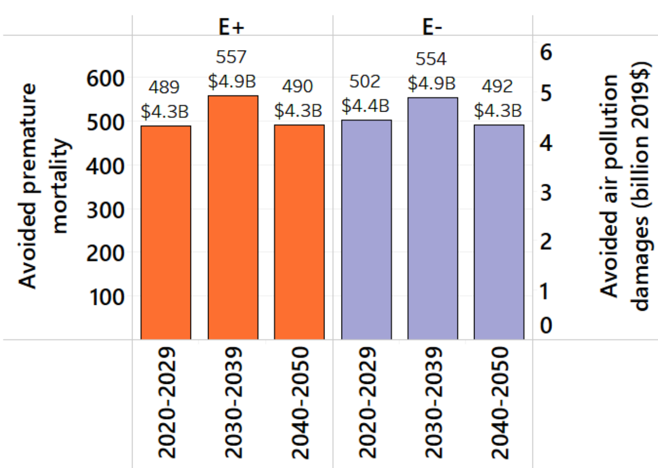


Figure 64. Avoided air quality impacts associated with coal mining by scenario and decade. Avoided air quality impacts are estimated as the air pollution impacts in the reference scenario minus the net-zero scenario.

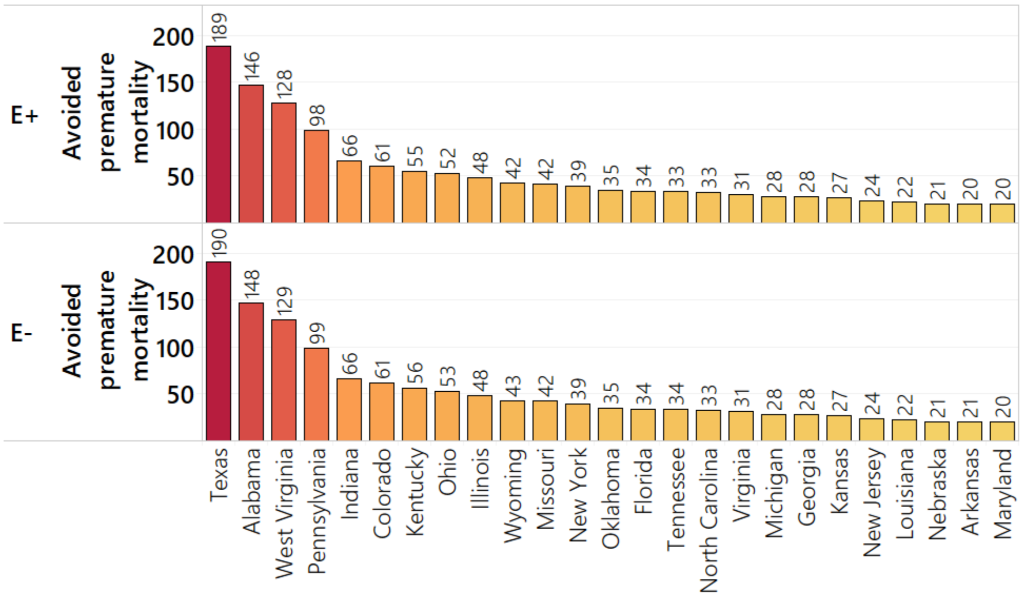


Figure 65. Cumulative avoided premature mortality associated with coal mining by state from 2020 to 2050. Includes top 25 states in terms of cumulative avoided premature mortalities.

2.7 Industrial processes – oil & gas production

Figure 66 shows annual mortality associated with oil and gas production, with variation across net-zero scenarios driven by the rate of electrification, constraints on renewables deployment, and imports and exports. Air pollution impacts decline substantially across all net-zero scenarios, as oil and gas production decline due to declining demand for transportation, electric power generation, and residential, commercial, and industrial heating and processes. Figure 67 and Figure 68 show the spatial distribution of mortality and avoided mortality, which are distributed across the US at present. As depicted in Figure 69, approximately 500 to 1,600 mortalities ($4-14 billion in damages) are avoided in the net-zero scenarios (relative to the reference scenario) in the first decade largely associated with declining natural gas production, and approximately 21,700 to 44,500 mortalities ($193-395 billion in damages) are avoided from 2020 to 2050. Figure 70 shows the cumulative avoided mortalities from 2020 to 2050 by state, where upwards of approximately 4,400 to 8,800 mortalities are avoided in Texas where there is substantial oil and gas production.

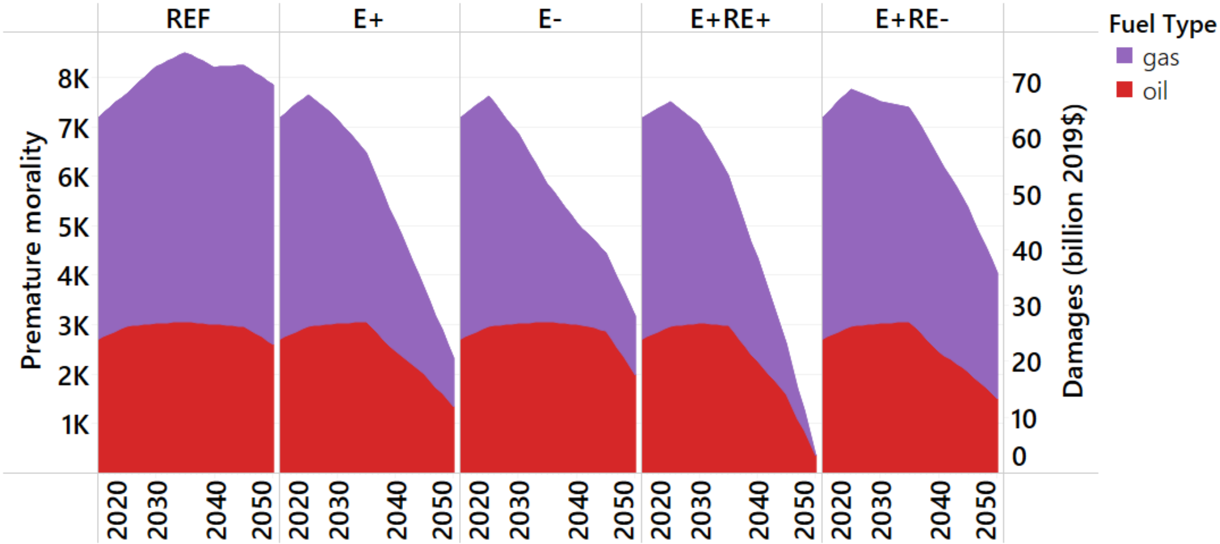


Figure 66. Annual air quality impacts associated with oil & gas production by scenario.

