Residential Building Electrification in the Northeast and Mid-Atlantic:

Criteria Pollutant and Greenhouse Gas Reduction Potential

Prepared by the Northeast States for Coordinated Air Use Management (NESCAUM)
and the Ozone Transport Commission (OTC)

Updated March 2025

Summary of Report Versions and Updates

Publication Date	Changes Made
August 25, 2023	N/A
March 3, 2025	• Minor edits to text to clarify which National Renewable Energy Laboratory (NREL) ResStock scenarios were used in the analysis. • Added volatile organic compound emissions to the analysis for both on-site fuel combustion and electricity generation-related emissions. • Updated the charts showing regional carbon dioxide and nitrogen oxides emissions by sector. • Updated the National Ambient Air Quality Standards attainment status for metropolitan areas in the region. • Updated the references for the health and environmental effects of nitrogen oxides and fine particulate matter. • Updated the summary of state buildings policies and greenhouse gas emission reduction targets. • Updated the on-site combustion emission factors for criteria pollutants using the U.S. Environmental Protection Agency's (EPA) 2020 National Emissions Inventory emission factors. • Updated electricity generation-related emissions using EPA's eGrid and the NREL's "Standard Scenarios."

Contents

Tables

Figures

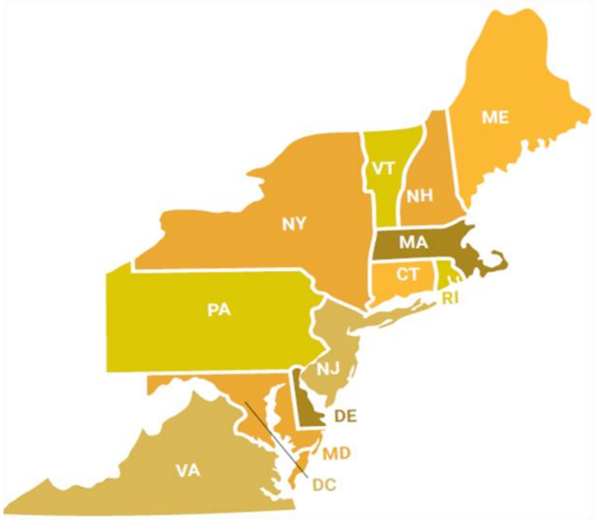
Acronyms

ACCA	Air Conditioning Contractors of America
ANSI	American National Standards Institute
AQMD	Air Quality Management District
BPS	Building performance standards
Btu	British thermal units
CARB	California Air Resources Board
CH_4	methane
CHS	clean heat standard
CO_2	carbon dioxide
EF	emission factor
eGRID	Emissions and Generation Resource Integrated Database
EMF	Emissions Modeling Framework
EPA	U.S. Environmental Protection Agency
EUI	energy use intensity
Gal	gallons
GHG	greenhouse gas
HFCs	hydrofluorocarbons
HSPF	Heating Seasonal Performance Factor
HVAC	heating, ventilation, and air conditioning
IIJA	Infrastructure Investment and Jobs Act
IMPROVE	Interagency Monitoring of Protected Visual Environments
IRA	Inflation Reduction Act
ISO NE	Independent System Operator New England
kWh	kilowatt hour
lbs/MWh	pounds per megawatt hour
LMU	locational marginal unit
LPG	liquified petroleum gas
MMBtu	million Btu
MMcf	million cubic feet
NAAQS	National Ambient Air Quality Standard
N_2O	nitrous oxide
NO_x	nitrogen oxides
NEI	National Emissions Inventory
NESCAUM	Northeast States for Coordinated Air Use Management
NPCC	Northeast Power Coordinating Council
NREL	National Renewable Energy Laboratory
NYCW	New York City/ Westchester
NYLI	NPCC Long Island
NYSERDA	New York State Energy Research and Development Authority
NYUP	NPCC Upstate NY
OTC	Ozone Transport Commission
$PM_{2.5}$	fine particulate matter

PUC	Public Utility Commission
RAP	Regulatory Assistance Project
RFCE	RFC East/Eastern Power Grid
RFCW	RFC West
SCC	Source Classification Code
SEER	Seasonal Energy Efficiency Ratio
SIP	State Implementation Plan
SO_2	sulfur dioxide
SRVC	SWERC Virginia/Carolina/Eastern Power Grid
TBtu	trillion Btu
UEF	uniform energy factor
VOCs	volatile organic compounds
VSHP	variable speed heat pump

1. Introduction

Geographic Area of NESCAUM and OTC Analysis



This report summarizes findings from an analysis of changes in emissions of nitrogen oxides (NO_x), fine particulate matter ($PM_{2.5}$), carbon dioxide (CO_2), volatile organic compounds (VOCs), and sulfur dioxide (SO_2) that could result from efficient residential building electrification in the Northeast and Mid-Atlantic. Efficient residential building electrification is the replacement of fossil fuel-fired furnaces, boilers, water heaters, clothes dryers, and cooking appliances with energy-efficient heat pumps and electric cooking in residential buildings. In this analysis, efficient electrification also assumes that electric resistance space heating and water heating and central and window air conditioning are converted to heat pumps. This analysis was conducted by the Northeast States for Coordinated Air Use Management (NESCAUM)[1] and the Ozone Transport Commission (OTC)[2] for the states[3] that are members of NESCAUM and the OTC: Connecticut, Delaware, the District of Columbia, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Pennsylvania, Rhode Island, Vermont, and Virginia.[4]

This study is a follow-on analysis to a 2021 pilot conducted by NESCAUM and OTC for the state of Connecticut to assess the use of the National Renewable Energy Laboratory (NREL) ResStock tool.[5] As in the 2021 pilot, NESCAUM and OTC have relied in part on the NREL ResStock tool to complete this study. ResStock evaluates changes in energy consumption resulting from the conversion of natural gas, fuel oil, and propane-fueled appliances, as well as electric resistance space heating, window and central air conditioning to heat pumps and electric cooking. ResStock does not evaluate energy consumption for coal or biomass-fueled appliances or the impacts from hydrofluorocarbons (HFCs) used in heat pumps and air conditioners. This analysis also does not assess the impacts of a changing climate, such as hotter summers with greater demand for cooling or warmer winters with lower demand for heating.

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[1] NESCAUM is the regional nonprofit association of state air quality agencies in Connecticut, Maine, Massachusetts, New Hampshire, New Jersey, New York, Rhode Island, and Vermont.

[2] The OTC was established by Congress in the 1990 Clean Air Act Amendments to address regional ozone pollution affecting the OTC member jurisdictions. In addressing their collective regional ozone problem, the OTC members are responsible for developing and implementing initiatives to reduce NO_x and VOCs, the emitted precursor air pollutants that contribute to the formation of ground-level ozone pollution.

[3] This report uses the term "state" to refer to states and the District of Columbia.

[4] A limited number of Maine and Virginia counties are in the Ozone Transport Region (OTR) and the remainder are outside the OTR. In this report, however, all counties in Maine and Virginia are included in the analysis.

[5] NESCAUM and OTC, "Estimating the Emissions Benefits of Switching to Heat Pumps for Residential Heating," June 21, 2021, *see* https://otcair.org/upload/Documents/Reports/nescaum-otc-emission-reduction-analysis-for-residential-heating-202106.pdf.

Section 2 of this report provides background information on building emissions, the need for criteria pollutant and greenhouse gas (GHG) emission reductions, and policy drivers for emissions reductions in the building sector. Section 3 reviews the methods used in the study. Section 4 summarizes the results of the analysis, and Section 5 provides conclusions and areas for further research.

2. Background

Fuel combustion in residential water heaters, furnaces, boilers, clothes dryers, and stoves and ovens produces emissions of NO_x, VOCs, $PM_{2.5}$, SO_2, methane (CH_4), nitrous oxide (N_2O), CO_2, and hazardous air pollutants, such as benzene, formaldehyde, and toluene.[6,7] These emissions adversely affect public health and air quality and contribute to climate change. This analysis evaluates how residential building electrification would affect outdoor air quality and does not assess impacts on indoor air quality. However, studies show that shifting from fuel-burning appliances to heat pumps or, in the case of cooking-related appliances, to induction or electric resistance stoves and ovens would improve indoor air quality.[8,9,10] Additionally, while other pollutants are also emitted from residential fuel combustion, this study is limited to quantifying the impacts from emissions of NO_x, VOCs, $PM_{2.5}$, SO_2, and CO_2.

Criteria Pollutant Emissions

According to EPA's National Emissions Inventory (NEI), onsite fuel combustion in residential buildings was responsible for 10% of total NO_x emissions in the OTC states in 2020.[11] An additional 7% of NO_x emissions resulted from fuel combustion in commercial and institutional buildings such as offices, retail spaces, schools, and government buildings. Figure 1 shows the relative contribution of fuel burning in residential and commercial buildings to overall NO_x emissions in the OTC states. Residential buildings are represented in the dark blue section of the chart and commercial and institutional buildings in orange. Residential buildings are the fourth largest contributor to NO_x emissions in the OTC states after on-road vehicles, nonroad equipment and machines, and industrial processes (which includes fuel combustion in boilers and engines).

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[6] Michanowicz, D.R.; Dayalu, A.; Nordgaard, C.L.; Buonocore, J.J.; Fairchild, M.W.; Ackley, R.; Schiff, J.E.; Liu, A.; Phillips, N.G.; Schulman, A.; Magavi, Z.; Spengler J.D., "Home is Where the Pipeline Ends: Characterization of Volatile Organic Compounds Present in Natural Gas at the Point of the Residential End User," Environmental Science & Technology, 2022 Jul 19;56(14):10258-10268. doi: 10.1021/acs.est.1c08298. Epub 2022 Jun 28. PMID: 35762409; PMCID: PMC9301916, *see* https://www.ncbi.nlm.nih.gov/pmc/articles/PMC9301916/.

[7] Lebel, E.D.; Finnegan, C.J.; Ouyang, Z.; Jackson, R.B., "Methane and NO_x Emissions from Natural Gas Stoves, Cooktops, and Ovens in Residential Homes," Environmental Science & Technology, 56, 4, Jan 2022, *see* https://pubs.acs.org/doi/10.1021/acs.est.1c04707.

[8] Seals, B.; Krasner, A., "Gas Stoves: Health and Air Quality Impacts and Solutions," 2020, *see* https://rmi.org/insight/gas-stoves-pollution-health/.

[9] Seltenrich N., "Take care in the kitchen: avoiding cooking-related pollutants," Environmental Health Perspectives. 2014 Jun;122(6):A154-9. doi: 10.1289/ehp.122-A154, *see* https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4050506/.

[10] Logue, J.M.; Klepeis N.E.; Lobscheid, A.B.; Singer, B.C.; "Pollutant exposures from natural gas cooking burners: a simulation-based assessment for Southern California," Environmental Health Perspectives. 2014 Jan;122(1):43-50. doi: 10.1289/ehp.1306673, *see* https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3888569/.

[11] Calculated using EPA's "National Tier 1 CAPS Trends (xlxs) Criteria Pollutants National Tier 1 for 1970-2022," March 2023, *see* https://www.epa.gov/air-emissions-inventories/air-pollutant-emissions-trends-data.

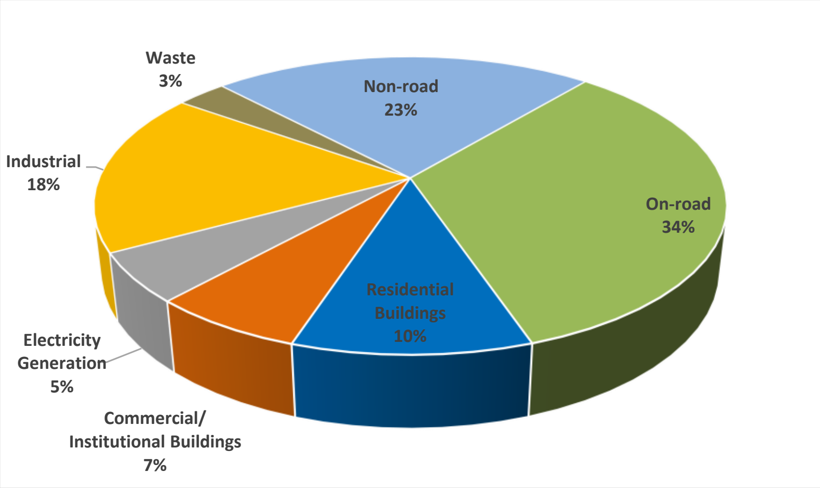

Figure 1: Sources of Annual NO_x Emissions in the Ozone Transport Region (Source: 2020 NEI)

Figure 2 breaks down contributions to residential building NO_x emissions by appliance and fuel, on an annual basis. It shows that 83% of residential building NO_x is from natural gas, fuel oil, and propane combustion for space heating. Water heating-related fuel combustion accounts for approximately 13% of building NO_x. An additional 3% of NO_x comes from fuel combustion for clothes drying, cooking, and other purposes.

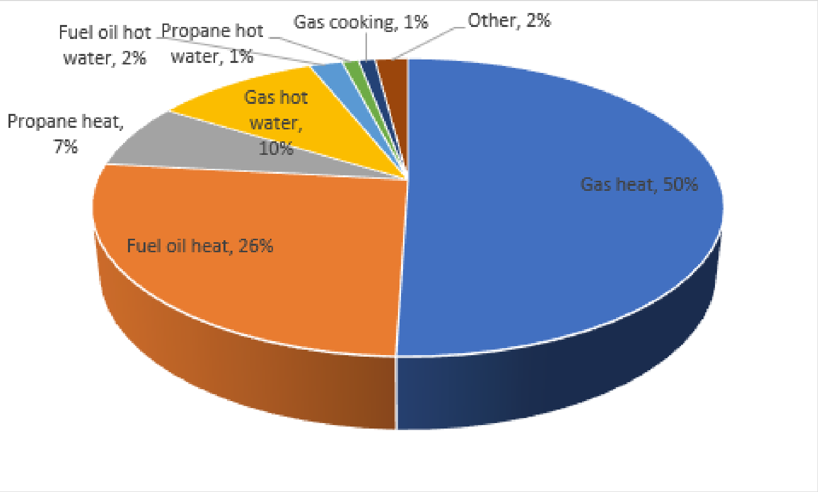

Figure 2: Annual NO_x Emissions in the Region by Building Appliance/Fuel Type (Residential Buildings)[12]

NO_x emissions are the major driver of surface ozone concentrations at the regional scale in the eastern United States. The ozone season used in this analysis was assumed to span 153 days from May 1 to September 30. Fuel combustion for water heating accounts for the majority of the onsite residential NO_x emissions during the ozone season, with fuel combustion in ovens, stoves, and dryers also contributing, as these appliances are used year-round. Because space heating occurs in the winter rather than the summer, it contributes only a small amount of ozone season NO_x.

