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)

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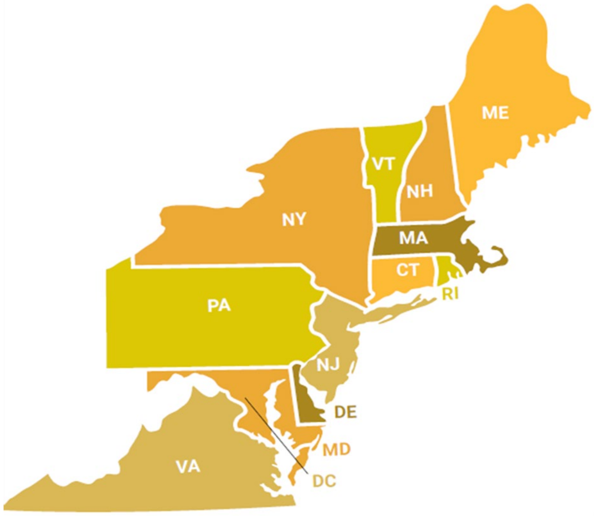
Acronyms

ACCA	Air Conditioning Contractors of America
ANSI	American National Standards Institute
BAAQMD	Bay Area 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
COBRA	Co-Benefits Risk Assessment
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 gases
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 Environment
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
NOx	nitrogen oxides
NEI	National Emissions Inventory
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
UEF	uniform energy factor
VSHP	variable speed heat pumps

1. Introduction

Geographic Area of NESCAUM and OTC Analysis



This report summarizes findings from an analysis of changes in emissions of nitrogen oxides (NOx), particulate matter (PM), carbon dioxide (CO_2), and sulfur dioxide (SO_2) that could result from residential building electrification in the Northeast and Mid-Atlantic – 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. The report also summarizes changes in natural gas, fuel oil, propane, and electricity consumption that could result from efficient residential building electrification. The impact of switching from electric resistance space heating and central and window air conditioning to heat pumps was also estimated. The 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.

The 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.[4] 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 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.

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

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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 NOx and volatile organic compounds, 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] 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.

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 NOx, PM, methane (CH_4), nitrous oxide (N_2O), CO_2, and hazardous air pollutants, such as benzene, formaldehyde, and toluene.[5,6] 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.[7,8,9]

Criteria Pollutant Emissions

According to EPA's National Emissions Inventory (NEI), onsite fuel combustion in residential buildings was responsible for 10% of total NOx emissions in the OTC states in 2020.[10] An additional 7% of NOx emissions resulted from fuel combustion in commercial and institutional buildings such as offices, retail space, schools, and government buildings. Figure 1 shows the relative contribution of fuel burning in residential and commercial buildings to overall NOx 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 building-related NOx emissions in OTC states is the fourth largest contributor after on-road vehicles, nonroad equipment and machines, and industrial processes.

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[5] 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/.

[6] Lebel, E.D.; Finnegan, C.J.; Ouyang, Z.; Jackson, R.B., "Methane and NOx 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.

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

[8] 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/.

[9] 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/.

[10] 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.