Figure 67. Annual, county-level premature morality associated with oil & gas production by scenario.

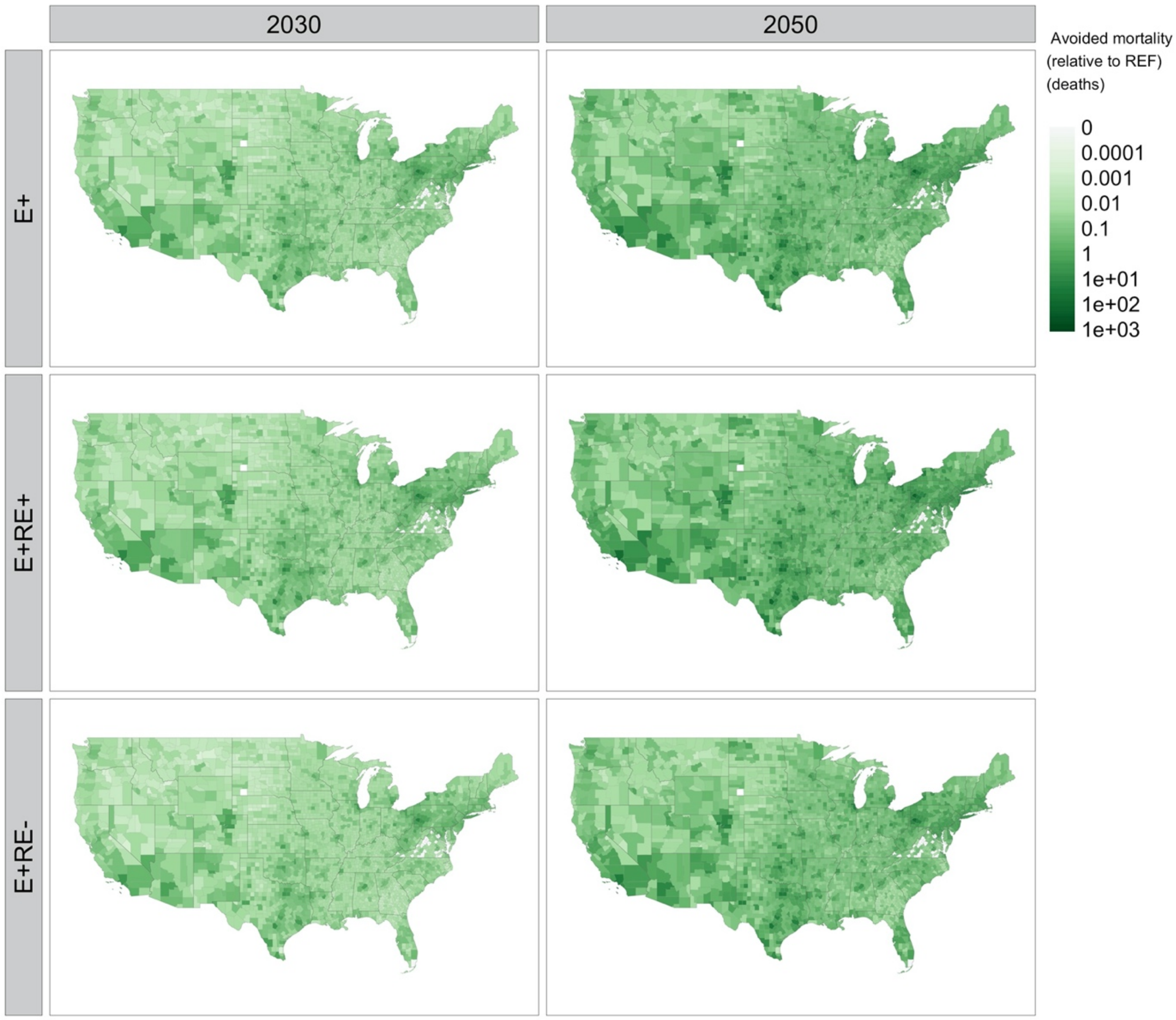


Figure 68. Annual, county-level avoided premature mortality associated with oil & gas production by scenario. Avoided premature mortality is estimated as premature mortality in the reference scenario minus the net-zero scenario.