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[12] Based on ResStock base case run for the OTC states.

Epidemiological studies provide strong evidence that ozone is associated with respiratory effects, including increased asthma attacks, as well as increased hospital admissions and emergency room visits for people suffering from respiratory diseases.[13] Parts of the Northeast and Mid-Atlantic continue to experience persistently high ozone levels affecting tens of millions of people. While air pollution levels have dropped over the years across much of the United States, portions of the region listed in Table 1 continue to persistently exceed both past and recently revised federal health-based air quality standards for ground-level ozone.

Table 1: Areas Exceeding the National Ambient Air Quality Standards (NAAQS) for Ozone in the Northeast and Mid-Atlantic

Nonattainment Area	**Population**	**2020 Design Value (ppm)[14]**	**2015 NAAQS Status**	**2008 NAAQS Status**
Greater Connecticut, CT	1,629,115	0.073	Serious	Severe
New York City, NY-NJ-CT	20,217,137	0.082	Serious	Severe
Philadelphia-Wilmington-Atlantic City, PA-NJ-MD-DE	7,437,135	0.074	Serious	Marginal
Baltimore, MD	2,662,691	0.072	Serious	Moderate
Washington, DC-MD-VA	5,136,216	0.071	Moderate	Marginal

Using the results from this study, OTC analyzed the impact of residential building electrification on daily 8-hour ozone. OTC found that daily 8-hour ozone would decrease by up to 0.6 parts per billion (ppb) on high ozone days in the Northeast and Mid-Atlantic region assuming the Whole Home Electrification scenario.[15] Air quality modeling for Maryland commissioned by the Sierra Club found that residential, commercial, and institutional building fossil fuel combustion sources contribute to over 1% of ambient ozone concentrations at times when the 70 ppb (0.07 ppm) NAAQS is exceeded at Maryland nonattainment area air quality monitors. The study found the maximum modeled ozone impact from buildings at a nonattainment monitor was 1.99 ppb,[16] a significant contribution to nonattainment ozone levels.

While ozone is largely a summertime issue in the region, NO_x is a year-round problem due to its role in acid deposition and the eutrophication of waterbodies, as well as the formation of nitrates contributing to elevated secondary $PM_{2.5}$ levels.[17] $PM_{2.5}$ exposure is associated with a variety of health effects, including reduced lung function, irregular heartbeat, asthma attacks, heart attacks, and premature

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[13] EPA, "Health Effects of Ozone Pollution," *see* https://www.epa.gov/ground-level-ozone-pollution/health-effects-ozone-pollution, last updated April 9, 2024 (accessed January 6, 2025).

[14] EPA Air Quality Design Values, *see* https://www.epa.gov/air-trends/air-quality-design-values#report (accessed April 25, 2022).

[15] Ozone Transport Commission, "OTC Modeling Committee Update OTC/MANEVU Annual Spring Meeting, June 13, 2024," *see* Microsoft PowerPoint - 2 20240613_OTC_MC_final.pptx.

[16] Sonoma Technology, "Ozone Impacts from Building Combustion Sources on Nonattainment Areas in Maryland," September 25, 2024, *see* Ozone Impacts from Building Combustion Sources on Nonattainment Areas in Maryland.

[17] EPA, "Technical Bulletin: Nitrogen Oxides (NO_x), Why and How They Are Controlled," *see* https://www3.epa.gov/ttncatc1/dir1/fnoxdoc.pdf, November 1999.

death in people with heart or lung disease.[18] The OTC modeling study found that with residential building electrification, wintertime $PM_{2.5}$ would decrease by as much as 1 microgram per cubic meter ($\mu g/m^3$) regionally. The same analysis found maximum daily wintertime region-wide $PM_{2.5}$ would decrease by as much as 7 $\mu g/m^3$ when daily-average $PM_{2.5}$ exceeds 35 $\mu g/m^3$.[19] Because of its role in secondary particulate formation, reducing NO_x emissions will improve public health by lowering exposure to $PM_{2.5}$.

In addition to improving public health, reducing NO_x emissions and associated secondary $PM_{2.5}$ nitrate formation will improve visibility in Mid-Atlantic Northeast Visibility Union (MANEVU) Class I Federal areas. The seven Class I Federal areas in the region have historically faced some of the worst visibility in the nation. Analyses of data from the Interagency Monitoring of Protected Visual Environments (IMPROVE) monitoring network show the increasing importance of nitrate formation on visibility impairment, in particular at the Brigantine Wilderness Area in the Edwin B. Forsythe National Wildlife Refuge in New Jersey.[20] Wintertime NO_x emissions from sources such as buildings can lead to formation of nitrates that impair visibility. Table 2 summarizes the public health and environmental impacts of NO_x.

Table 2: Adverse Public Health and Environmental Impacts of NO_x in the Northeast and Mid-Atlantic

Ozone and $PM_{2.5}$ Formation[21]	• Reduces lung function, aggravates asthma and other chronic lung diseases • Repeated exposure can cause permanent lung damage • Contributes to premature death • Disproportionate impact on overburdened communities[22]
Acid Deposition[23]	• Damages forests • Damages aquatic ecosystems, e.g., Adirondacks and Great Northern Woods • Erodes manmade structures
Coastal and Marine Eutrophication[24]	• Depletes oxygen in the water, which suffocates fish and other aquatic life in bays and estuaries, such as Chesapeake Bay, Narragansett Bay, and Long Island Sound
Visibility Impairment[25]	• Contributes to regional haze that mars vistas and views in wilderness and urban areas

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[18] EPA, "Health and Environmental Effects of Particulate Matter (PM)," *see* https://www.epa.gov/pm-pollution/health-and-environmental-effects-particulate-matter-pm, last updated July 20, 2018 (accessed April 25, 2022).

[19] *See* footnote 14.

[20] NESCAUM and OTC, "The Nature of the Fine Particle and Regional Haze Air Quality Problems in the MANE-VU Region: A Conceptual Description," *see* https://otcair.org/manevuUpload/Publication/Reports/pm-haze-conceptual-descrip-update-20120731-final.pdf, last updated July 2012.

[21] EPA, "Health Effects of Ozone and Particulate Matter," *see* https://www.epa.gov/advance/health-effects-ozone-and-particulate-matter, last updated June 14, 2024 (accessed January 6, 2024).

[22] Cheeseman, M.; Ford, B.; Anenberg, S.C.; et al., "Disparities in Air Pollutants Across Racial, Ethnic, and Poverty Groups at US Public Schools," Geohealth, 2022 Dec. 1; 6(12): e2022GH000672. doi: 10.1029/2022GH000672, *see* https://www.ncbi.nlm.nih.gov/pmc/articles/PMC9714311/ (accessed September 12, 2024).

[23] EPA, "Effects of Acid Rain," *see* https://www.epa.gov/acidrain/effects-acid-rain, last updated May 7, 2024 (accessed September 13, 2024).

[24] Whitall, D.; Bricker, S., "Assessment of Eutrophication in Estuaries: Pressure-State-Response and Source Apportionment," NOAA, USDA Forest Service Proceedings RMRS-P-42CD, 2006, *see* https://www.fs.usda.gov/rm/pubs/rmrs_p042/rmrs_p042_334_342.pdf (accessed September 12, 2024).

[25] See footnote 20.

Residential fuel combustion also contributes to direct $PM_{2.5}$ emissions. Based on EPA's 2020 NEI data, we estimate that in the Northeast and Mid-Atlantic, approximately 5,600 tons of direct $PM_{2.5}$ were emitted from fossil fuel combustion in residential buildings in 2020.[26] While these emissions are significant, they are far below the $PM_{2.5}$ emissions resulting from wood and biomass burning for space and water heating: over 135,000 tons of $PM_{2.5}$ were emitted in the Northeast and Mid-Atlantic in 2020 from wood and biomass combustion in buildings, according to NEI data.

Greenhouse Gas Emissions

Commercial and residential buildings accounted for 13% percent of GHG emissions in the United States in 2022.[27] Approximately 89% of residential and 54% of commercial onsite GHG emissions were from the burning of fossil fuels.[28] Figure 3 provides a breakdown of GHG emissions sources and shows that U.S. residential and commercial buildings are the fourth largest contributor, after transportation, electric power, and industry.

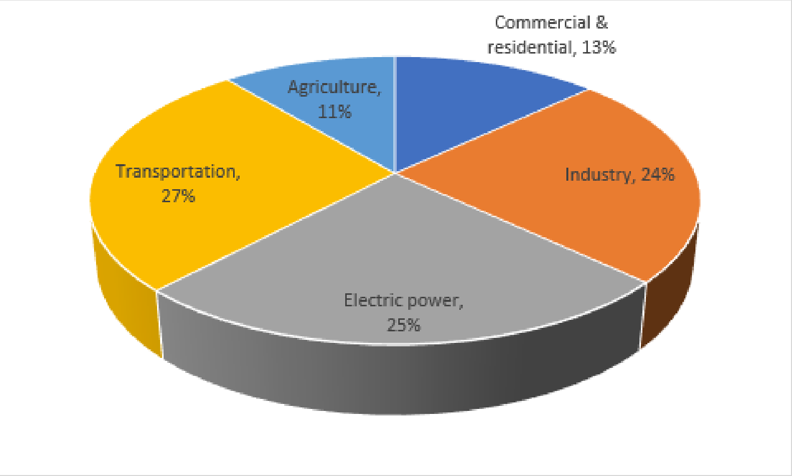

Figure 3: Commercial and Residential Building-Related GHGs as a Fraction of Total U.S. GHG Emissions

State estimates of the percentage contribution of fossil fuel combustion in buildings to overall GHG emissions are similar to or greater than those in the national inventory presented above. For example, New York estimates that residential and commercial buildings emit 34% of total GHG emissions in the state[29] and New Jersey found that building-related GHG emissions make up 26% of overall GHG emissions.[30]

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[26] Calculated using EPA's "National Tier 1 CAPS Trends (xlxs) Criteria Pollutants National Tier 1 for 1970-2022," March 2023, *see* https://www.epa.gov/air-emissions-inventories/air-pollutant-emissions-trends-data.

[27] EPA, "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2020," EPA 430-R-22-003, 2022, *see* https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks.

[28] EPA, "Commercial and Residential Sectors," *see* https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions#commercial-and-residential.

[29] New York State Climate Action Council, "New York State Climate Action Council Scoping Plan," December 2022, *see* https://climate.ny.gov/resources/scoping-plan/.

[30] New Jersey Board of Public Utilities, Department of Transportation, *et al.*, "New Jersey's Global Warming Response Act, 80 X 50 Report," October 2020, *see* https://www.nj.gov/dep/climatechange/docs/nj-gwra-80x50-report-2020.pdf.

The next section discusses state climate goals and targets for the building sector and the need to implement measures to reach those goals.

Policy Landscape

Several jurisdictions in the U.S. adopted low-NO_x emissions limits in the 1980s and 1990s for natural gas-fueled water heaters and furnaces.[31] In general, however, regulations to reduce building-related criteria pollutant and GHG emissions have lagged behind controls for other area sources and for other sectors, such as motor vehicles and electricity generation, at both the federal and the state level. As a result, emissions from buildings constitute a growing share of total emissions.[32] States are now looking to adopt building-related policies that substantially reduce criteria pollutant and GHG emissions to meet their air quality, environmental justice, and climate goals. Addressing emissions from existing buildings is especially important: as many as 80% of existing buildings will still be in use in 2050.[33] This section discusses recent state and air management district regulations to reduce building-related emissions.

Building Emission Reduction Targets in the Northeast and Mid-Atlantic

Many states have established economy-wide GHG emission reduction goals and specific targets for the building sector.

Table 3 lists examples of building-related targets for selected states in the Northeast and Mid-Atlantic.

Table 3: Example State Building-Related Targets

State	Near-Term Targets	Long-Term Targets
Maryland	20% reduction in net GHGs by 2030 for buildings covered by a statewide Building Performance Standard.[34] Propose a zero-emission heating equipment standard regulation.[35]	Net-zero GHGs for covered buildings by 2040.[36]
Massachusetts	29% reduction in GHGs from residential buildings and 35% reduction from commercial buildings in	Statewide target to reduce GHGs to net zero by 2050 with

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[31] Utah Administrative Code. (2015). Rule R307-230: NO[x] Emission Limits for Natural Gas-Fired Water Heaters, *see* https://casetext.com/regulation/utah-administrative-code/environmental-quality/title-r307-air-quality/rule-r307-230-nox-emission-limits-fornatural-gas-fired-water-heaters; Texas Administrative Code. (2007). Title 30, Part 1, Chapter 117, Subchapter E, Division 3: Water Heaters, Small Boilers and Process Heaters (effective June 14), *see* https://texreg.sos.state.tx.us/public/readtac%24ext.ViewTAC?tac_view=5&ti=30&pt=1&ch=117&sch=E&div=3&rl=Y; South Coast Air Quality Management District (SCAQMD). Rule 1146.2, "Emissions of Oxides of Nitrogen from Large Water Heaters and Small Boilers and Process Heaters, *see* Rule 1146.2 (aqmd.gov). Bay Area Air Quality Management District, "Regulation 9 Inorganic Gaseous Pollutants Rule 6 Nitrogen Oxides Emissions from Natural Gas-Fired Water Heaters," 2023 Amendment, *see* 20230315_rg0906-pdf.pdf (baaqmd.gov) and Regulation 9 Inorganic Gaseous Pollutants Rule 4 Nitrogen Oxides from Natural Gas-Fired Furnaces," *see* 20230315_rg0904-pdf.pdf (baaqmd.gov).

[32] US Department of Energy (DOE), "Decarbonizing the U.S. Economy by 2050," *see* https://www.energy.gov/eere/articles/decarbonizing-us-economy-2050, April 2024.

[33] World Economic Forum, "To create net-zero cities, we need to look hard at our older buildings," November 8, 2022, *see* https://www.weforum.org/agenda/2022/11/net-zero-cities-retrofit-older-buildings-cop27.

[34] Maryland General Assembly, "Climate Solutions Now Act of 2022," *see* Legislation - SB0528 (maryland.gov).

[35] Maryland Executive Order, "Leadership by State Government: Implementing Maryland's Climate Pollution Reduction Plan," June 4, 2024., *see* https://governor.maryland.gov/Lists/ExecutiveOrders/Attachments/52/EO%2001.01.2024.19%20Leadership%20by%20State%20Government-%20Implementing%20Maryland%27s%20Climate%20Pollution%20Reduction%20Plan_Accessible.pdf

[36] Ibid.