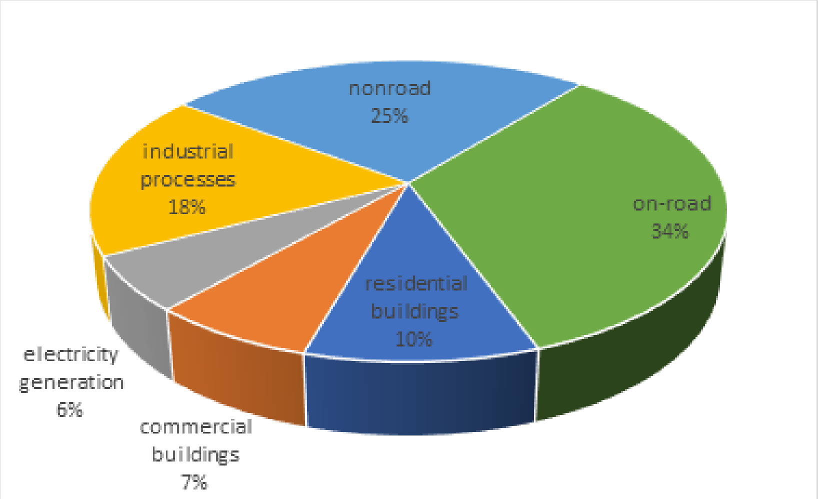

Figure 1: Sources of Annual NOx Emissions in the Ozone Transport Region

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

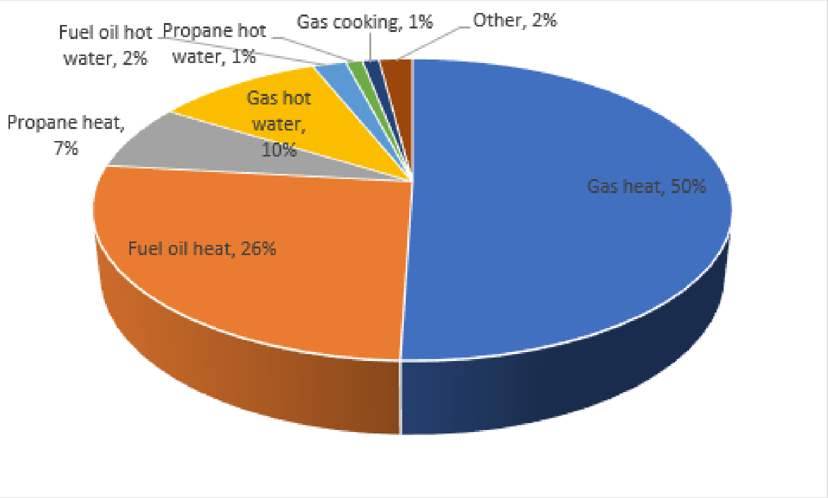

Figure 2: Annual NOx Emissions in the Region by Building Appliance/Fuel Type (Residential Buildings)[11]

NOx emissions are the major driver of surface ozone concentrations at the regional scale in the eastern United States. The ozone season spans 153 days from May 1 to September 30. Fuel combustion for water heating contributes a majority of onsite residential NOx 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 NOx.

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[11] 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.

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, the 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)[12]**	**2015 NAAQS Status**	**2008 NAAQS Status**
Greater Connecticut, CT	1,629,115	0.073	Moderate	Attaining
New York City, NY-NJ-CT	20,217,137	0.082	Moderate	Severe
Philadelphia-Wilmington-Atlantic City, PA-NJ-MD-DE	7,437,135	0.074	Moderate	Attaining
Baltimore, MD	2,662,691	0.072	Moderate	Attaining
Washington, DC-MD-VA	5,136,216	0.071	Moderate	Maintenance

While ozone is largely a summertime issue in the region, NOx is a year-round problem, due to its role in acid deposition and the eutrophication of waterbodies, as well as the formation of secondary fine particulate matter ($PM_{2.5}$). $PM_{2.5}$ exposure is associated with a variety of health effects, including reduced lung function, irregular heartbeat, asthma attacks, heart attacks, and premature death in people with heart or lung disease.[13] Because of its role in secondary particulate formation, reducing NOx emissions 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 Environment (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. Wintertime NOx emissions from sources such as buildings can lead to the formation of nitrates that impair visibility.

The public health and environmental impacts of NOx are summarized in Table 2.

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

[13] 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).

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

Ozone and $PM_{2.5}$ Formation	• 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
Acid Deposition	• Damages forests • Damages aquatic ecosystems, e.g., Adirondacks and Great Northern Woods • Erodes manmade structures
Coastal and Marine Eutrophication	• Depletes oxygen in the water, which suffocates fish and other aquatic life in bays and estuaries, e.g., Chesapeake Bay, Narragansett Bay, and Long Island Sound
Visibility Impairment	• Contributes to regional haze that mars vistas and views in wilderness and urban areas

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 $PM_{2.5}$ was emitted from fossil fuel combustion in buildings in 2020.[14] 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

GHG emissions from commercial and residential buildings accounted for 13% percent of GHG emissions in the United States in 2022.[15] Approximately 89% of residential and 54% of commercial onsite GHG emissions were from the burning of fossil fuels.[16] Figure 3 provides a breakdown of GHG emissions sources and shows that U.S. residential and commercial buildings are the fourth largest contributors, after transportation, electric power, and industry.

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[14] See footnote 10.

[15] 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.