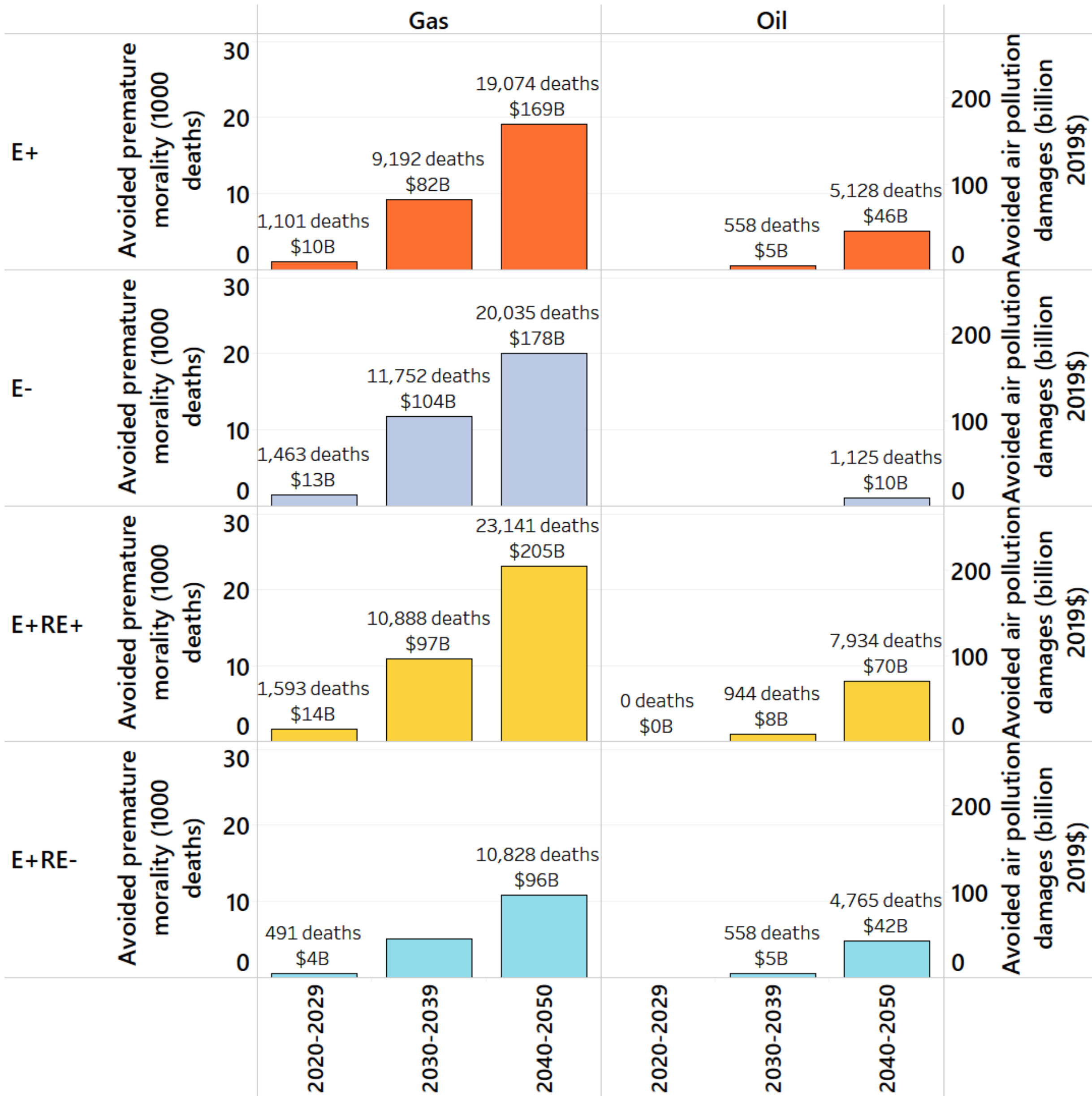


Figure 69. Avoided air quality impacts associated with oil & gas production by scenario and decade. Avoided air quality impacts are estimated as the air pollution impacts in the reference scenario minus the net-zero scenario.

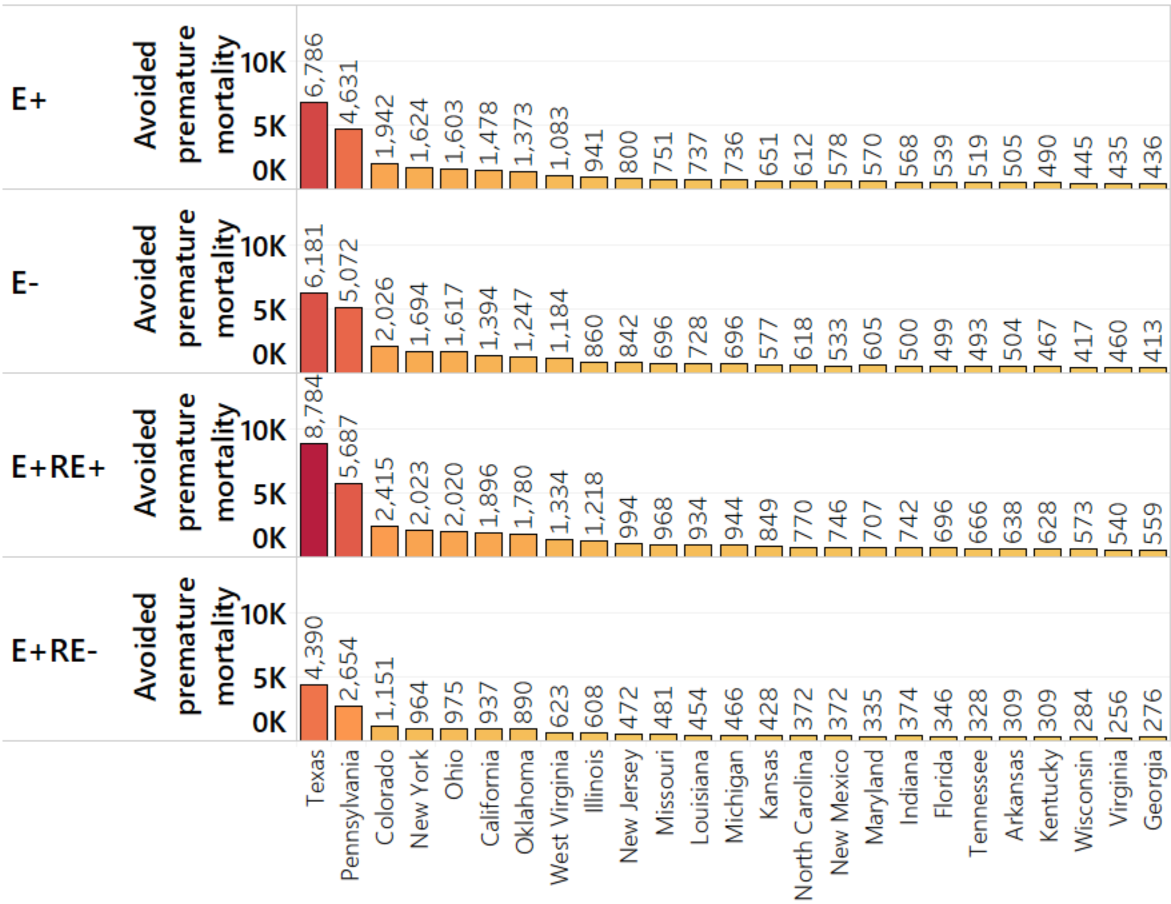


Figure 70. Cumulative avoided premature mortality associated with oil & gas production by state from 2020 to 2050. Includes top 25 states in terms of cumulative avoided premature mortalities.