	2025. 49% reduction in GHGs from residential and commercial buildings in 2030.[37]	corresponding sector targets.[38]
New York	Electrify 1-2 million homes with heat pumps by 2030 and 10% to 20% of commercial space.[39] Prohibit the installation of fossil-fuel equipment and building systems in new buildings.[40]	85% of homes and commercial building space statewide should be electrified by 2050.[41]
New Jersey	Convert 22% of residential and commercial buildings to electric by 2030.[42]	Reduce residential and commercial building GHG emissions 89% by 2050.[43]

Other states in the region have also set building sector GHG reduction requirements or recommendations in statutes, executive orders, and plans. Many of these policies are still in the planning or rulemaking process and have not yet been fully implemented. Examples of policies to address existing building emissions are provided below. In addition to these state policies, a range of federal, state, utility, and local incentives, financing options, and tax credits are available in the region to support heat pump adoption.

State Policy Examples

Multistate Residential Buildings Memorandum of Understanding

In 2024, the states of California, Colorado, Maine, Maryland, Massachusetts, New Jersey, New York, Oregon, Rhode Island, and the District of Columbia signed a multistate Memorandum of Understanding (MOU) coordinated by NESCAUM, *Accelerating the Transition to Zero-Emission Residential Buildings.* The MOU sets a target for heat pumps to make up at least 65% of residential-scale heating, air conditioning and water heating shipments by 2030 and 90% by 2040 across the participating states. Signatories also agreed to develop an Action Plan that identifies priorities for electrifying residential buildings; to direct 40 percent of funding for building electrification to disadvantaged communities; to engage in research on building electrification technologies and costs; and to engage in other joint activities. A multistate Building Electrification Task Force is leading the effort.

Zero-Emission Standards for Water and Space Heating Equipment

Zero-emission equipment standards require that water and space heating equipment installed after a future date have zero onsite emissions. In March 2023, the Bay Area Air District in California became the first jurisdiction in the nation to promulgate zero-NO_x equipment standards when it voted to approve Regulations 9-4 and 9-6, requiring the sale of zero-NO_x emitting water and space heaters. The zero-NO_x

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[37] Massachusetts Executive Office of Energy and Environmental Affairs, “Massachusetts Clean Energy and Climate Plan for 2025 and 2030,” June 30, 2022, *see* Massachusetts Clean Energy and Climate Plan for 2025 and 2030 | Mass.gov.

[38] The General Court of the Commonwealth of Massachusetts, “An Act Creating a Next-Generation Roadmap for Massachusetts Climate Policy,” March 26, 2021, *see* Session Law - Acts of 2021 Chapter 8 (malegislature.gov).

[39] New York State Climate Action Council, “Scoping Plan,” December 2022, *see* Scoping Plan - New York's Climate Leadership & Community Protection Act (ny.gov).

[40] The New York State Department of State is amending the State Energy Conservation Construction Code and has released a Notice of Rule in Development, *see* https://dos.ny.gov/notice-rule-development.

[41] New York State Climate Action Council, “Scoping Plan,” December 2022, *see* https://climate.ny.gov/resources/scoping-plan/.

[42] New Jersey Board of Public Utilities, et al., “2019 Energy Master Plan Pathway to 2050,” 2019, *see* 2020_NJBPU_EMP.pdf.

[43] New Jersey Department of Environmental Protection, et al., “New Jersey’s Global Warming Response Act 80 X 50 Report,” *see* nj-gwra-80x50-report-2020.pdf.

requirements phase in between 2027 and 2030, depending on the equipment type.[44] The rules apply to new equipment purchases after the phase-in dates, and do not require early replacement of existing water and space heating systems used in homes and businesses.

In June 2024, the South Coast Air Quality Management District (South Coast AQMD) approved updates to Rule 1146.2 that will require new and existing residential and commercial buildings to transition to zero-emission water heaters. With this change, natural gas-fired pool heaters, large water heaters, small commercial water heaters, boilers, and process heaters must meet a zero emission NO_x standard when replaced.[45]

The California Air Resources Board (CARB) included a measure in its 2022 State Implementation Plan (SIP) Strategy to develop zero-GHG emission standards for space and water heaters sold in California.[46] The measure was included in the SIP Strategy because of the significant NO_x reductions that would be achieved with implementation of the rule. The CARB proposal states that, beginning in 2030, 100% of new space and water heaters sold in California (for either new construction or new equipment for use in existing buildings) would need to meet the zero-emission standard. It is expected that electric heat pump technologies, which have zero GHG and NO_x emissions, would be the primary way to comply with this regulation. CARB estimates the measure could reduce NO_x by 13.5 tons per day and reactive organic gases by 1.5 tons per day in 2037. CARB began a public process in 2023 and expects to bring the zero-emission rules to its Board for approval in 2025.

Informed by the progress in California, NESCAUM and the Regulatory Assistance Project (RAP) released a Model Rule: NOx and GHG Emissions Standards for Space and Water Heaters[47] in October 2024, along with supporting technical and cost information,[48] as a resource for states interested in adopting zero-emission standards for space and water heating equipment. In June 2024, Maryland's governor signed Executive Order 01.01.2024.19 entitled "Leadership by State Government: Implementing Maryland's Climate Pollution Reduction Plan." The Executive Order requires the Maryland Department of the Environment (MDE) to propose a zero-emission heating equipment standard (ZEHES) regulation that over time will reduce carbon pollution and improve air quality both indoors and outdoors.[49] MDE plans to develop its ZEHES regulation in 2025 based on the NESCAUM-RAP Model Rule.[50]

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[44] Bay Area Air Quality Management District, "Regulation 9 Inorganic Gaseous Pollutants Rule 4 Nitrogen Oxides from Natural Gas-Fired Furnaces," *see* 20230315_rg0904-pdf.pdf (baaqmd.gov), and BAAQMD, "Regulation 9 Inorganic Pollutants Rule 6 Nitrogen Oxides Emissions From Natural Gas-Fired Boilers and Water Heaters," *see* 20230315_rg0906-pdf.pdf (baaqmd.gov).

[45] South Coast Air Quality Management District, "Rule 1146.2 Emissions of Oxides of Nitrogen from Large Water Heaters and Small Boilers and Process Heaters," Amended June 7, 2024, *see* Rule 1146.2 (aqmd.gov).

[46] California Air Resources Board, "2022 State Strategy for the State Implementation Plan (2022 State SIP Strategy)," *see* https://ww2.arb.ca.gov/sites/default/files/2022-08/2022_State_SIP_Strategy.pdf.

[47] NESCAUM and RAP, "Model Rule: NO_x and GHG Emissions Standards for Space and Water Heaters, Version 1.0," *see* https://www.nescaum.org/documents/Model-Rule-1.0---Emissions-Standards-for-Space-and-Water-Heaters.pdf, October 30, 2024.

[48] NESCAUM, "Zero-Emission Heating Equipment Standards," *see* https://www.nescaum.org/our-work/stationary-sources/zehes, accessed January 6, 2025.

[49] Executive Order 01.011.2024.19 "Leadership by State Government: Implementing Maryland's Climate Pollution Reduction Plan," *see* EO 01.01.2024.19 Leadership by State Government: Implementing Maryland's Climate Pollution Reduction Plan.

[50] Maryland Department of the Environment, Clean Heat Rules website, *see* https://mde.maryland.gov/programs/air/Climate-in-md/Pages/Clean-Heat-Rules.aspx.

The New York Department of State has released a Notice of Rule in Development that would require zero-emission water and space heating equipment in new construction.[51] In addition, New York's Climate Scoping Plan includes a target that heat pumps should become the majority of new purchases for space and water heating by the late 2020s and, by 2050, 85% of homes and commercial building space statewide should be electrified with energy-efficient heat pumps and thermal energy networks.[52] The Scoping Plan also recommends that the New York State Energy Research and Development Authority (NYSERDA), New York State Department of Environmental Conservation, and New York State Department of State work together to adopt regulatory requirements that will bring about the end of fossil fuel combustion in buildings. The Plan recommends state regulations to require zero-emission equipment at the time of replacement.

Clean Heat Standards

States in the region are exploring Clean Heat Standards (CHS), a policy in which heating energy suppliers, such as gas utilities and heating fuel suppliers, are required to ramp up the use of clean heat over time by implementing clean heat measures (e.g., heat pumps, weatherization, or low-carbon fuels) or purchasing credits.[53] In Massachusetts, the Clean Energy and Climate Plan for 2025 and 2030 includes goals for reducing GHG emissions from the residential, commercial, and industrial heating and cooling sectors.[54] The Plan tasks the Massachusetts Department of Environmental Protection (MassDEP) with developing a "a high-level program to meet the emissions limit for residential, commercial, and industrial heating" and identifies a CHS as a regulatory option for addressing this requirement. MassDEP expects to release a draft CHS regulation in 2025.

Vermont's Climate Action Plan recommended addressing building emissions through a CHS that would reduce and regulate emissions from natural gas, fuel oil, and propane by creating a cap-and-trade mechanism.[55] Vermont's Affordable Heat Act legislation followed this recommendation and became law on May 11, 2023.[56] The Act directs the Vermont Public Utility Commission (PUC) to develop a CHS that obligates the natural gas utility and heating fuel suppliers to earn or buy clean heat credits through measures such as weatherization, heat pumps, or biofuels. The PUC is required to design and study the impacts of a CHS, then in two years present its findings to the Legislature. The Vermont PUC submitted the draft CHS rule and report to the Legislature in January 2025.[57]

Building Energy Performance Standards

Several states and cities in the Northeast and Mid-Atlantic have adopted Building Energy Performance Standard (BEPS) policies to tackle emissions from existing buildings. BEPS require larger existing buildings to achieve certain levels of whole-building GHG emissions or energy performance. The District of Columbia has established a BEPS setting specific targets for energy use intensity (EUI) in D.C.

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[51] New York Department of State, "State Energy Conservation Construction Code (19 NYCRR Part 1240) Notice of Rule in Development," *see* https://dos.ny.gov/notice-rule-development.

[52] New York State Climate Action Council, "Scoping Plan," December 2022, *see* Final Scoping Plan (ny.gov).

[53] Massachusetts Department of Environmental Protection, Massachusetts Clean Heat Standard, *see* https://www.mass.gov/info-details/massachusetts-clean-heat-standard.

[54] Massachusetts Office of Energy and Environmental Affairs, "Massachusetts Clean Energy and Climate Plan for 2025 and 2030," June 30, 2022, *see* Massachusetts Clean Energy and Climate Plan for 2025 and 2030 | Mass.gov.

[55] Vermont Climate Council, "Initial Vermont Climate Plan," December, 2021, *see* Initial Vermont Climate Action Plan.

[56] Vermont General Assembly, "Affordable Heat Act," *see* https://legislature.vermont.gov/Documents/2024/Docs/ACTS/ACT018/ACT018%20As%20Enacted.pdf.

[57] VT PUC, "Clean Heat Standard," *see* https://puc.vermont.gov/clean-heat-standard, accessed January 30, 2025.

buildings, starting with large commercial and multifamily buildings. The targets become more stringent over time and smaller commercial and multifamily buildings will also be phased into the program. In Maryland, the Climate Solutions Now Act of 2022 required the state to develop BEPS that achieve a 20% reduction in net direct GHGs from covered buildings by 2030 and net-zero direct GHGs from covered buildings by 2040.[58] Maryland initiated a rulemaking process in 2022 and finalized its BEPS regulation in 2024.[59] Several large cities in the region, including Boston[60] and New York City,[61] have also enacted BPS policies.

These and other policies will help states reach their climate and air quality goals. The next section provides an overview of the methods used in this study to estimate potential emissions reductions from building electrification.

3. Overview of Study Method

There were four basic steps as part of this study: 1) compile energy consumption outputs from the NREL ResStock tool for a baseline scenario and three building electrification scenarios for states in the region; 2) convert residential building-related energy consumption to NO_x, $PM_{2.5}$, CO_2, VOC, and SO_2 emissions using emission factors from EPA's data supporting the 2020 National Emissions Inventory for the baseline and three building electrification scenarios;[62] 3) estimate the NO_x, CO_2, SO_2, VOC, and $PM_{2.5}$ emissions from power plants for the baseline and three building electrification scenarios; and 4) conduct two additional analyses, an estimate of ozone season NO_x emissions and an analysis in which electrification is phased in over time.

The three electrification scenarios evaluated for states in the Northeast and Mid-Atlantic were:

1) **Water Heating:** This scenario replaces hot water heaters currently fueled with fuel oil, natural gas, or propane with variable-speed heat pumps (VSHPs) and electric resistance water heaters with heat pump water heaters;
2) **High-Efficiency Space Heating:** This scenario replaces home furnaces and boilers currently fueled with fuel oil, natural gas, or propane with high-efficiency electric VSHPs. It also assumes that cooling loads are shifted from window and central air conditioning to heat pumps, and electric resistance heaters are replaced by heat pumps; and
3) **High-Efficiency Whole Home Electrification:** This scenario replaces fuel oil, natural gas, and propane fired furnaces and boilers with VSHPs. It also replaces electric resistance hot water heaters, space heaters, and clothes dryers with heat pumps and assumes that cooking appliances are converted to electric. Cooling loads are shifted from central air conditioning or window air conditioners to heat pumps.

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[58] Maryland Climate Solutions Now Act of 2022, statute §2-1602(a), *see* https://mgaleg.maryland.gov/mgawebsite/Legislation/Details/sb0528?ys=2022RS.

[59] Maryland, "Building Energy Performance Standards," *see* https://mde.maryland.gov/programs/air/ClimateChange/Pages/BEPS.aspx, accessed January 30, 2025.

[60] City of Boston, "Building Emissions Reduction and Disclosure," *see* https://www.boston.gov/departments/environment/berdo, accessed September 13, 2024.

[61] City of New York, "Local Law 97," *see* https://www.nyc.gov/site/sustainablebuildings/ll97/local-law-97.page, accessed September 13, 2024.

[62] EPA, "Wagon Wheel 2020 v7 Final," *see* 2020 NEI Supporting Data and Summaries | US EPA.

None of the above scenarios replace fuel-fired appliances with electric resistance appliances. However, some heat pump systems are assumed to have electric resistance heaters as back-up. Heating loads are shifted in part to electric resistance heat if heat pumps would not produce sufficient heat, using the latest industry standards for heating. More information on the sizing of systems is provided in the ResStock Scenarios and Assumptions section below.

Information on the ResStock Tool is provided below, followed by details on each of the steps in the methodology.

NREL ResStock Tool

ResStock is a physics-based simulation model developed to represent the energy use and savings potential of residential building stocks with high granularity at national, regional, and local scales. NREL has characterized the U.S. residential building stock and developed a national typology of buildings to support the Department of Energy's Advanced Building Construction Collaborative. The model uses a large amount of data from public and private sources, as well as statistical sampling and sub-hourly building simulations.[63] The tool was designed to help users identify which building stock improvements could save the most energy and money.