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

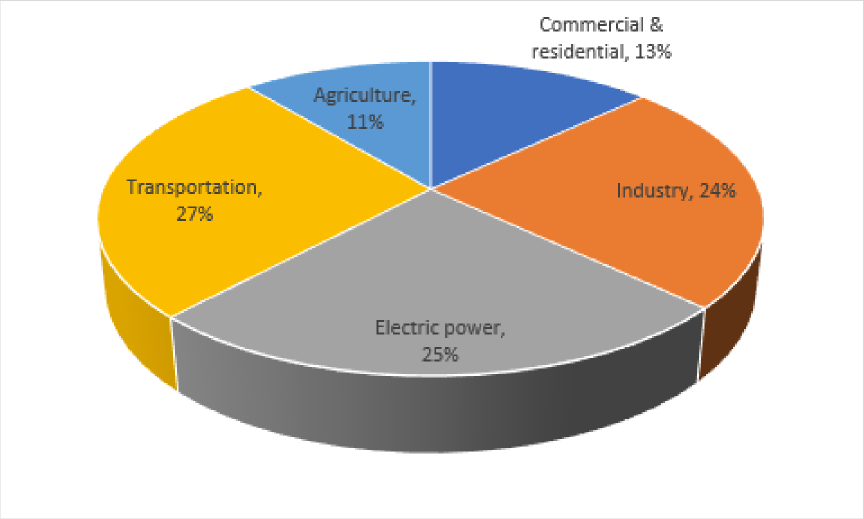

Figure 3: Commercial and Residential Building-Related GHGs as a Fraction of Total U.S. GHG Emissions

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 State estimates that residential and commercial buildings emit 34% of total GHG emissions in the state[17] and New Jersey found that building-related GHG emissions make up 26% of overall GHG emissions.[18]

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. have adopted NOx emissions limits for natural gas-fueled water heaters.[19] In general, however, regulations to reduce building-related criteria pollutant and GHG emissions have lagged behind controls 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. 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.[20]

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

[18] 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.

[19] 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 1121.

[20] 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.

Building Emission Reduction Targets in the Northeast and Mid-Atlantic

Many states have established ambitious 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 regions.

Table 3: Example State Building-Related Targets

State	Near-Term Targets	Long-Term Targets
Maryland	20% reduction in net GHG by 2030 for buildings covered by a statewide Building Performance Standard.[21]	Net-zero GHG for covered buildings by 2040.[22]
Massachusetts	29% reduction in GHGs from residential buildings and 35% reduction from commercial buildings in 2025. 49% reduction in GHGs from residential and commercial buildings in 2030.[23]	Statewide target to reduce GHGs to net zero by 2050 with corresponding sector targets.[24]
New York	Electrify 1-2 million homes with heat pumps by 2030 and 10% to 20% of commercial space.[25]	85% of homes and commercial building space statewide should be electrified by 2050.[26]
New Jersey	Convert 22% of residential and commercial buildings to electric by 2030.[27]	Reduce residential and commercial building GHG emissions 89% by 2050.[28]

Other states in the region have also set building sector GHG reduction requirements or recommendations in statute, executive order, 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.

State Policy Examples

Zero-Emission Standards for Water and Space Heating Equipment

Zero-emission equipment standards are an emerging policy in which state and local air quality agencies require that water and space heating equipment installed after a future date has zero onsite emissions. In March 2023, the Bay Area Air Quality Management District (BAAQMD) in California became the first jurisdiction in the nation to promulgate zero-NOx equipment standards when it voted to approve Regulations 9-4 and 9-6, requiring the sale of zero-NOx emitting water and space heaters. The zero-NOx

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

[22] Ibid.

[23] 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.

[24] 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).

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

[26] Ibid.

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

[28] 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.[29] 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.

The California Air Resources Board (CARB) included a measure in its 2022 State Implementation Plan (SIP) Strategy to develop zero-emission standards for space and water heaters sold in California.[30] When implemented, the measure will regulate GHG emissions from space and water heaters. It was included in the SIP Strategy because of the significant NOx 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 NOx emissions, would be the primary way to comply with this regulation. CARB estimates the measure would reduce NOx by 13.5 tons per day and reactive organic gases by 1.5 tons per day in 2037. CARB is beginning a public process in 2023 and expects to bring the zero-emission rules to its Board for approval in 2025.

Among the OTC states, New York is considering zero-emission equipment standards as a strategy to support the Climate Scoping Plan's electrification goals. The 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.[31] 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. It also recommends that regulations should be coordinated with action taken by the Public Service Commission and New York State Department of Public Service to regulate gas utilities and with the New York State Department of Labor and the Office of Just Transition to promote workforce development.