2.8 Mobile – on-road vehicles

Figure 71 shows annual mortality associated with on-road vehicles (including light duty autos, light duty trucks, medium duty vehicles, heavy duty vehicles, and buses), with variation across net-zero scenarios driven by the rate of electrification. Figure 72 and Figure 73 show the spatial distribution of mortality and avoided mortality, with a concentration of impacts in more populated areas of the US where there is more traffic. As depicted in Figure 74, minimal net air quality benefit in the net-zero scenarios (relative to the reference scenario) in the first decade, and approximately 64,000 to 167,000 mortalities ($570-1,490 billion in damages) are avoided from 2020 to 2050. Figure 39 shows the cumulative avoided mortalities from 2020 to 2050 by state, where upwards of approximately 20,000 to 152,000 mortalities are avoided in California.

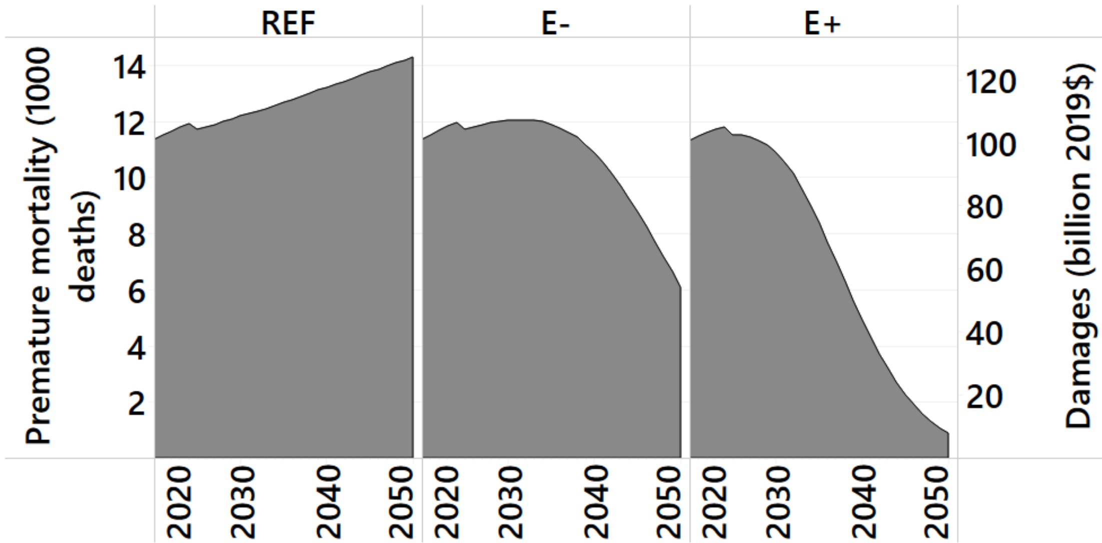


Figure 71. Annual air quality impacts associated with on-road vehicles by scenario.

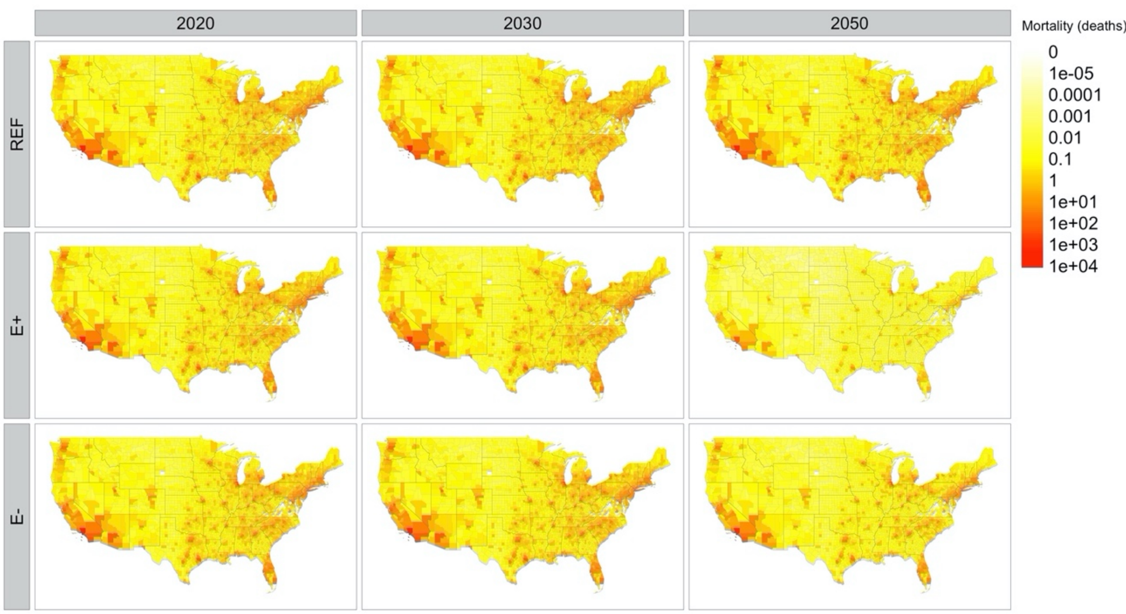


Figure 72. Annual, county-level mortality associated with on-road vehicles by scenario.