To develop a typology of residential buildings in the U.S., NREL segmented the housing stock into 165 subgroups based on climate zone, wall structure, housing type, and year of construction. For each subgroup, NREL quantified the thermal energy use (defined in the NREL documentation as energy for heating, ventilation, and air conditioning (HVAC) and water heating) by end use and segment. This analysis allows NREL to prioritize specific building segments and technologies for targeted efficiency or electrification upgrades.

The model quantifies:

- Energy consumption at the state level for residential building types.
- Energy consumption for all appliances found in buildings by fuel type.
- Energy consumption by fuel type for natural gas, fuel oil, propane, and electricity.

The model does not quantify:

- Energy consumption for wood and biomass-fueled appliances.
- Building electrification impacts on power system emissions under a future zero-carbon electricity grid.
- Building electrification impacts on power system costs.
- The impact of electrification, especially from heating, on electricity system peak loads.
- Embodied emissions across different phases of building life.
- Non-energy operational emissions (e.g., refrigerant leakage).

NREL has determined that single-family detached homes constitute the majority of residential buildings in the United States and account for the largest share of residential thermal end-use energy. Only mobile homes have a higher thermal end-use intensity.[64] However, multifamily units predominate in

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[63] NREL Restock Analysis Tool webpage, *see* https://www.nrel.gov/buildings/resstock.html, Accessed October 13, 2022.

[64] Reyna, J., *et al.* 2022. U.S. Building Stock Characterization Study: A National Typology for Decarbonizing U.S. Buildings. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5500-83063, p. 56, *see* https://www.nrel.gov/docs/fy22osti/83063.pdfhttps://www.nrel.gov/docs/fy22osti/83063.pdf.

some areas, including urban areas with extensive population exposure to air pollutants. Therefore, ResStock, in its current form, includes all segments of housing stock in its analyses.

ResStock Scenarios and Assumptions

ResStock is pre-programmed with ten measure packages representing various electrification and energy efficiency technologies and scenarios.[65] These packages include scenarios with and without added envelope efficiency measures (e.g., insulation and air sealing). Because this analysis focuses on the impact of electrification and heat pump technology, we selected scenarios that did not assume additional envelope measures. We used three scenarios: scenario 4 “Heat pumps, high-efficiency, electric back-up;” scenario 6 “Heat pump water heaters;” and scenario 8 “Whole home electrification, high-efficiency” from the ten measure packages available in ResStock to estimate the emissions impacts of building electrification. In this report we refer to the scenarios as follows:

Scenario 4 Heat pumps, high-efficiency is referred to as “Space Heating Electrification;”

Scenario 6 Heat pump water heaters is referred to as “Water Heating Electrification;” and

Scenario 8 Whole home electrification, high-efficiency is referred to as “Whole Home Electrification.”

Below, we summarize the assumptions used in ResStock for these electrification scenarios. Full information on ResStock assumptions is available in NREL’s documentation.[66]

Water Heating Assumptions

In this scenario, only water heaters are converted to heat pumps. The ResStock model assumes replacement of water heaters currently fueled with fuel oil, natural gas, or propane, as well as electric resistance water heaters, to one of three types of heat pump water heaters. The assumed efficiency of baseline water heaters is the current federal efficiency requirement. The type and size of the assumed replacement water heater depends on the type of residence. For example, for dwelling units with 1-3 bedrooms with an existing water heater other than a tankless water heater, the model assumes a 50-gallon capacity, 3.45 uniform energy factor (UEF) heat pump replaces the fuel-burning water heater. For units with 4 bedrooms and an existing water heater other than an electric tankless water heater, ResStock replaces the fuel-burning water heater with a 66 gallon, 3.35 UEF heat pump water heater. In the largest residential units with more than 4 bedrooms, an 80 gallon, 3.45 UEF heat pump replaces the existing water heater.

The scenario also accounts for increases or decreases in heating and cooling-related electricity demand resulting from heat pump water heaters venting cool air into living spaces.

Space Heating Assumptions

In this scenario, only space heating and window and central air conditioning systems are converted to heat pumps. The ResStock model assumes replacement of home furnaces and boilers currently fueled with fuel oil, natural gas, and propane with high-efficiency VSHPs and replacement of electric resistance

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[65] Measure packages are: basic and enhanced enclosures, minimum and high-efficiency heat pumps with and without electric backup, heat pump water heaters, minimum and high-efficiency whole home electrification with and without enhanced enclosure.

[66] NREL, “End-Use Savings Shapes Residential Round 1 Technical Documentation and Measure Applicability Logic, *see* https://oedi-data-lake.s3.amazonaws.com/nrel-pds-building-stock/end-use-load-profiles-for-us-building-stock/2022/EUSS_ResRound1_Technical_Documentation.pdf.

heat with heat pumps. The assumed efficiency of the baseline appliances is the current federal efficiency requirement. Heat pump assumptions depend on the type of residential units. For example, in a dwelling unit with ducts and no heat pumps or a less efficient heat pump,[67] ResStock applies an upgrade to a high-efficiency ducted heat pump (24 Seasonal Energy Efficiency Ratio (SEER), 13 Heating Seasonal Performance Factor (HSPF)). In homes with ducts, ResStock also assumes that:

- Heat pumps will be sized to Air Conditioning Contractors of America (ACCA) Manual S.
- Backup heat will be provided by electric resistance, active only when the heat pump cannot meet the load.
- Heat pumps are sized for a residential unit's cooling load, with the rest of the heating load served by electric resistance heat. This assumption may overestimate the electricity used for heating because resistance heat uses considerably more electricity than heat pumps.
- Data from the 2009 RECS indicate that the majority of homes that use window air conditioners for cooling do not condition the entire home; for these homes, it is assumed that only 50% of the finished floor area is cooled in the baseline. The replacement room air conditioning (capacities and number of units) is determined in accordance with ACCA/American National Standards Institute (ANSI) Manual J.

For dwelling units without ducts and no heat pump or a less-efficient heat pump, the model replaces the fuel-burning heating system or the electric resistance heating system with a high-efficiency ductless variable-speed mini-split heat pump (29.3 SEER, 14 HSPF). ResStock also assumes that heat pumps will be sized to the maximum load.

Whole Home Electrification Assumptions

The Whole Home Electrification Scenario models replacing fuel oil, natural gas, and propane fired furnaces, hot water heaters, electric resistance heat, and central or window air conditioning systems with heat pumps as specified in the above scenarios. It also assumes that fossil fuel clothes dryers and cooking appliances are converted to electric. This scenario includes all the assumptions described above in the Water and Space Heating scenarios, plus the following assumptions:

- Ventless heat pump dryer (combined energy factor "CEF" = 5.2) for all dwelling units with non-electric dryers or less-efficient electric dryers.
- Electric oven and induction range for all dwelling units.
- Some fossil fuel-powered appliances such as pool heaters, grills, and hot tub heaters were excluded from this analysis, largely because of a lack of currently available electric technologies to replace these appliances.

Cross-Cutting Assumptions

The ResStock Tool does not provide a phase-in option for the scenarios evaluated. In other words, all fossil fuel and electric resistance appliances are assumed to be converted overnight to heat pumps or electric cooking throughout the region. In reality, this transition would happen gradually as appliances are replaced with zero-emitting equipment upon replacement.

The ResStock Tool applies heat pump technology to all technically feasible residential applications, without regard to cost. Therefore, this analysis assumes that, across all three electrification scenarios, all homes that do not already have heat pumps or that have less-efficient heat pumps will be upgraded to

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[67] A less efficient heat pump is defined as having a SEER less than 24 and an HSPF less than 13.

high-efficiency VSHPs, with the exception of those with tankless water heaters. A previous (2021) version of ResStock included a scenario option that was considered economic, e.g., had a net present value of zero or higher. Using the economic filter in the older version resulted in many fewer residences being converted to heat pumps than in the current version of the model. This was due to either higher upfront costs for heat pumps compared to fuel-burning appliances, more expensive operating costs for heat pumps, or both at the time the model was released.

Passage of the Inflation Reduction Act (IRA) and the Infrastructure Investment and Jobs Act (IIJA) may significantly change the economics of installing heat pumps in residential buildings, likely driving down costs over time.[68] However, because ResStock does not account for customer economics, this analysis does not explicitly account for potential impacts of federal funding or state, utility, and local incentives.

We did not evaluate any scenarios that include weatherization measures such as air sealing and insulation. ResStock analyses have demonstrated that air infiltration reduction measures, including wall paneling, drill-and-fill insulation, and window retrofits are cost-effective residential energy reduction strategies for many of the OTC states. Ideally, weatherization coupled with installation of heat pumps for space heating and cooling would deliver the best performance, comfort, and cost savings. However, for the purposes of this analysis, we did not assume that homes would be weatherized before installing electrification technologies. Subsequent analyses could look at the combined impact of electrification and weatherization.

Step 1: Assess Changes in Residential Building Energy Consumption

In the first step of this analysis, we used ResStock tool outputs in kilowatt hours (kWh) for each fuel and by appliance type to compile baseline and efficient electrification scenario data for each OTC state. The baseline fuel consumption assumptions in ResStock are based on modeling NREL conducted to reflect current fuel use in residential buildings. Outputs of the ResStock tool include baseline energy consumption by fuel, by appliance, and by state. ResStock converts consumption of natural gas, fuel oil, and propane fuel from gallons or therms to kWh. We imported these data into an Excel spreadsheet for the baseline scenario and the three electrification scenarios. We subtracted the energy consumption, in kWh, for the appliances in each electrification scenario from the baseline appliance energy consumption to calculate the change in energy consumption associated with each electrification strategy. For each state, we summed savings for each appliance type and fuel type to estimate the total change in energy consumption, in kWh, for each scenario.

Step 2: Convert Energy Data into Onsite Emissions of Criteria Pollutants and CO_2

In the second step, we used the energy consumption data from the ResStock model to estimate criteria and CO_2 emissions for the baseline scenario and the three electrification scenarios.

Outputs (in kWh) were converted to British Thermal Units (Btus) as:

1 million Btus (1 MMBtu) = 293.3 kWh
1 trillion Btus (1 TBtu) = 2.93×10^8 kWh

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[68] H.R.3684 - Infrastructure Investment and Jobs Act, *see* https://www.congress.gov/bill/117th-congress/house-bill/3684/text; H.R. 5376 Inflation Reduction Act, *see* https://www.congress.gov/bill/117th-congress/house-bill/5376/text.

Onsite emissions were calculated using fuel volumes. Fuel volumes were derived from reductions in energy output associated with each scenario as follows:

For fuel oil:

1 TBtu = 7,220,217 gallons (gal)

For natural gas:

1 TBtu = 980.39 million cubic feet (MMcf)

For propane:

1 TBtu = 10,928.96 gal

CO_2 emissions were estimated using EPA's AP-42: Compilation of Air Emissions Factors (EF) for external combustion in residential furnaces, as shown in Table 3. Emissions of NO_x, SO_2, $PM_{2.5}$, and VOC were estimated using EPA's emission factors developed for the 2020 NEI, as shown in Table 4.

Table 3: Emission Factors for Fuel Oil, Natural Gas, and Propane Furnaces

Pollutant	**Fuel Oil Combustion**	**Natural Gas Combustion**	**Propane Combustion**
CO_2	22,300 pounds (lbs)/1,000 gal	120,000 lbs/MMcf	14,300 lbs/1,000 gal
NO_x	18 lbs/1,000 gal	94 lbs/MMcf	13.4 lbs/1,000 gal
SO_2	0.21 lbs/1,000 gal	0.6 lbs/MMcf	0.06 lbs/1,000 gal
$PM_{2.5}$	2.13 lbs/1,000 gal	0.43 lbs/MMcf	0.04 lbs/1,000 gal
VOC	0.71 lbs/1,000 gal	5.5 lbs/MMcf	0.52 lbs/1,000 gal

We used EPA's emission factors for furnaces listed above for water heaters, because there are no water heater emission factors listed in AP-42 or in EPA's emission factors used in the 2020 NEI (the Wagon Wheel). Research conducted by RAP on water heater NO_x emissions found that the burner technologies and emission characteristics for water heaters are virtually the same as for boilers. In its 2022 report, RAP compared AP-42 values for furnace NO_x emissions with available data.[69] The study cited a 2019 staff report from the Imperial County Air Pollution Control District in California that proposed new NO_x emissions limits for natural gas-fueled water heaters. The staff report found that unregulated gas-fueled water heaters can be assumed to have a NO_x emission factor of 55 ppm at 3% oxygen (O_2). This rate is consistent with the 94 lbs/MMcf shown in Table 4.

It is important to note that this study's assumptions about fuel consumption and GHG emissions at a state level may not exactly match the values in each state's GHG inventory. The reason for this is twofold. First, the ResStock model uses a five-year rolling average of heating oil use from the American Community Survey (2014-2019 version). Thus, fuel oil consumption in the ResStock model may not align with the same calendar years used in state fuel oil usage estimates. In addition, ResStock uses data from 2018 to estimate natural gas use in residential buildings. This may differ from state GHG inventory methods.

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[69] Brutkoski, D.; Prause, E.; Seidman, N.; Shenot, J.; Williams, S., "NO_x Standards for Water Heaters: Model Rule Technical Support Document," *see* NOx Standards for Water Heaters: Model Rule Technical Support Document - Regulatory Assistance Project (raponline.org).

Step 3: Estimate Changes in Emissions from Power Plants

In each of the electrification scenarios, switching from fossil fuel appliances to VSHPs and electric cooking increased electricity consumption in the majority of states. The increased demand is the result of the additional amount of electricity used by the heat pumps and other electric appliances that replace the fossil-fueled furnaces, hot water heaters, clothes dryers, and stoves/ovens. In some states, however, electricity consumption decreased with a switch to heat pumps. This is because heat pumps are a much more efficient technology than electric resistance heating and central air conditioners. In states with high prevalence of electric resistance space and water heaters and central air conditioning, there is a potential to decrease electricity consumption by switching homes to high-efficiency VSHPs. The ResStock model provides the increase or decrease in electricity generation from power plants associated with each scenario for each appliance type and for each state.

To estimate criteria pollutant and GHG emissions resulting from changes in electricity generation due to residential building electrification, we analyzed two different scenarios: one based on the current electricity generation mix in the region and another based on a future, cleaner electricity grid. For both the current and future grid scenarios, electricity consumption from the ResStock model (in kWh) was converted to MWh and those values were multiplied by the emission factors in Tables 5 and 7.