Clean Heat Standards

Other states in the region are exploring clean heat standards (CHS), a policy in which heating energy suppliers are required to replace fossil heating fuels with clean heat over time by implementing clean heat measures (e.g., heat pumps, weatherization, or low-carbon fuels) or purchasing credits.[32] 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.[33] The Plan tasks the Massachusetts Department of Environmental Protection with developing a "a high-level program to meet the emissions limit for residential, commercial, and industrial heating" and identifies a CHS as a

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[29] 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).

[30] 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.

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

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

[33] 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.

regulatory option for addressing this requirement. A CHS requiring GHG reductions from heating fuels is currently under development.

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.[34] Vermont's Affordable Heat Act legislation followed this recommendation and became law on May 11, 2023.[35] 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 for final approval before the CHS would be implemented.[36]

Building Performance Standards

Several states and cities in the Northeast and Mid-Atlantic have adopted Building Performance Standard (BPS) policies to tackle emissions from existing buildings. BPS require larger existing buildings to achieve certain levels of whole-building GHG emissions or energy performance. The District of Columbia has established a Building Energy Performance Standard setting specific targets for energy use intensity (EUI) in D.C. 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 requires the state to develop Building Energy Performance Standards that achieve a 20% reduction in net direct GHGs from covered buildings by 2030 and net-zero direct GHGs from covered buildings by 2040.[37] Maryland initiated a rulemaking process in 2022 and anticipates finalizing the standards in late 2023. Several large cities and counties in the region, including Boston and New York City, 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 NOx, PM, CO_2, and SO_2 emissions using EPA's AP-42 emission factors for the baseline and three building electrification scenarios[38,39]; 3) estimate the NOx, CO_2, SO_2, and $PM_{2.5}$ emissions from power plants for the baseline and three building

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

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

[36] "Clean heat bill clears final hurdle as House overrides Phil Scott's veto," VTDigger, May 11, 2023, *see* https://vtdigger.org/2023/05/11/clean-heat-bill-clears-final-hurdle-as-house-overrides-phil-scotts-veto/.

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

[38] EPA, "AP-42 Fifth Edition, Volume I Chapter 1: External Combustion Sources," *see* https://www.epa.gov/air-emissions-factors-and-quantification/ap-42-fifth-edition-volume-i-chapter-1-external-0.

[39] AP-42 provides emission factors for filterable particulate matter which includes $PM_{2.5}$, but AP-42 does not provide emission factors for $PM_{2.5}$ alone.

electrification scenarios; [40] and 4) conduct two additional analyses, an estimate of ozone season NOx 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) **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) **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.

None of the above scenarios replace fuel-fired appliances solely 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.[41] 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.

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[40] Particulate matter emission factors for electricity generation are in the form of $PM_{2.5}$.

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

- 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 account for the largest share of residential thermal end-use energy and constitute the majority of residential buildings in the United States. Only mobile homes have a higher thermal end-use intensity.[42] However, multifamily units predominate in 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.[43] 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 (Water Heating, Space Heating, and Whole Home Electrification) from the ten measure packages available in ResStock to estimate the emissions impacts of building electrification. Below, assumptions used in ResStock for these electrification scenarios are summarized. Full information on ResStock assumptions is available in NREL's documentation.[44]

Water Heating Assumptions

In this scenario, only water heaters are converted to heat pumps. The ResStock model assumes replacement of hot 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 hot water heaters. The assumed efficiency of baseline hot 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

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[42] 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.

[43] 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.

[44] 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.

water heater, ResStock replaces the fuel-burning water heater with a 66 gallon, 3.35 UEF heat pump hot 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 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,[45] 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 can't 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 use for heating, since 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) are 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 conventional 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.

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

- 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 high-efficiency heat pumps, with the exception of those with tankless water heaters. The 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.[46] However, because ResStock does not account for customer economics, this analysis does not explicitly account for potential impacts of IRA or the IIJA funding.

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

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[46] 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.