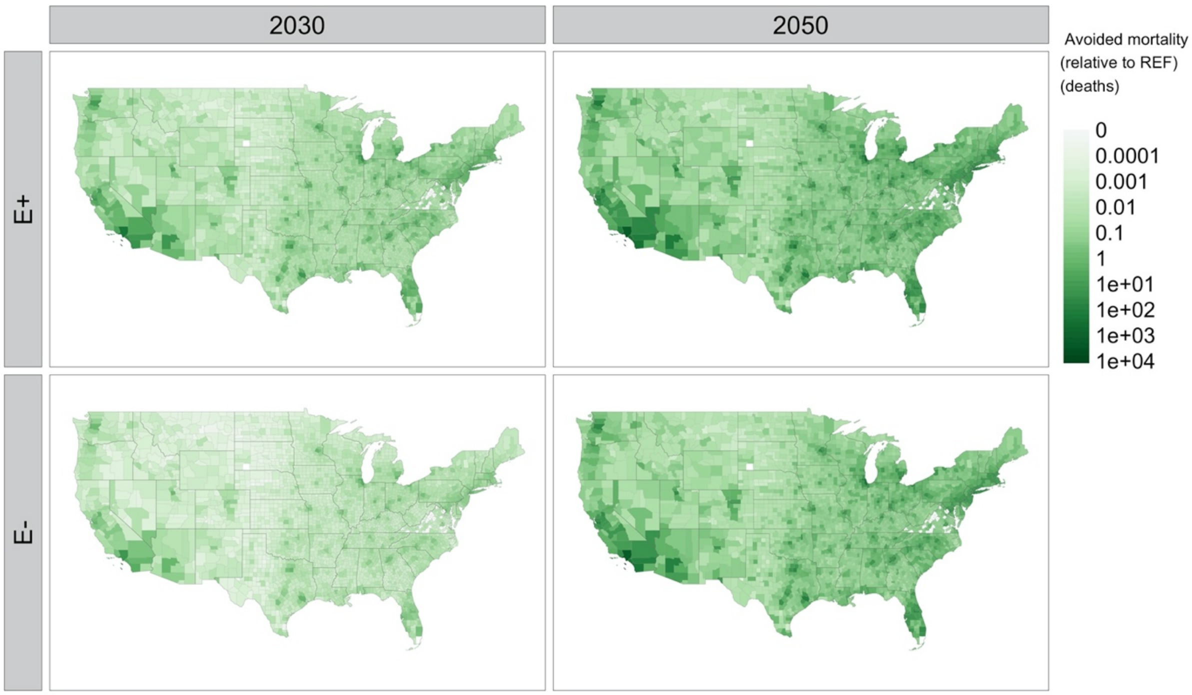


Figure 73. Annual, county-level avoided premature mortality associated with on-road vehicles by scenario. Avoided premature mortality is estimated as premature mortality in the reference scenario minus the net-zero scenario.

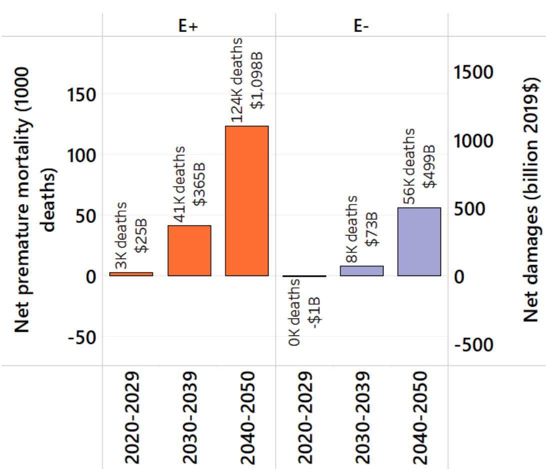


Figure 74. Avoided air quality impacts associated with on-road vehicles by scenario and decade. Avoided air quality impacts are estimated as the air pollution impacts in the reference scenario minus the net-zero scenario.

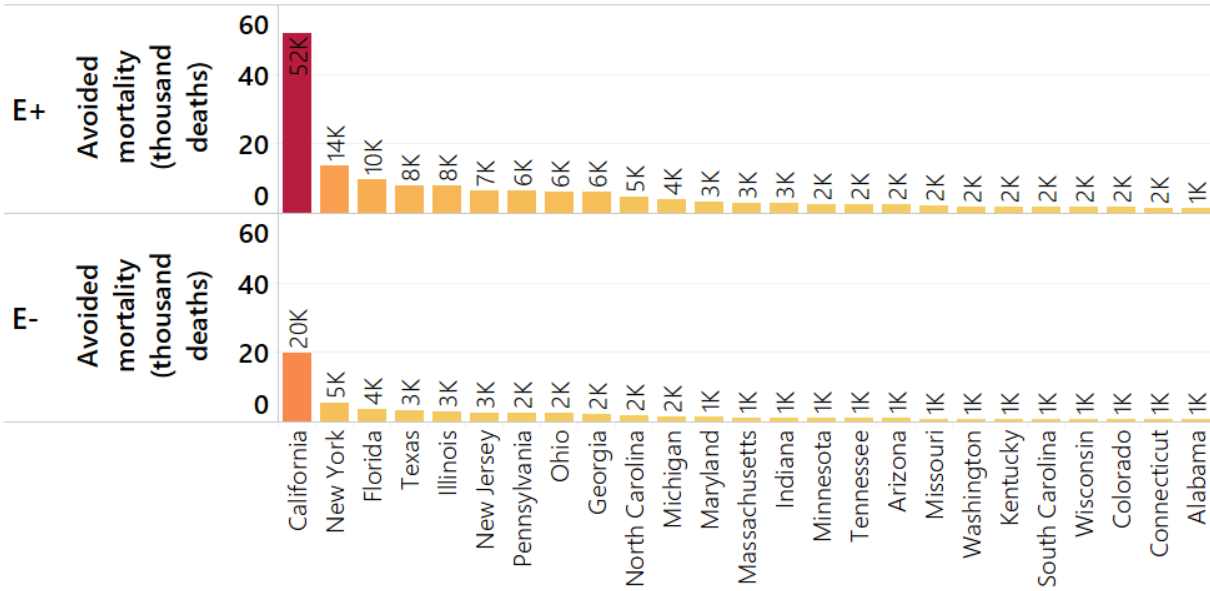


Figure 75. Cumulative avoided premature mortality associated with on-road vehicles by state from 2020 to 2050. Includes top 25 states in terms of cumulative avoided premature mortalities.