Current Grid Scenario

We calculated NO_x, CO_2, $PM_{2.5}$, VOC, and SO_2 emissions associated with the changes in electricity demand for each scenario and each state, based on the current electricity grid. We used emission factors, in pounds per megawatt hour (lbs/MWh), published in EPA's Emissions and Generation Resource Integrated Database (eGRID) database for calendar year 2021[70] for $PM_{2.5}$ and VOC emissions. VOC emissions in lbs/MWh were available for each state on the EPA website. For $PM_{2.5}$, we used EPA eGRID emission factors for the following subregions: Northeast Power Coordinating Council (NPCC), New York City/Westchester (NYCW), NPCC Long Island (NYLI), NPCC Upstate NY (NYUP), and RFC East/Eastern Power Grid (RFCE) to estimate power plant-related emissions for Delaware, DC, Maryland, New York, and New Jersey. For Pennsylvania, RFCE and RFC West (RFCW) were used and for Virginia, the SWERC Virginia/Carolina/Eastern Power Grid (SRVC). For NO_x, SO_2, and CO_2 emission factors, we relied on the NREL standard scenario for 2024.[71] Emissions factors for the Northeast and Mid-Atlantic states in the current grid scenario are shown in Table 4.

Table 4: NO_x, CO_2, $PM_{2.5}$, VOC, and SO_2 Emission Factors for Power Generation in the Current Grid Scenario

State	**NO_x (lbs/MWh)**	**SO_2 (lbs/MWh)**	**CO_2 (lbs/MWh)**	**$PM_{2.5}$ (lbs/MWh)**	**VOC (lbs/MWh)**
CT	0.236	0.064	505	0.014	0.005
DC	0.601	0.368	442	0.082	0.023
DE	0.186	0.331	946	0.064	0.035
MA	0.622	0.239	455	0.120	0.156
ME	0.208	0.382	164	0.086	0.072
MD	0.601	0.368	442	0.031	0.020

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[70] EPA, Emissions & Generation Resource Integrated Database (eGRID), 2021, *see* https://www.epa.gov/egrid/egrid-related-materials#eGRID%20PM2.5 and https://www.epa.gov/system/files/documents/2022-01/egrid2020_summary_tables.pdf.

[71] National Renewable Energy Laboratory, Standard Scenarios, *see* Scenario Viewer (nrel.gov).

NH	0.131	0.130	128	0.046	0.008
NJ	0.122	0.022	490	0.013	0.014
NY	0.259	0.080	323	0.038	0.040
PA	0.260	0.293	693	0.045	0.008
RI	0.042	0.015	71	0.072	0.020
VT	0.148	0.120	28	0.007	0.071
VA	0.117	0.055	452	0.039	0.017

The emissions that result in the current grid scenario assume an immediate conversion to building electrification in the OTC states, based on the current electricity generation mix, without any demand management measures. This scenario does not estimate any changes in power plant emissions that would result from decarbonization of the electricity sector. Further, the analysis does not assume any load shifting, such as through grid-interactive heat pump water heaters, to mitigate impacts of electrification on system peaks. This means that the emissions from power plants modeled in the current grid analysis likely represent a worst-case scenario. In reality, electrification is likely to occur gradually as the grid simultaneously gets cleaner, and some negative impacts can be mitigated through the thoughtful deployment of demand flexibility and weatherization measures alongside electric technologies. To estimate how electricity-related emissions could change in a future year, we analyzed a future grid scenario, described in the next section.

Future Grid Scenario

Electricity-related emissions are likely to decline significantly in future years, given that grid emissions have steadily decreased in recent years[72] and most OTC states have committed to 100% clean electricity by 2040, as shown in Table 6. Almost all OTC state climate legislation and/or climate plans target net-zero grid emissions by 2050 or earlier. As states implement plans to reduce electricity sector emissions, criteria pollutant and GHG emissions will continue to decline in the region, making residential building electrification increasingly beneficial from an emissions standpoint.

Table 5: OTC State Targets for Electricity Decarbonization

State	Electricity Decarbonization Goal
CT	Eliminate GHG emissions from electricity by 2040[73]
DC	100% renewable electricity by 2032[74]
MA	Power sector GHG emissions 70% below 1990 levels in 2030,[75] 93% below 1990 levels in 2050[76]

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[72] Between 2005 and 2021, U.S. power-sector emissions declined 36%, *see* https://www.c2es.org/content/u-s-emissions/.

[73] State of Connecticut, Senate Bill No. 10, Public Act No. 22-5 An Act Concerning Climate Change Mitigation. Approved May 22, 2022, *see* https://www.cga.ct.gov/2022/act/pa/pdf/2022PA-00005-R00SB-00010-PA.pdf.

[74] Council of the District of Columbia, D.C. Law 22-257. Clean Energy DC Omnibus Amendment Act of 2018, *see* https://code.dccouncil.gov/us/dc/council/laws/22-257.

[75] Massachusetts Executive Office of Energy and Environmental Affairs, Massachusetts Clean Energy and Climate Plan for 2025 and 2030, page 63. June 30, 2022, *see* https://www.mass.gov/doc/clean-energy-and-climate-plan-for-2025-and-2030/download.

[76] Massachusetts Executive Office of Energy and Environmental Affairs, Clean Energy and Climate Plan for 2050, page 65. December 2022, *see* https://www.mass.gov/doc/2050-clean-energy-and-climate-plan/download.

MD	50% renewable electricity by 2030 and state planning to reach 100% clean power by 2040[77]
ME	80% renewable electricity by 2030, 100% renewable electricity by 2050[78]
NJ	50% renewable electricity by 2030,[79] 100% clean electricity by 2035[80]
NY	70% renewable electricity by 2030, 100% zero-emission electricity by 2040[81]
RI	100% renewable electricity by 2033[82]
PA	Goal articulated in PA climate plan for 100% renewable electricity by 2050[83]
VT	75% renewable electricity by 2032[84]
VA	100% zero carbon by 2050, net-zero carbon in electric sector by 2040[85]

In addition to evaluating state plans for grid decarbonization, we also researched completed or announced coal plant retirements in the region. These include: the Bridgeport Harbor unit in Connecticut, the Logan plant in New Jersey, and the Homer City and Cheswick power plants in Pennsylvania. We researched announced plant closures in the region and found that those closures will substantially reduce power plant emissions in the region.

To estimate grid emissions in future years, we used emission factors for calendar year 2044 in lbs/MWh from the NREL 2023 Standard Scenarios[86] and 2023 Cambium datasets.[87] Emission factors from NREL's 2023 Standard Scenario for NO_x, SO_2, CO_2, and $PM_{2.5}$ and from the 2023 Cambium datasets for CO_2 are shown in Table *6*.

Table 6: Emission Factors for the Future (2044) Grid Scenario

State/Region	**NO_x (lbs/MWh)**	**SO_2 (lbs/MWh)**	**CO_2 (lbs/MWh)**	**$PM_{2.5}$ (lbs/MWh)**	**VOC (lbs/MWh)**
DC	0.230	0.142	119	0.032	0.009
CT	0.190	0.049	430	0.011	0.004
DE	0.011	0.004	69	0.001	0.002
MA	0.121	0.052	245	0.026	0.030

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[77] Maryland Clean Energy Jobs Act of 2019, *see* https://mgaleg.maryland.gov/mgawebsite/Legislation/Details/SB0516?ys=2019RS.

[78] State of Maine S.P. 457 - L.D. 1494, An Act To Reform Maine's Renewable Portfolio Standard. Approved by Governor June 26, 2019, *see* https://legislature.maine.gov/bills/getPDF.asp?paper=SP0457&item=3&snum=129.

[79] New Jersey Clean Energy Act (P.L.2018, c.17). Signed on May 23, 2018.

[80] 2019 New Jersey Energy Master Plan: Pathway to 2050, *see* https://www.nj.gov/emp/docs/pdf/2020_NJBPU_EMP.pdf.

[81] New York State Climate Leadership and Community Protection Act. S. 6599. A.8429. June 18, 2019. Available at https://legislation.nysenate.gov/pdf/bills/2019/s6599.

[82] Amendments to R.I. Gen. Laws § 39-26-4, Renewable Energy Standard, signed June 29, 2022, *see* http://webserver.rilin.state.ri.us/Statutes/TITLE39/39-26/39-26-4.htm.

[83] Pennsylvania Climate Action Plan 2021, page 85, *see* https://www.dep.pa.gov/Citizens/climate/Pages/PA-Climate-Action-Plan.aspx.

[84] Renewable Energy Programs, Vermont Statute 30 V.S.A. § 8005, *see* https://legislature.vermont.gov/statutes/section/30/089/08005.

[85] Virginia Energy Plan; Climate Change Pressing Challenge. SB 94, HB 714. Signed by Governor on April 11, 2020, *see* https://lis.virginia.gov/cgi-bin/legp604.exe?201+sum+SB94.

[86] Gagnon, P., Pham, A., Cole, W.,"2023 Standard Scenario Report A U.S. Electricity Sector Outlook," National Renewable Laboratory Technical Report, NREL/TP-6A40-87724, Revised January 2024, *see* https://www.nrel.gov/docs/fy24osti/87724.pdf.

[87] National Renewable Energy Laboratory 2023 Cambium datasets, *see* https://www.nrel.gov/analysis/cambium.html.

ME	0.053	0.007	266	0.002	0.018
MD	0.230	0.142	119	0.012	0.008
NH	0.010	0.010	111	0.004	0.001
NJ	0.055	0.013	244	0.008	0.006
NY	0.044	0.010	0	0.005	0.007
PA	0.114	0.045	503	0.007	0.004
RI	0.052	0.010	100	0.048	0.023
VT	0.002	0.004	0	0.000	0.001
VA	0.024	0.013	91	0.009	0.004

We estimated criteria pollutant and GHG emissions for the future grid scenario by converting electricity consumption from ResStock (in kWh) to MWh and multiplying by the emission factors shown in Table 7 for each pollutant.

Step 4: Additional Analyses

We conducted two additional analyses, which are described below. The first estimated changes in ozone season NO_x emissions and the second evaluated a phase-in scenario for residential building electrification.

Estimate Ozone Season NO_x Emissions

A fraction of the estimated annual NO_x reductions occurs in the summer months when the ozone NAAQS are commonly exceeded at several monitors in the region. The ozone season spans 153 days annually from May 1 to September 30. Most of the residential building-related emissions during the ozone season are from water heating, clothes drying, and cooking since NO_x from space heating mainly occurs in the winter months.

To estimate NO_x emissions in the ozone season, we identified the source classification codes (SCCs) for fossil fuel combustion in residential buildings. To assist with this analysis, the Mid-Atlantic Regional Air Management Association (MARAMA) used EPA's Emissions Modeling Framework (EMF) and NEI's 2017 and 2020 temporalization files to estimate ozone season NO_x from the SCC codes listed in Table 7 .

Table 7: Source Classification Codes Used to Determine Ozone Season NO_x Emissions

SCC Code	**Category**	**Sector**	**Fuel Type**
2104004000	Stationary Source Fuel Combustion	Residential	Distillate Oil
2104005000	Stationary Source Fuel Combustion	Residential	Residual Oil
2104006000	Stationary Source Fuel Combustion	Residential	Natural Gas
2104006010	Stationary Source Fuel Combustion	Residential	Natural Gas
2104007000	Stationary Source Fuel Combustion	Residential	Liquified Petroleum Gas (LPG)

MARAMA's analysis found that ozone season emissions were 15% of the annual emissions in the 2020 NEI for the residential building sector. NESCAUM and OTC applied this fraction to the NO_x emission reductions calculated from the ResStock model outputs for the Whole Home Electrification scenario.

Estimate Annual Emissions Assuming a Phase-In of Residential Electrification

The approach described above assumes that building electrification happens instantaneously. To assist states in understanding how a phase-in of zero-emission appliances could help meet states' air quality and climate goals, we estimated annual emission reductions between 2030 and 2045 assuming a linear rate of residential building electrification for all three electrification scenarios. For the phase-in scenario, we assume a policy that requires replacement of fossil fuel space and water heaters, clothes dryers, and cooking appliances with heat pumps or electric cooking at the end of the useful life of each appliance. This analysis also incorporates the following assumptions:

- A start year of 2030 for a 100% requirement for all fossil fuel appliances to be replaced at the end of the appliance useful life with heat pumps or electric cooking;
- Fossil fuel-fired appliances have a useful life of 15 years;
- A consistent level of annual appliance turnover (e.g., 1/15th or 6.7% of appliances would be replaced in each year) regardless of factors such as state and federal incentive availability, sunset of IRA incentives, technology or cost advances, or differences in appliance useful life.

To estimate changes in electricity consumption and related emissions in the phase-in scenario, we assumed electricity consumption would increase gradually as appliances are converted from fossil fuels to heat pumps and electric cooking over the 15 years from 2030 to 2045. We estimated an annual increase in electricity consumption by dividing the change in consumption in MWh from the baseline to the Whole Home Electrification Scenario by 15. As a result, electricity consumption increases at a constant rate through 2045. We also established a phase-in for the future grid scenario. To do this, we assumed electricity-related emission factors would decrease at a constant rate each year to reflect the change from the current grid scenario to the future grid. We used the NREL 2044 grid electricity emission factors as the endpoint for grid emissions in 2045.

We used these phase-in assumptions to estimate net emissions changes for CO_2 and NO_x for each electrification scenario.

4. Results: Energy and Emissions Changes for Electrification Scenarios

This section presents results for the three electrification scenarios evaluated: 1) Water Heating Electrification; 2) Space Heating Electrification; and 3) Whole Home Electrification. Changes in energy consumption by state, fuel type, and scenario are provided first, followed by NO_x, CO_2, $PM_{2.5}$, SO_2, and VOC emission changes for each scenario for both the current and future grid.[88] For the Whole Home Electrification scenario, ozone season NO_x emissions are also provided, along with annual NO_x and CO_2 results for the phase-in of both residential building electrification and a cleaner grid.

Changes in Energy Consumption

All three electrification scenarios result in substantial reductions in energy consumption, factoring in both reductions in fuel consumption and changes in electricity consumption. This is because heat pumps

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[88] To calculate net emissions, we have summed onsite PM emissions and power-plant related $PM_{2.5}$ emission changes.

are more efficient than fuel-burning appliances and electric resistance heating, except at extremely low temperatures, when their efficiencies are similar to electric resistance heaters. Heat pumps are also more efficient than central and window air conditioners.

A summary of energy-related changes across the region for all three electrification scenarios is presented in Table 8. Positive numbers indicate a reduction in energy consumption and negative numbers indicate an increase in energy consumption. In the table, units for fuel consumption are not normalized but rather are presented in the typical units used for each fuel. Later tables show the fuel normalized as MWh for all fuels. As discussed above, the Whole Home Electrification scenario assumes implementation of all measures associated with the Water Heating and Space Heating Electrification scenarios, along with electrification of additional appliances. As a result, for fuel oil, natural gas, and propane, the Whole Home Electrification scenario results in the greatest reduction in fossil fuel consumption. The next greatest reduction in fossil fuels is seen in the Space Heating Electrification scenario because space heating appliances require the most energy of all the appliances evaluated in the study.