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

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, NOx, SO_2, and PM emissions were estimated using EPA's AP-42: Compilation of Air Emissions Factors (EF) for external combustion in residential furnaces, as shown in Table 4.[47]

Table 4: 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	0.10815 lbs/MMBtu	94 lbs/mmcf	15 lbs/1,000 gal
SO_2	0.213 lbs/1,000 gal	0.6 lbs/mmcf	0.0486 lbs/1,000 gal[48]
PM	0.4 lbs/1,000 gal	7.6 lbs/mmcf	EF not available

We used the emission factors for furnaces listed above for water heaters, because there are no water heater emission factors listed in AP-42. Research conducted by the Regulatory Assistance Project (RAP) on water heater NOx 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 the AP-42 values for furnace NOx emissions with available data.[49] The study cited a 2019 staff report from the Imperial County Air Pollution Control District in California that proposed new NOx emissions limits for natural

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[47] Particulate emission factors listed in AP-42 are for filterable PM which is collected using EPA Method 5 (or equivalent).

[48] EF for SO_2 is 0.09*S where S is sulfur content of residential propane. According to (1) national sulfur fuel content for LPG is 0.54 grains/100 ft^3, *see* https://www3.epa.gov/ttnchie1/conference/ei12/area/haneke.pdf.

[49] Brutkoski, D.; Prause, E.; Seidman, N.; Shenot, J.; Williams, S., "NOx 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).

gas-fueled water heaters. The staff report found that unregulated gas-fueled water heaters can be assumed to have a NOx emission factor of 55 ppm at 3% oxygen (O_2). This rate is consistent with the 94 lbs/mmcf shown in Table 4.

Emission factors for oil burning furnaces in AP-42 have a high rating (”A”) for NOx and SO_2 and a ”B” rating for PM. Emission factors for propane have a poor rating: the NOx, SO_2, and PM emission factors are rated ”E” in AP-42 documentation. Identifying more robust emission factors for propane could be an action for a follow-on analysis.

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 (last updated 2014-2019). 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.

Step 3: Estimate Changes in Emissions from Power Plants

In each of the electrification scenarios, switching from fossil fuel appliances to heat pumps and electric cooking increased electricity consumption in most 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. Conversely, switching from conventional air conditioning systems, electric resistance space heating, water heating, or clothes drying to heat pumps decreases electricity consumption. 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 decarbonized 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 first calculated NOx, CO_2, $PM_{2.5}$, and SO_2 emissions associated with the changes in electricity demand for each scenario and each state, based on the current electricity grid. We estimated changes in power plant emissions using emission factors, in pounds per megawatt hour (lbs/MWh), published in EPA’s Emissions and Generation Resource Integrated Database (eGRID) database and, for the New England states, the locational marginal units (LMUs) time weighted emission factors for 2020 in the Independent System Operator New England (ISO NE) 2022 report.[50,51] In the ISO NE case, the electricity generation mix is largely natural gas (49%), with small contributions from other fossil fuel-fired plants and wood and

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[50] ISO NE, “2020 ISO New England Electric Generator Air Emissions Report,” April, 2022. *see* https://www.iso-ne.com/static-assets/documents/2022/05/2020_air_emissions_report.pdf.

[51] EPA, Emissions & Generation Resource Integrated Database (eGRID), 2020, see https://www.epa.gov/system/files/documents/2022-01/egrid2020_summary_tables.pdf.

wood derived fuels. The remainder of electricity generation comes from non-emitting sources such as renewable and nuclear energy.

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). Emissions factors for the Northeast and Mid-Atlantic states in the current grid scenario are shown in Table 5.

Table 5: NOx, CO_2, $PM_{2.5}$, and SO_2 Emission Factors for Power Generation in the Current Grid Scenario

State	NOx (lb/MWh)	SO_2 (lb/MWh)	$PM_{2.5}$ (lb/MWh)	CO_2 (lb/MWh)
CT	0.11	0.02	0.046	706
MA	0.11	0.02	0.046	706
ME	0.11	0.02	0.046	706
NH	0.11	0.02	0.046	706
RI	0.11	0.02	0.046	706
VT	0.11	0.02	0.046	706
DC	0.30	0.30	0.041	673
DE	0.30	0.30	0.041	673
MD	0.30	0.30	0.041	673
NJ	0.28	0.21	0.041	639
NY	0.27	0.05	0.054	646
PA	0.35	0.36	0.044	718
VA	0.30	0.20	0.045	640

The emissions that result in the current grid scenario assume an immediate conversion to building electrification in the OTC states, based on the electricity generation mix as of 2020/2021, without any demand management measures. The analysis does not incorporate load shifting, such as through grid-interactive heat pump water heaters, to mitigate impacts of electrification on system peaks. Further, this scenario does not estimate any changes in power plant emissions that would result from decarbonization of the electricity sector. 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[52] and most OTC states have committed to 100% clean electricity by 2040, as shown in Table 6. Almost all state climate legislation and/or climate plans target net-zero grid emissions by 2050. As states implement plans to reduce electricity sector emissions, criteria pollution and GHG emissions will continue to decline in the region, making residential building electrification increasingly beneficial from an emissions standpoint.