2.9 Miscellaneous source categories

Figure 76 shows annual mortality associated with commercial cooking where variation across demand scenarios is driven by the rate of electrification of cooking demands, and gas stations where the variation across demand scenarios is driven by the rate of electrification in the transport sector. Figure 77 and Figure 78 show the spatial distribution of mortality and avoided mortality, which are distributed across the Eastern US and Southwest. As depicted in Figure 79, approximately 700 to 4,500 mortalities ($6-40 billion in damages) associated with commercial cooking are avoided in the net-zero scenarios (relative to the reference scenario) in the first decade, and approximately 65,000 to 129,400 mortalities ($576-1,146 billion in damages) are avoided from 2020 to 2050. Few mortalities associated with gas station emissions are avoided in the net-zero scenarios in the first decade, and approximately 3,600 to 9,400 mortalities ($32-83 billion in damages) are avoided from 2020 to 2050. Figure 80 shows the cumulative avoided mortalities from 2020 to 2050 by state, where upwards of approximately 300 to 800 mortalities associated with gas stations and 14,700 to 28,900 mortalities associated with commercial cooking are avoided in New York.

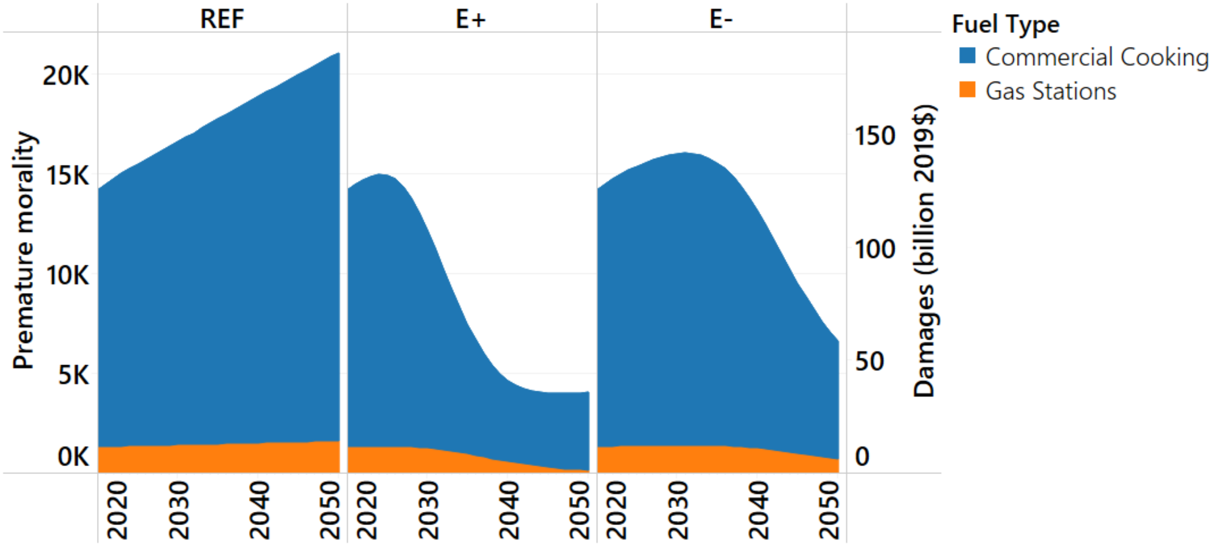


Figure 76. Annual air quality impacts associated with miscellaneous source emissions categories by scenario and source.