Table 8: Reduction in Energy Consumption for All Scenarios, Region-Wide

Scenario	Natural Gas (therms)	Fuel Oil (gallons)	Propane (gallons)	Electricity (MWh)
Water Heating	1,637,718,449	136,138,603	107,542,694	-1,652,995
Space Heating	11,978,529,074	3,801,599,851	1,033,061,846	-62,136,109
Whole Home	14,714,380,503	4,136,118,329	1,265,492,109	-54,801,730

As can be seen in Table 9, for the region as a whole, all three scenarios increase electricity consumption. The increase in electricity demand to power heat pumps results in this greater electricity consumption in all three scenarios, relative to the baseline. The Space Heating scenario has the largest increase in electricity consumption, followed by the Whole Home Electrification scenario. Even though more appliances are being switched to efficient electrification in the Whole Home scenario, less electricity is used in this scenario than in the Space Heating scenario. This is because of energy efficiency gains when central and window AC units are switched to heat pumps, and electric resistance water heating and clothes drying equipment are switched to heat pumps.

To compare the change in energy demand across fuels for the three scenarios, we normalized energy consumption by converting all energy into MWhs, as shown in Table 10. As in Table 9, positive numbers represent a decrease in energy consumption and negative numbers indicate an increase in energy consumption. The scenario with the greatest reduction in energy was for natural gas in the Whole Home scenario, followed by natural gas in the Space Heating Scenario. This is because natural gas is the most commonly used fuel for space and water heating in the region. The third largest reduction in fuel consumption was found for fuel oil in the Whole Home scenario. This is because many homes in the Northeast are heated with fuel oil, especially in areas that do not have access to natural gas pipelines.

Table 9: Change in Energy Consumption for All Scenarios, Region-Wide (MWh)

Scenario	Natural Gas (MWh)	Fuel Oil (MWh)	Propane (MWh)	Electricity (MWh)
Water Heating	49,187,034	18,669,717	4,987,173	-1,652,995
Space Heating	350,970,902	154,344,954	27,892,670	-62,136,109
Whole Home	431,131,349	167,926,404	34,168,287	-54,801,730

Figure 4 shows the change in annual consumption of propane, fuel oil, and natural gas for each of the 13 states analyzed for the Whole Home Electrification Scenario. Fuel volumes are normalized in MWh. Natural gas is shown in green, fuel oil in blue, and propane in black. The figure shows the differences between states in the types of fuel used. Natural gas is used in the greatest volume across the region and thus conversion to heat pumps and electric stoves and ovens reduces more natural gas than any other fuel. In some states, where heating oil represents a large share of heating fuels, such as Vermont, Connecticut, Maine, and New Hampshire, reductions in heating oil are greater than natural gas. Overall, the greatest reductions in fuel consumption are in New York, Pennsylvania, and New Jersey because the population is largest in these states. All states in the analysis would realize substantial reductions in fuel consumption in this scenario: over 600 million MWh of fuel is reduced annually across the region in the Whole Home Electrification scenario.

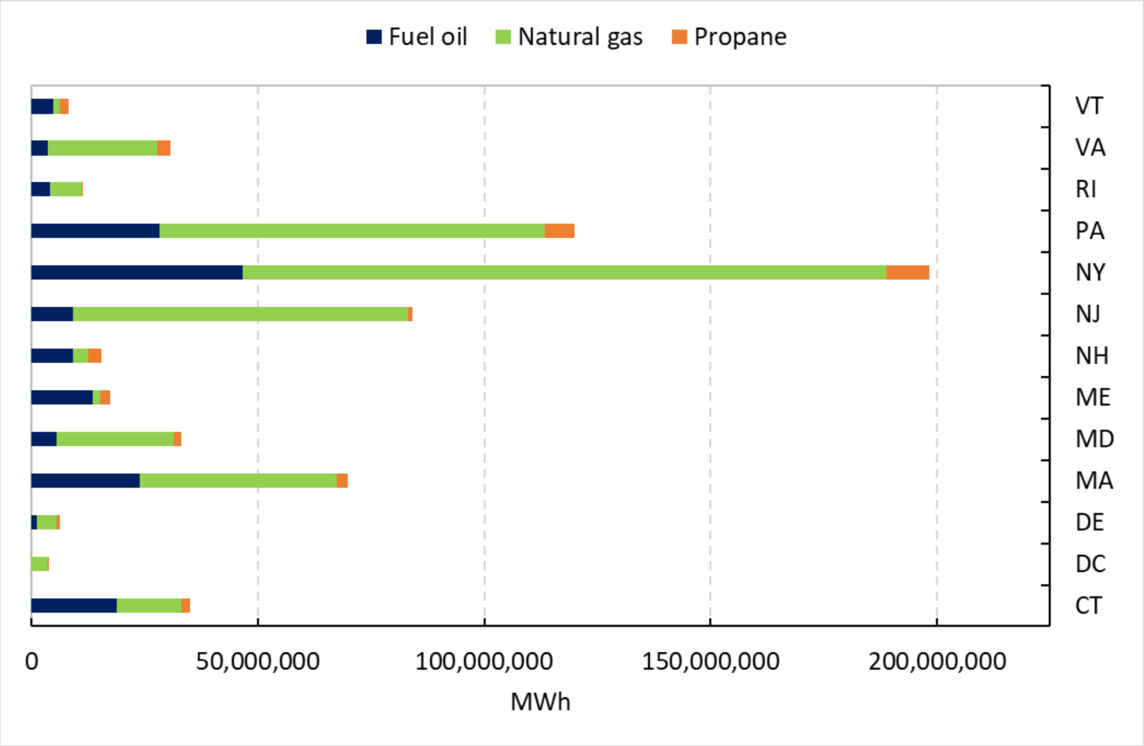

Figure 4: Whole Home Electrification Scenario: Reduction in Propane, Natural Gas, and Fuel Oil Consumption (MWh)

On a population-normalized basis, eight states had greater reductions in energy consumption than other states in the region. These states are Connecticut, Massachusetts, Maine, New Jersey, New York, Pennsylvania, Rhode Island, and Vermont. This is largely due to the greater requirement for space heating in these states. Cooling requirements are greater in the southern states, but cooling requires less energy than heating because the temperature differential between ambient air and indoor air is greater in the winter than in the summer. To compare energy consumption on a per capita basis, without the influence of differences in heating requirements, we normalized energy consumption by population-weighted degree days.[89] We found that states used approximately the same amount of energy when consumption was normalized by population and heating degree days.

Figure 5 illustrates the change in electricity consumption across all states analyzed in the Whole Home Electrification Scenario. Orange bars indicate an increase in electricity consumption with electrification and blue bars represent a decrease in consumption. Net decreases in emissions are shown as positive numbers and net increases in emissions are shown as negative numbers.

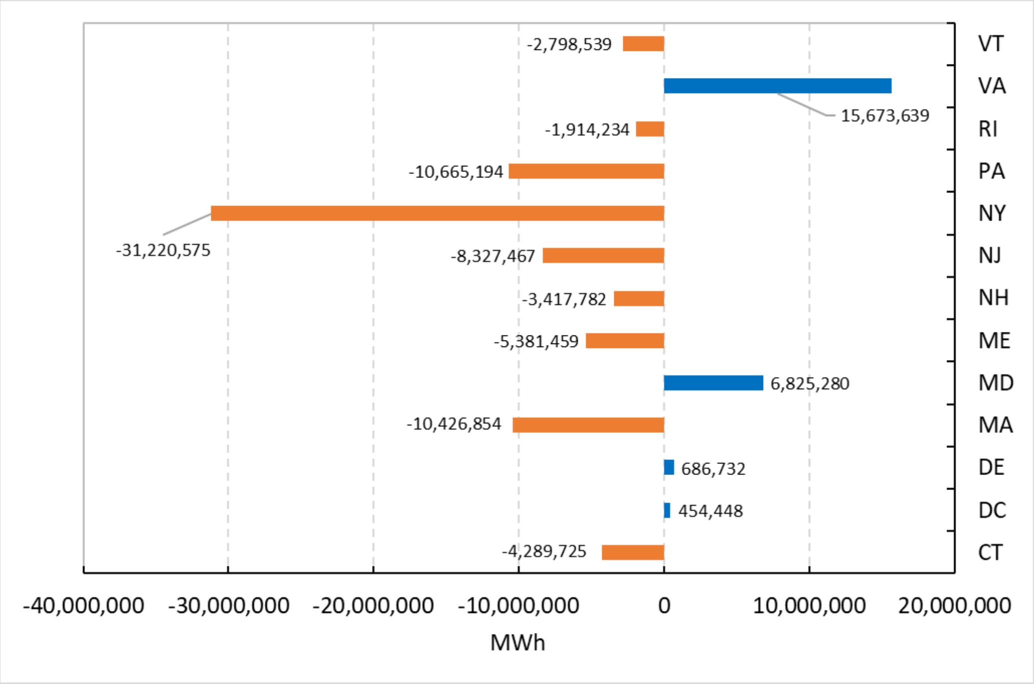

Figure 5: Change in Electricity Consumption, Whole Home Electrification Scenario

As noted earlier, most states in the region saw an increase in electricity consumption with a switch to heat pumps. However, Figure *5* shows that the Whole Home Electrification scenario reduces overall electricity consumption in Virginia, Maryland, Delaware, and DC due to the prevalence of electric resistance space and water heating and central air conditioning in the baseline. VSHPs are considerably more efficient than electric resistance space and water heaters, as well as central air conditioning systems. When these appliances are switched to heat pumps, overall electricity usage goes down, even as more appliances are electrified.

As noted earlier, in residences without central air conditioning or with only window air conditioning, all living space is assumed to be air conditioned after conversion to heat pumps. The level of air conditioning assumed in the ResStock model conforms to industry standards for cooling in the scenarios after heat pump installation.

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[89] Population-weighted degree days from the U.S. Energy Information Administration were used in this analysis, *see* Degree-days - U.S. Energy Information Administration (EIA).

In the four states that had overall lower electricity consumption after conversion to heat pumps, three also had lower electricity consumption for heating: DC, Maryland, and Virginia. This is due to widespread use of electric resistance heat in those states. In Delaware, electricity consumption for space heating increased in the electrification scenarios, likely due to a lesser amount of electric resistance heating in the baseline than in the three other states.

In the other nine states, electricity usage increases in the Whole Home Electrification scenario as fossil fuel-fired appliances are converted to heat pumps. Space heating is the largest driver of increased electricity consumption.

Emissions Changes: Water Heating Scenario

In the Water Heating Scenario, fuel-burning and electric resistance water heaters are converted to heat pump water heaters. No other appliances are converted. Certain water heaters, such as pool and hot tub heaters, are not included in this conversion analysis.

Table 10 shows results for the Water Heating scenario by pollutant and for the entire region. In the Table, three sets of results are shown. In column two, just the fossil fuel-related emission reductions from residential buildings are provided ("onsite"). This is the sum of fuel oil, gas, and propane related emission reductions that occur with the conversion of fossil fuel-fired water heaters to heat pumps. The third column shows onsite emission reductions plus changes in power plant-related emissions, or "net" emissions. In this case, power plant-related emissions assume the current electricity grid generation mix. In the fourth column, net emissions changes are provided for onsite emissions combined with electricity-related emissions assuming a future, cleaner electricity grid. Significant annual NO_x and CO_2 emissions reductions are shown for both onsite and the net cases in this scenario.

Table 10: Annual Water Heating Scenario Emissions Reductions, Onsite and Net

Pollutant	**Onsite Annual Tons Reduced**	**Net Annual Tons Reduced (current grid)**	**Net Annual Tons Reduced (future grid)**
NO_x	9,496	9,761	9,616
$PM_{2.5}$	182	212	190
CO_2	11,923,815	12,425,372	12,039,299
SO_2	66	342	155
VOC	518	504	517

As was discussed previously, a switch to efficient electrification could either increase electricity consumption (as fossil fuel equipment is replaced with heat pumps) or decrease electricity consumption as electric resistance heating is switched to heat pumps. In the Water Heating scenario, overall electricity consumption decreases across the region as water heating is converted to heat pumps and becomes more efficient. This illustrates how efficient electrification can benefit the grid in addition to helping states meet their air quality and climate goals. We see the greatest emission reductions for NO_x, $PM_{2.5}$, CO_2, and SO_2 in the third column of Table 11 where current grid emissions are assumed. As the grid becomes cleaner (in column four) total emissions reductions are still higher than the onsite only scenario but are slightly lower than the current grid scenario.

Table 11 presents net annual changes in NO_x, CO_2, $PM_{2.5}$, SO_2, and VOC emissions on a state-by-state basis for the Water Heating scenario. Net decreases in emissions are shown as positive numbers and net increases in emissions are shown as negative numbers.

Table 11: State-by-State Net Emissions Impacts for the Water Heating Scenario

State	**NO_x (net tons reduced)**		**CO_2 (net tons reduced)**		**$PM_{2.5}$ (net tons reduced)**		**SO_2 (net tons reduced /increased)**		**VOC (net tons reduced/ increased)**	
	2024 grid	2044 grid	2024 grid	2044 grid	2024 grid	2044 grid	2024 grid	2044 grid	2024 grid	2044 grid
CT	514	514	639,784	639,502	21	21	4	4	26	26
DC	84	71	95,435	83,779	3	1	14	6	4	4
DE	92	73	191,715	98,840	6	-1	35	1	8	5
MA	933	1,008	1,218,596	1,249,941	12	26	-28	0	31	50
MD	832	611	863,898	670,793	16	5	223	88	40	32
ME	218	212	259,543	263,226	15	12	16	2	12	10
NH	210	208	253,298	253,002	9	9	4	2	10	10
NJ	1,293	1,315	1,529,413	1,611,798	12	14	1	5	71	74
NY	2,736	2,867	3,444,856	3,642,104	28	48	-29	14	135	155
PA	1,867	1,855	2,376,088	2,359,637	41	38	38	17	101	101
RI	167	167	208,864	208,049	4	4	1	1	8	8
VA	707	607	1,215,020	829,722	41	10	62	17	52	37
VT	108	108	128,862	128,906	4	4	1	1	5	5
Total	**9,761**	**9,616**	**12,425,372**	**12,039,299**	**212**	**190**	**342**	**155**	**504**	**517**

Water heating electrification would decrease NO_x, CO_2, $PM_{2.5}$, and VOC emissions significantly in both the current and future grid scenarios. Table 12 provides more granular information on the impact of a changing grid on residential building electrification than did Table 11. In some states, grid emissions decline sharply and in others grid-related emissions stay largely the same between 2024 and 2044, as projected by the NREL Standard Scenario. This can be seen in small or large emissions changes between the current and future grid scenarios. In the 2044 grid scenario, one state, Delaware, has a slight $PM_{2.5}$ emissions increase. The reason for this increase is that fossil fuel-fired space heating is assumed to increase slightly to make up for cool air released from heat pump hot water heaters. There is no increase in the 2024 grid scenario because the reductions in electricity consumption and related emissions, as electric resistance water heaters are converted to heat pumps, offset additional emissions from fossil fuel heating. In the cleaner 2044 grid, however, energy savings and related power plant emissions that result from switching from resistance to heat pump hot water heaters no longer offset the small increase associated with the switch from fuel oil heating. This reflects the baseline condition for space heating in the ResStock model, which is that fossil fuel space heating is in use. However, with conversion of space heating to heat pumps, an emissions increase would not occur.