Table 6: OTC State Targets for Electricity Decarbonization

State	Electricity Decarbonization Goal
CT	Eliminate GHG emissions from electricity by 2040[53]
DC	100% renewable electricity by 2032[54]
MA	Power sector GHG emissions 70% below 1990 levels in 2030,[55] 93% below 1990 levels in 2050[56]
MD	50% renewable electricity by 2030 and state planning to reach 100% clean power by 2040[57]
ME	80% renewable electricity by 2030, 100% renewable electricity by 2050[58]
NJ	50% renewable electricity by 2030,[59] 100% clean electricity by 2035[60]
NY	70% renewable electricity by 2030, 100% zero-emission electricity by 2040[61]
RI	100% renewable electricity by 2033[62]
PA	Goal articulated in PA climate plan for 100% renewable by 2050[63]
VT	75% renewable electricity by 2032[64]
VA	VA – 100% zero carbon by 2050, net-zero carbon in electric sector by 2040[65]

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

[53] 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.

[54] 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.

[55] 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.

[56] 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.

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

[58] 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.

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

[60] 2019 New Jersey Energy Master Plan: Pathway to 2050, *see* https://www.nj.gov/emp/docs/pdf/2020_NJBPU_EMP.pdf.

[61] 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.

[62] 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.

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

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

[65] 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.

In addition to evaluating state plans for grid decarbonization, we also researched completed or announced coal plant retirements in the region. Several coal plants have closed that were assumed to be operating when the 2020/2021 current grid emission factors were developed. These include: the Bridgeport Harbor unit in Connecticut, the Logan plant in New Jersey, and the Homer City and Cheswick power plants in Pennsylvania. A number of other high-emitting power plants are scheduled to close by 2030. We researched announced plant closures in the region and found that those closures will substantially reduce power plant emissions in the region.

Based on the plant retirement analysis and the targets for renewable electricity in the region, we projected a 90% reduction in power plant-related emissions for the future grid scenario. The future grid scenario represents our estimate of grid-related emissions in 2045. Emission factors for this scenario are shown in Table 7.

Table 7: Emission Factors for the Future Grid Scenario

State/Region	NOx (lb/MWh)	SO_2 (lb/MWh)	CO_2 (lb/MWh)	$PM_{2.5}$ (lb/MWh)
NE ISO	0.01	0.002	70.6	0.005
DC	0.03	0.030	67.3	0.004
CT	0.01	0.002	70.6	0.005
DE	0.03	0.030	67.3	0.004
MA	0.01	0.002	70.6	0.005
ME	0.01	0.002	70.6	0.005
MD	0.03	0.030	67.3	0.004
NH	0.01	0.002	70.6	0.005
NJ	0.03	0.021	63.9	0.004
NY	0.03	0.005	64.6	0.005
PA	0.03	0.036	71.8	0.004
RI	0.01	0.002	70.6	0.005
VT	0.01	0.002	70.6	0.005

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 NOx emissions and the second evaluated a phase-in scenario for residential building electrification.

Estimate Ozone Season NOx Emissions

A fraction of the estimated annual NOx 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 NOx from space heating mainly occurs in the winter months.

To estimate NOx 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 NOx from these SCC codes. Table 8 lists the SCC codes used in the analysis.

Table 8: Source Classification Codes Used to Determine Ozone Season NOx 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 NOx 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 in 2032, 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 Scenario by 15. As a result, electricity consumption increases by 6.7% each year. 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 of 6% per year to reflect state goals to reduce electricity-related emissions by 90% or more by 2045. As a result, in 2035 emission factors for electricity generation are 30% lower than in 2030. In 2040, electricity-related emission factors are 60% lower than in 2030, and in 2045 they are 90% lower than in 2030.