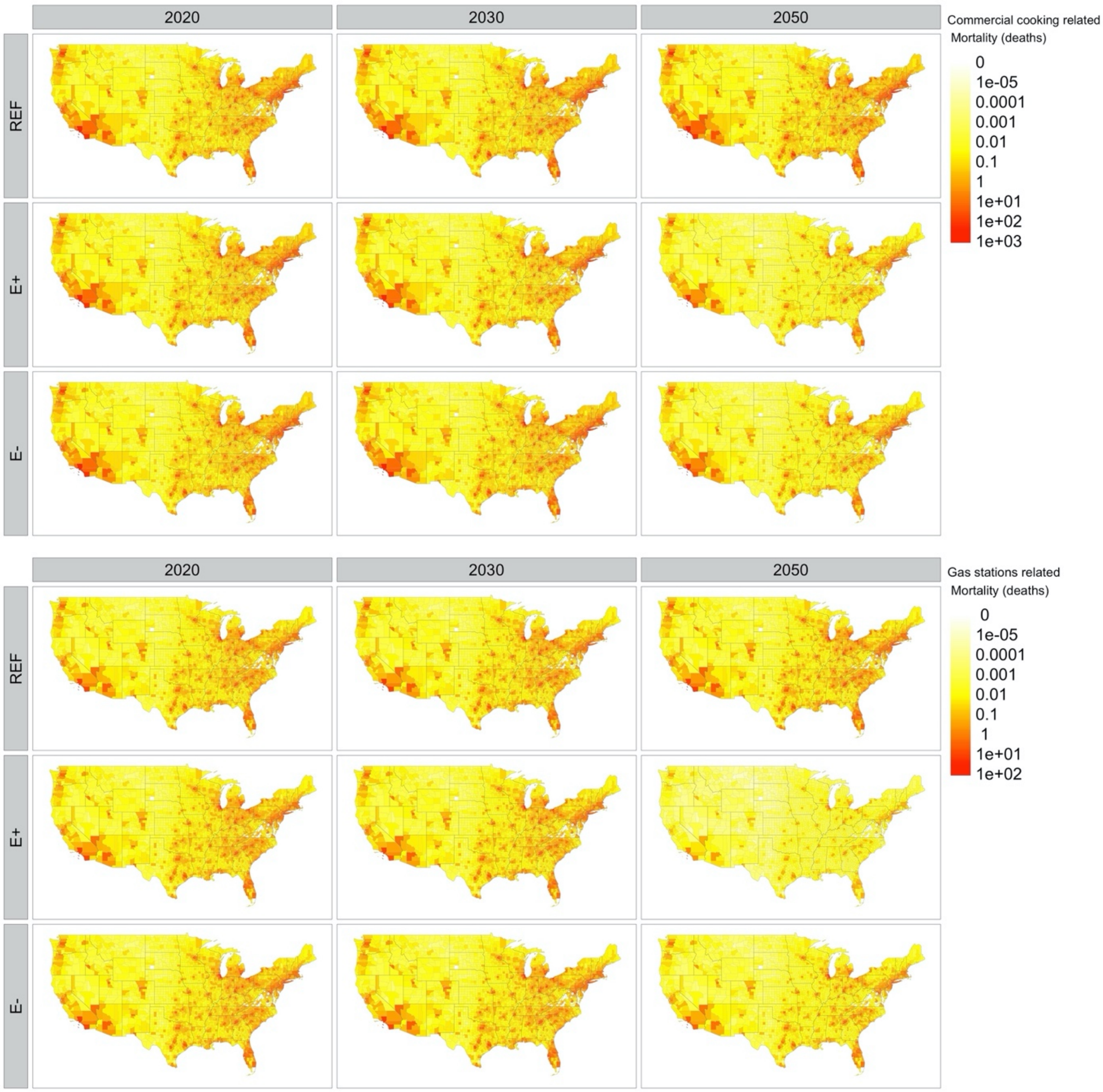


Figure 77. Annual, county-level premature mortality associated miscellaneous source emissions categories by scenario and source.

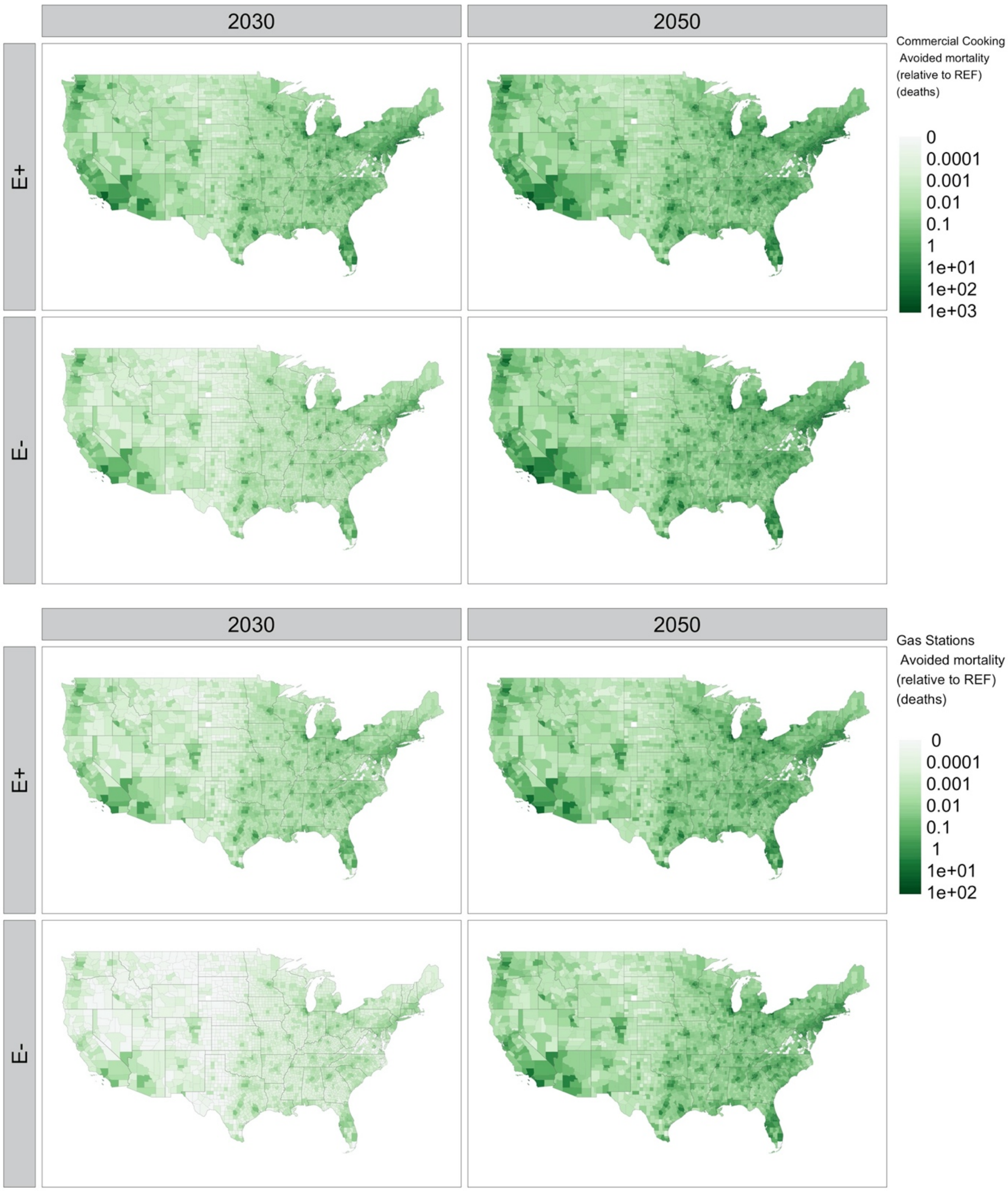


Figure 78. Annual, county-level avoided premature mortality associated miscellaneous source emissions categories by scenario and source. Avoided premature mortality is estimated as premature mortality in the reference scenario minus the net-zero scenario.