This can be seen in the Whole Home Electrification scenario where there is no increase in space heating-related emissions when hot water heaters are converted to heat pumps. This is because additional space heating is produced from emission-free heat pumps rather than oil and gas-fired furnaces. Net SO_2 decreases in 11 states in the 2024 grid scenario and increases in 2 states. Additional electricity-related SO_2 is the reason for the increase. In the 2044 grid scenario, SO_2 emissions decrease in all states.

Onsite water heater-related NO_x emissions decreases are realized over the entire year, including in the ozone season, providing air quality benefits in areas struggling to attain or maintain the NAAQS for ozone.

Emissions Changes: Space Heating Scenario

In the Space Heating scenario, fuel-burning furnaces, boilers, electric resistance heaters, and central and window air conditioning systems are converted to efficient heat pumps. No other appliances are converted in this scenario. Table 12 shows onsite and net emissions changes (onsite plus power plant emissions) that result from space heating conversions in the region as a whole. Net reductions are nearly ten times greater for the Space Heating scenario compared to the Water Heating scenario. As in the Water Heating scenario, net emissions are presented for both the current and future grid. Substantial NO_x, CO_2, $PM_{2.5}$, and VOC emissions are reduced in this scenario. Over 90,000 tons of NO_x are reduced annually, more than all the electric generating units produce each year in the region. Lower NO_x emissions from onsite fossil fuel combustion would also result in lower secondary $PM_{2.5}$ formation and its associated adverse health effects. Onsite SO_2 emission reductions result from eliminating fuel oil combustion for space heating. In the power sector, SO_2 emissions are driven by coal and distillate fuel use in power plants.

Table 12: Space Heating Scenario Emissions Changes, Onsite and Net

Pollutant	Onsite Annual Tons Reduced	Net Annual Tons Reduced/ Increased (current grid)	Net Annual Tons Reduced (future grid)
NO_x	96,372	87,717	94,235
$PM_{2.5}$	4,323	2,678	4,050
CO_2	120,279,844	108,949,589	113,901,554
SO_2	787	-3,858	303
VOC	4,856	3,123	4,506

Table 14 presents net annual changes in NO_x, CO_2, $PM_{2.5}$, and SO_2 emissions on a state-by-state basis for the current and future grid for the Space Heating scenario. VOC emission changes are not shown for each state. All states see a reduction in VOCs in the future grid scenario. In the current grid scenario, some states see a small VOC increase and most realize a decrease. In the table, emission reductions are shown as positive numbers and emission increases are shown as negative numbers.

Table 13: State-by-State Net Emissions Changes for the Space Heating Scenario

State	**NO$_x$ (net tons reduced)**		**CO$_2$ (net tons reduced)**		**PM$_{2.5}$ (net tons reduced)**		**SO$_2$ (net tons reduced /increased)**	
	Current grid	Future grid	Current grid	Future grid	Current grid	Future grid	Current grid	Future grid
CT	5,375	5,480	6,182,780	6,354,058	426	433	-88	-53
DC	552	499	657,163	611,267	15	7	55	23
DE	983	951	1,343,940	1,181,310	43	31	68	8
MA	7,589	10,253	11,211,806	12,328,438	-38	459	-1,177	-183
MD	6,310	5,422	7,157,822	6,384,450	231	186	918	377
ME	2,830	3,265	3,695,186	3,408,967	89	325	-1,037	15
NH	2,632	2,846	3,235,909	3,266,015	140	215	-203	9
NJ	11,048	11,305	12,705,481	13,648,781	210	230	-3	32
NY	25,756	29,097	32,234,702	37,254,094	620	1,138	-1,004	76
PA	16,500	17,344	18,396,811	19,525,404	460	689	-1,597	-124
RI	1,730	1,721	2,147,695	2,119,668	33	56	2	6
VA	5,077	4,510	8,163,080	5,961,892	344	164	364	109
VT	1,334	1,543	1,817,213	1,857,212	106	116	-158	8
Total	**87,717**	**94,235**	**108,949,589**	**113,901,554**	**2,678**	**4,050**	**-3,858**	**303**

As can be seen in Table 14, the magnitude of emissions reductions that could be achieved in each state with a shift to heat pumps shows the importance of electrifying heating systems in residential buildings.

Emissions Changes: Whole Home Electrification Scenario

The Whole Home Electrification scenario assumes the conversion of space and water heaters, clothes dryers, air conditioning, stoves, and ovens from fossil fuels or electric resistance to VSHPs and electric cooking appliances. Of the three scenarios evaluated, emission reductions are largest in this scenario because it includes all measures in the previous scenarios plus additional electrification measures, such as the installation of induction cooktops, electric ovens, and heat pump clothes dryers. Table 14 shows onsite and net (power plant plus onsite) annual emissions changes in the region for this scenario for the current and future grid. Note that these emission impacts assume full conversion of all applicable equipment, and therefore represent the annual emissions changes in a future year, such as 2045, when all residential appliances are assumed to be converted to heat pumps and other electric technologies.

As shown in Table 15, net annual emissions of NO$_x$ would be reduced by over 100,000 tons with electrification of space and water heating, clothes drying, and cooking appliances in the OTC states. This scenario would also result in the reduction of over 3,000 tons of primary PM$_{2.5}$ and more than 130 million tons of CO$_2$. Not shown here are the many tons of secondary PM$_{2.5}$ that could be avoided by greatly reducing NO$_x$ emissions from residential buildings. In the current grid scenario, net emissions for NO$_x$, CO$_2$, PM$_{2.5}$, and VOC are within 5% to 10% of onsite emissions reductions. Power plant-related SO$_2$ emissions increase in the current grid scenario but decrease in the future grid scenario, due to cleaner electricity generation. In the future grid scenario, net emissions reductions for some pollutants are nearly the same as onsite emissions reductions because we assume fossil fuel power plants have largely been replaced with emission-free electricity generation.

Table 14. Whole Home Electrification Scenario Emission Changes, Onsite and Net

Pollutant	Onsite Annual Tons Reduced	Net Annual Tons Reduced/Increased (current grid)	Net Annual Tons Reduced (future grid)
NO_x	113,555	106,027	111,810
PM	4,742	3,262	4,507
CO_2	141,773,232	132,248,859	136,044,259
SO_2	910	-2,928	642
VOC	5,774	4,124	5,445

Table 16 shows net annual emission reductions for the Whole Home Electrification scenario for each state. Each state would have substantial annual NO_x, VOC, and CO_2 emissions reductions in this scenario. States in the southern part of the region realize reductions in net SO_2 emissions because lower electricity consumption resulting from the conversion of resistance heating and air conditioning systems to heat pumps outweighs emissions increases from electricity generation needed to power heat pumps. In other states, the reductions in SO_2 emissions from heating oil combustion offsets some but not all of the increases in SO_2 emissions from the power sector.

The current grid scenario assumes full conversion of all fossil fuel appliances to heat pumps with current grid emissions and does not account for the cleaner grid that will occur as states decarbonize electricity. Because of this, the future grid scenario likely represents emissions reductions at a future date when a full conversion to heat pumps is realized. With future grid assumptions, all emissions decrease, with the exception of SO_2 in Connecticut, Massachusetts, and Pennsylvania. Table 16 provides results for all states with both the current and future grid emissions assumptions.

Table 16: State-by-State Net Emission Changes for the Whole Home Electrification Scenario

State	NO_x (net tons reduced)		CO_2 (net tons reduced)		$PM_{2.5}$ (net tons reduced)		SO_2 (net tons reduced /increased)	
	current grid	future grid	current grid	future grid	current grid	future grid	current grid	future grid
CT	6,352	6,451	7,423,337	7,584,201	473	480	-72	-39
DC	701	616	819,297	745,904	22	11	87	36
DE	1,167	1,106	1,684,330	1,383,198	54	32	121	9
MA	9,500	12,112	13,569,778	14,664,598	37	524	-1,138	-163
MD	7,774	6,508	8,680,873	7,578,590	267	204	1,298	526
ME	3,274	3,691	4,219,299	3,944,845	128	355	-989	20
NH	3,042	3,249	3,727,812	3,756,863	163	236	-192	13
NJ	13,433	13,712	15,618,916	16,643,194	236	259	6	44
NY	31,028	34,384	38,845,070	43,887,192	740	1,260	-972	113
PA	19,927	20,684	22,906,243	23,919,437	563	768	-1,396	-74

RI	2,033	2,024	2,527,152	2,499,396	45	68	4	8
VA	6,258	5,529	10,170,859	7,341,767	418	186	465	137
VT	1,538	1,742	2,055,894	2,095,074	116	125	-152	10
Total	**106,027**	**111,810**	**132,248,860**	**136,044,259**	**3,261**	**4,507**	**-2,928**	**642**

The largest emissions reductions are realized in New York, Pennsylvania, and New Jersey, because the number of residential housing units is highest in these states. However, all states realize substantial emissions reductions in the Whole Home Electrification scenario. The regional CO_2 emission reductions in this scenario are equivalent to removing 27 million cars from the road for a year and lowering gasoline consumption by 14 billion gallons annually.[90] As such, residential building electrification is one of the most effective measures states can take to reduce criteria and GHG emissions.

Table 17 shows changes in electricity-related emissions only for each state, without onsite emission reductions. Reductions are shown for the Whole Home Electrification scenario. Electricity-related NO_x emissions decrease in the District of Columbia, Delaware, Maryland, and Virginia but increase for the other states in the current grid scenario. The increases are small relative to the large onsite emissions reductions that can be achieved with residential building efficient electrification.

Table 15: Whole Home Electrification Scenario Electricity Generation-Related Emissions Changes

State	**NO_x (tons reduced/ increased)**		**CO_2 (tons reduced/increased)**		**PM (tons reduced/ increased)**		**SO_2 (tons reduced/increased)**	
	Current grid	Future grid	Current grid	Future grid	Current grid	Future grid	Current grid	Future grid
CT	-506	-408	-1,083,156	-922,291	-30	-23	-137	-104
DC	137	52	100,433	27,040	19	7	84	32
DE	64	4	324,824	23,692	22	0	113	1
ME	-3,243	-631	-2,372,109	-1,277,290	-625	-137	-1,247	-272
MD	2,051	785	1,508,387	406,104	104	41	1,256	484
MA	-560	-143	-441,280	-715,734	-231	-5	-1,028	-20
NH	-224	-17	-218,738	-189,687	-79	-6	-222	-17
NJ	-508	-229	-2,040,229	-1,015,951	-55	-32	-93	-55
NY	-4,043	-687	-5,042,123	0	-592	-71	-1,247	-162
PA	-1,365	-608	-3,695,490	-2,682,296	-242	-36	-1,562	-240
RI	-40	-50	-67,955	-95,712	-69	-46	-14	-10
VA	917	188	3,542,243	713,151	305	73	429	100
VT	-207	-3	-39,180	0	-10	0	-168	-6
Total	**-7,528**	**-1,745**	**-9,524,373**	**-5,728,974**	**-1,481**	**-235**	**-3,837**	**-268**

As noted earlier in this report, emissions reductions that could be achieved by converting residential wood burning appliances to heat pumps were not estimated in this study. For context, however, Table

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[90] EPA GHG equivalency calculator, *see* https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator#results.

18 lists total annual NO_x, CO_2, $PM_{2.5}$, and SO_2 emissions from residential wood burning in the OTC states, as reported in EPA's 2020 National Emissions Inventory. The 2020 inventory of emissions for residential wood burning shows that, in the region as a whole, $PM_{2.5}$ emissions from wood burning are much greater than $PM_{2.5}$ emissions from fossil fuel combustion in residential buildings. $PM_{2.5}$ emissions from fossil fuel combustion in residential buildings are approximately 5,600 tons according to the 2020 NEI, less than 5% of the $PM_{2.5}$ from wood burning. Conversely, NO_x and CO_2 emissions from residential buildings using fossil fuels for space and water heating are much higher than from residences relying on wood burning for heating.

Table 16: 2020 NO_x, CO_2, $PM_{2.5}$, and SO_2 Emissions from Residential Wood Burning in the Region

	NO_x (tons)	**CO_2 (tons)**	**$PM_{2.5}$ (tons)**	**SO_2 (tons)**
OTC State Total	12,735	858,266	135,586	3,811

Ozone Season NO_x Emissions

Table 19 shows ozone season reductions that could be realized with full electrification of residential buildings across the region. In the region overall, ozone season NO_x is reduced by approximately 16,000 tons in the Whole Home Electrification scenario. In every jurisdiction, at least one ton of NO_x per ozone season day could be mitigated with a conversion of fuel-burning appliances to VSHPs. In the largest state (New York), nearly 30 tons of NO_x could be reduced per ozone season day, assuming there are 153 days in the ozone season.

Table 17: Ozone Season NO_x Reductions for the Whole Home Electrification Scenario

State	**Ozone Season NO_x Reduction (net tons – current grid)**	**Ozone Season NO_x Reduction (net tons – future grid)**
CT	953	968
DC	105	92
DE	175	166
ME	1,425	1,817
MD	1,166	976
MA	491	554
NH	456	487
NJ	2,015	2,057
NY	4,654	5,158
PA	2,989	3,103
RI	305	304
VA	939	829
VT	231	261
Total	**15,904**	**16,771**

In addition to assisting states in meeting the NAAQS for ozone, the NO_x reductions resulting from the efficient electrification of residential buildings would assist states in meeting the regional haze requirement that natural visibility conditions (i.e., no human-caused visibility impairment) be met in certain national parks and wilderness areas by 2064. Meeting these goals will require sustained reductions in haze forming emissions. This is especially relevant to this study because the importance of wintertime nitrates has been increasing in recent years and they are becoming a more significant contributor to poor visibility.[91] NO_x emissions impair visibility by contributing to secondary formation of nitrate $PM_{2.5}$. From this analysis, we can see that a substantial amount of NO_x is emitted in the wintertime from fuel use in space heating and other appliances.