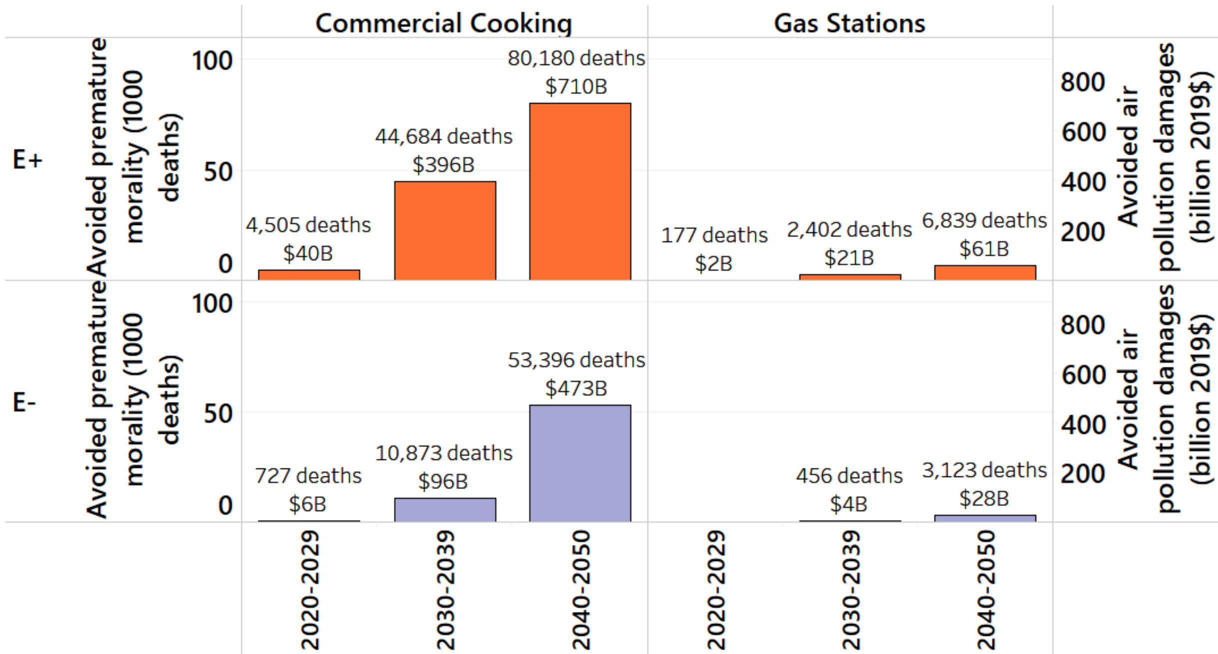


Figure 79. Avoided air quality impacts associated with miscellaneous source emissions categories by scenario, decade, and source. Avoided air quality impacts are estimated as the air pollution impacts in the reference scenario minus the net-zero scenario.

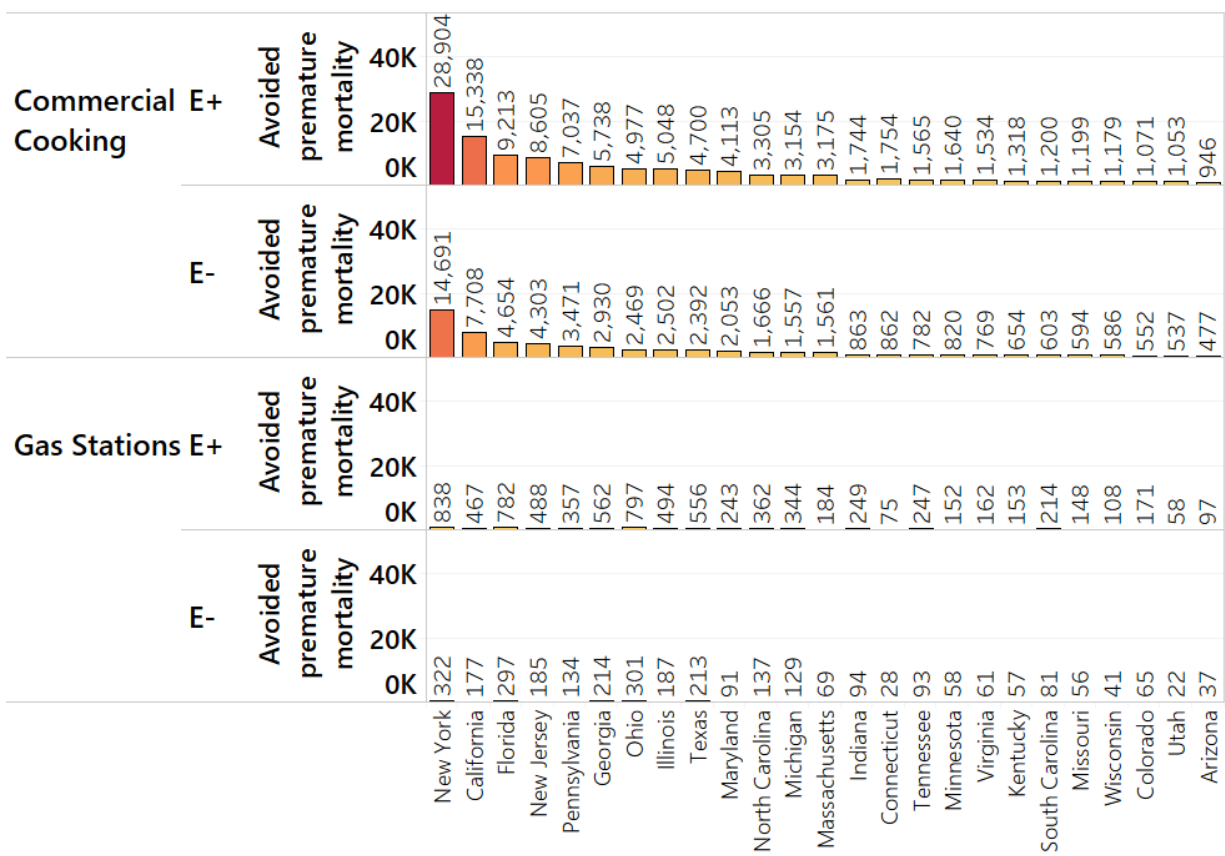


Figure 80. Cumulative avoided premature mortality associated with miscellaneous source emissions categories by state from 2020 to 2050. Includes top 25 states in terms of cumulative avoided premature mortalities.

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