Phased Introduction of Zero-Emission Appliances

The results reported so far have been annual emissions changes assuming instantaneous electrification of all residential appliances. We also modeled a simplified phase-in scenario in which all homes are electrified gradually over a 15-year period, with emissions calculated annually for calendar years 2030 to 2045. The scenario includes emission reductions from the phase-out of residential fossil fuel consumption as well as electricity generation-related emissions. The phase-in assumes that 6.7% of fossil fuel appliances are replaced each year with heat pumps, beginning in 2030 as appliances are replaced at end of life. It also assumes that the electric grid gradually becomes cleaner each year through 2044. Therefore, this scenario provides an estimate of the annual emissions reductions that could be achieved if states were to implement policies that require sales of new residential appliances to be zero-emission starting in 2030, while the grid simultaneously gets cleaner.

Figure 6 shows CO_2 emissions reductions in 2035, 2040, and 2045 for the phase-in analysis. Space heating-related CO_2 reductions are shown in blue, water heating in orange, cooling/clothes drying/cooking in gray, and other sources such as fans in dark blue. The Whole Home Electrification scenario is the sum of the four colors combined. Assuming a start year of 2030 for a 100% requirement for all fossil fuel appliances to be replaced at the end of their useful lives with heat pumps or electric cooking, and assuming all central and window air conditioners are replaced with heat pumps, in 2035, approximately 40 million net tons of CO_2 would be reduced annually regionwide. CO_2 reductions rise to 80 million tons reduced each year in 2040, and over 130 million tons in 2045. The reduction in 2045 represents a full phase-in of heat pumps for space heating, water heating, cooling, clothes drying, and induction stoves for cooking, with a cleaner 2044 grid.

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[91] Davis, S.; Healy, D.; Karambelas, A., "The Changing Nature of Visibility Impairment in the Northeast/Mid-Atlantic Visibility (MANE-VU) Region," EM, April 2022, *see* https://www-f.nescaum.org/documents/the-changing-nature-of-visibility-impairment-in-the-mid-atlantic-northeast-visibility-union-mane-vu-region/changing-nature-visibility-mane-vu-region-em202204.pdf.

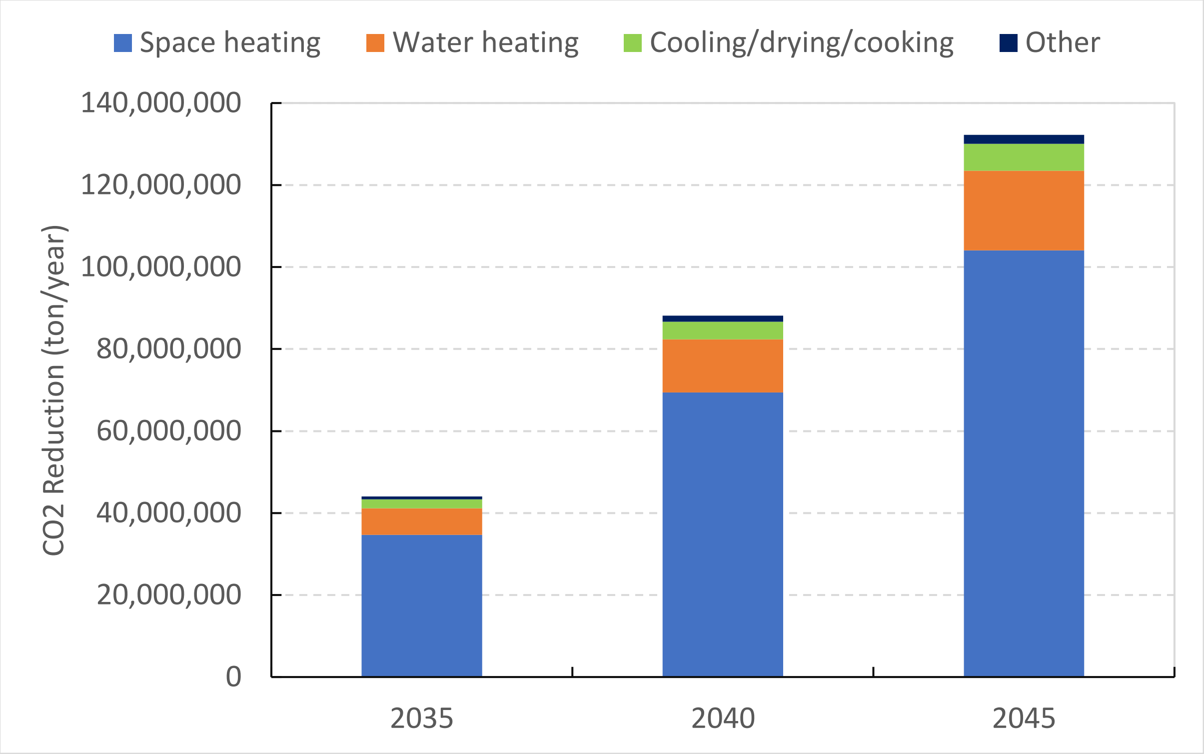

Figure 6: Annual CO_2 Reductions in the Whole Home Scenario Assuming Replacement at the End of Useful Life

We also estimated NO_x emission reductions for the phase-in scenario. As seen in Figure 7, NO_x reductions exceed 35,000 tons in the OTC states by 2035. By 2040, 72,000 tons of NO_x would be reduced annually in the region. And by 2045, over 106,000 tons of NO_x are reduced annually. Approximately 20% of the NO_x reduced in 2035 (over 7,000 tons) would be from sources that emit year-round and thus contribute in the summer months to ozone formation. Also in 2035, approximately 1,500 tons of NO_x would be reduced from cooling equipment related emissions (these are electric grid-related emissions) exclusively in the ozone season.

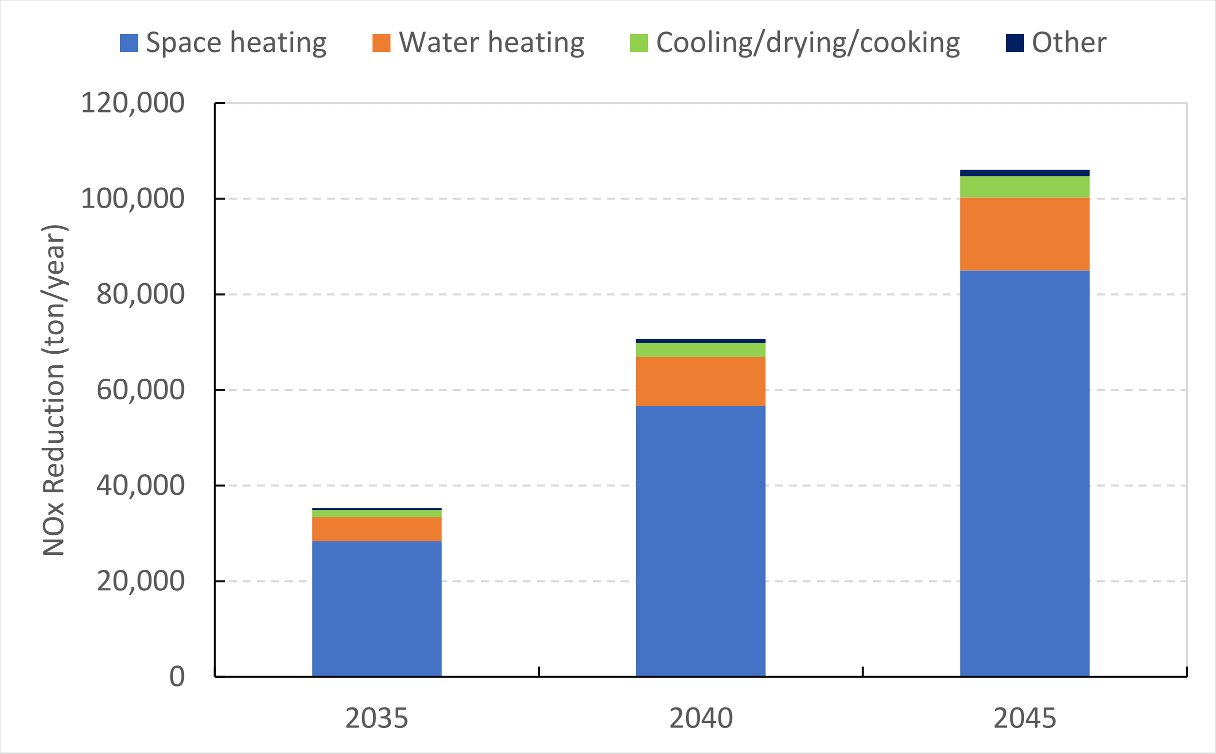

Figure 7: Annual NO_x Reductions in the Whole Home Scenario Assuming Replacement at the End of Useful Life

In 2040, approximately 7,500 tons of this NO_x would be reduced from operating more efficient cooling equipment, water heaters, clothes dryers, and cooking equipment in the ozone season. By 2045, approximately 11,000 NO_x tons are reduced in the ozone season from heat pump air conditioning, water heating, and clothes drying.

5. Conclusions

Substantial reductions in criteria pollutant and GHG emissions can be realized in the OTC region through efficient residential building electrification. Whole home electrification provides the greatest reductions in NO_x and CO_2 emissions. Space heating electrification is a significant portion of these reductions, with smaller contributions from electrification of water heating, clothes drying, and cooking.

Energy Consumption Changes

- In all three residential electrification scenarios, total energy consumption decreases significantly. More natural gas is reduced than any other fuel type in all scenarios.
- 14 billion therms of natural gas, 4 billion gallons of fuel oil, and 1 billion gallons of propane could be reduced through whole home electrification.
- In four jurisdictions (District of Columbia, Delaware, Maryland, and Virginia), electricity consumption is projected to decline with whole home electrification, due to replacement of electric resistance heat and central or window unit air conditioning with energy-efficient VSHPs.
- For other states, electricity consumption is projected to increase with whole home electrification, as fossil fuel-fired appliances are replaced. Across the region, electricity

consumption would increase by 54,000 GWh annually if all homes were fully electrified, if no demand management strategies are deployed.

Emission Changes

- A switch of all housing units in the region to heat pumps and other electric appliances would result in 106,000 tons of NO_x, more than 4,000 tons of $PM_{2.5}$, and 132 million tons of CO_2 reduced annually, net of power plant-related emissions with the current generation mix on the electricity grid.
- Space heating emissions make up approximately 85% of residential building emissions; converting current heating systems to efficient heat pumps would reduce over 108 million tons of CO_2 and 87,000 tons of NO_x annually.
- Converting fossil fuel and electric resistance water heaters to heat pump water heaters would reduce over 12 million tons of CO_2 and nearly 10,000 tons of NO_x annually.
- Ozone season NO_x emissions would be reduced by approximately 16,000 tons over the 153-day ozone season each year across the OTC states with whole home electrification, and the NO_x savings from water heating electrification are particularly valuable during the ozone season.
- For the region as a whole, assuming the current power plant mix in the Northeast and Mid-Atlantic, increased electricity generation from whole home electrification would reduce the total emissions benefit from residential electrification by 7% for NO_x, 7% for CO_2, and 31% for $PM_{2.5}$, before factoring in that electricity grids are likely to get cleaner over time.
- Assuming the grid continues to become cleaner in alignment with state goals and planned power plant retirements, increased electricity generation from residential building electrification would reduce the total emissions benefit of residential electrification by a small fraction: 2% for NO_x, 5% for $PM_{2.5}$, and 4% for CO_2.
- With the introduction of a zero-emission standards in 2030 for newly installed appliances and phased replacement of household appliances at the end of their useful life, NO_x emissions could be reduced in the region by over 35,000 tons in 2035, 72,000 tons in 2040, and 106,000 tons in 2045, net of power plant related emissions. This assumes a gradual transition to a cleaner electric grid between now and 2045.
- Using the same phase-in assumptions for zero-emission equipment standards, CO_2 could be reduced in the region by 40 million tons in 2035, 80 million tons in 2040, and over 130 million tons in 2045, assuming a transition to a cleaner grid over the same time period.
- Reductions in emissions from residential building efficient electrification would help states reach their air quality, public health, climate, and regional haze goals.

Based on the findings of this analysis, all jurisdictions in the OTC would realize significant emissions reductions from implementing policies that require or encourage a switch from fossil fuel heating, cooking, and clothes drying to heat pumps and electric cooking.

6. Potential Additional Research

Non-Linear Phasing-in of Emission Benefits

This study includes a simplified estimate of emission reductions if electrification was phased in starting in 2030. A more detailed study of annual changes in emissions might include assumptions about how the increased federal or state funding could change the uptake for electrification technologies. A future study could also model emissions impacts for specific building electrification policies and timelines that states propose, which would provide a more accurate estimate of state-specific impacts than the simplified analysis conducted here. Such an analysis could assist states in determining how appliance emissions standards and other building electrification policies could help them meet their climate, air quality, and public health goals.

Electricity Grid Impacts

This analysis assumes an immediate conversion to residential building electrification in the Northeast and Mid-Atlantic without inclusion of demand management measures. A future study could incorporate strategies to mitigate impacts of electrification on system peaks, such as weatherization to reduce peak demand or load shifting through grid-interactive heat pump water heaters or time of use electricity rates. Further analysis could also include a more detailed analysis using EPA's AVERT or other models to assess the impacts of state requirements to increase renewable energy generation and decarbonize the grid. At the same time, future studies should evaluate when and where localized increases in emissions from power plants due to building electrification could occur, and consider the health and equity impacts on the communities affected.

Compare the Emissions for Residential Wood Burning and Residential Fossil Fuel Use

NESCAUM's Residential Heating Task Force is evaluating emissions from residential wood heating in the region. This work includes refining the criteria pollutant and GHG emissions inventories for residential wood burning and evaluating emission factors from different types of wood-burning devices. Further analysis could estimate the criteria pollutant and GHG emission reduction potential of replacing wood burning for residential space and water heating with heat pumps.

Commercial Building Emissions Analysis

NREL has developed a commercial building stock model (ComStock™)[92] which segments commercial buildings into 168 subgroups based on climate region, building type, building size, and heating, ventilating, and air-conditioning (HVAC) classification. For each subgroup, ComStock quantifies the thermal energy use (defined here as energy for HVAC and water heating) by end use and segment. This allows for prioritization of different building segments and technologies for targeted efficiency or electrification upgrades. One possible area of future work is to replicate the analysis completed for the residential sector for the commercial sector, using NREL's ComStock model.

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[92] For more information on the ComStock model, *see* https://www.nrel.gov/buildings/comstock.html.