We used these phase-in assumptions to estimate net emissions changes for CO_2 and NOx 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 NOx, CO_2, PM, and SO_2 emission changes for each scenario for both the current and future grid.[66] For the Whole Home Electrification scenario, ozone season NOx emissions are also provided, along with 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 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 air conditioners.

A summary of energy-related changes across the region for all three electrification scenarios is presented in Table 9. Positive numbers indicate a reduction in energy consumption, negative numbers indicate an increase in energy consumption. 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 9: 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

For the region as a whole, the increase in electricity demand to power heat pumps results in an increase in 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 scenario. This is because

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[66] We have summed PM emission changes calculated using AP-42 and $PM_{2.5}$ emission changes uses EPA's eGRID.

some efficiencies that are realized in the Whole Home scenario are included in the electricity consumption values. An example is lower electricity consumption for heat pump water heating as compared to electric resistance water heating. Similarly, conversion of clothes dryers to heat pumps from electric resistance results in electricity savings.

To compare the change in energy demand across fuels in the electrification scenarios, we normalized energy consumption by converting all energy into MWhs, as shown in Table 10.

Table 10: Reduction 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 the 13-state region in 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. Natural gas is used in the greatest volume in the 13-state region and conversion to heat pumps and electric stoves and ovens thus reduces more natural gas than any other fuel. Fuel oil is second and propane third across the region, although 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. 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.

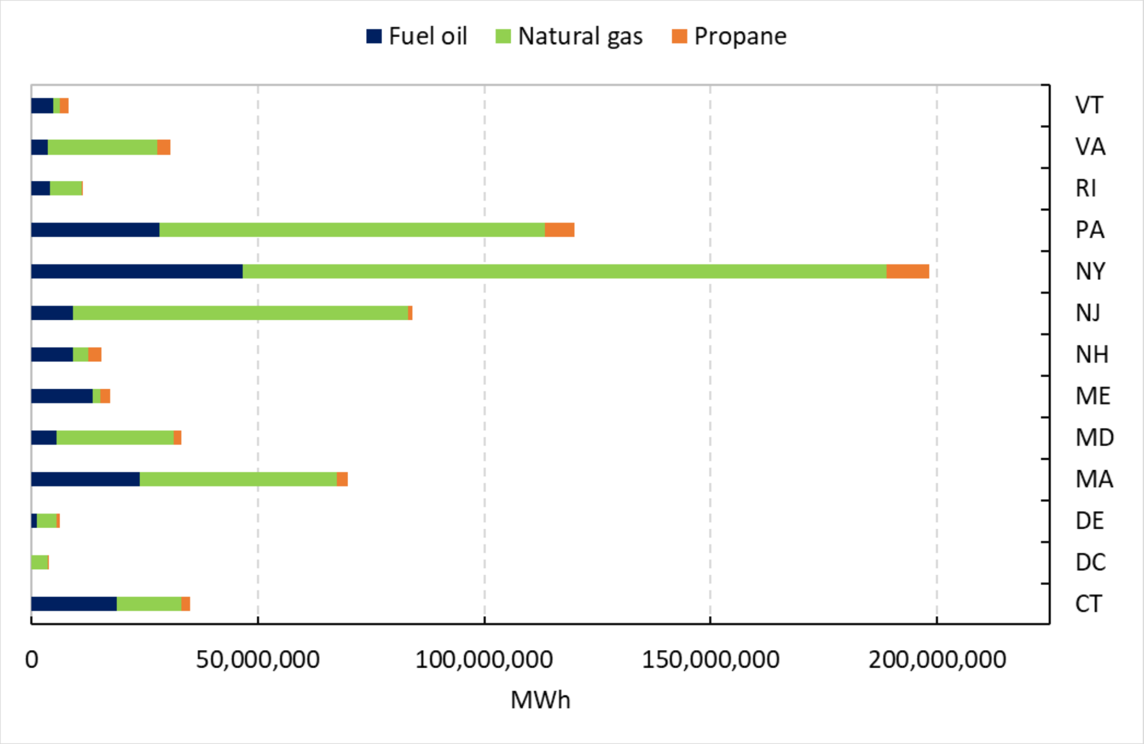

Figure 4: Whole Home Electrification Scenario: Reduction in Propane, Natural Gas, and Fuel Oil Consumption (MWh)

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.[67] 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. Red bars indicate an increase in electricity consumption with electrification and blue bars represent a decrease in consumption.

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[67] 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).]

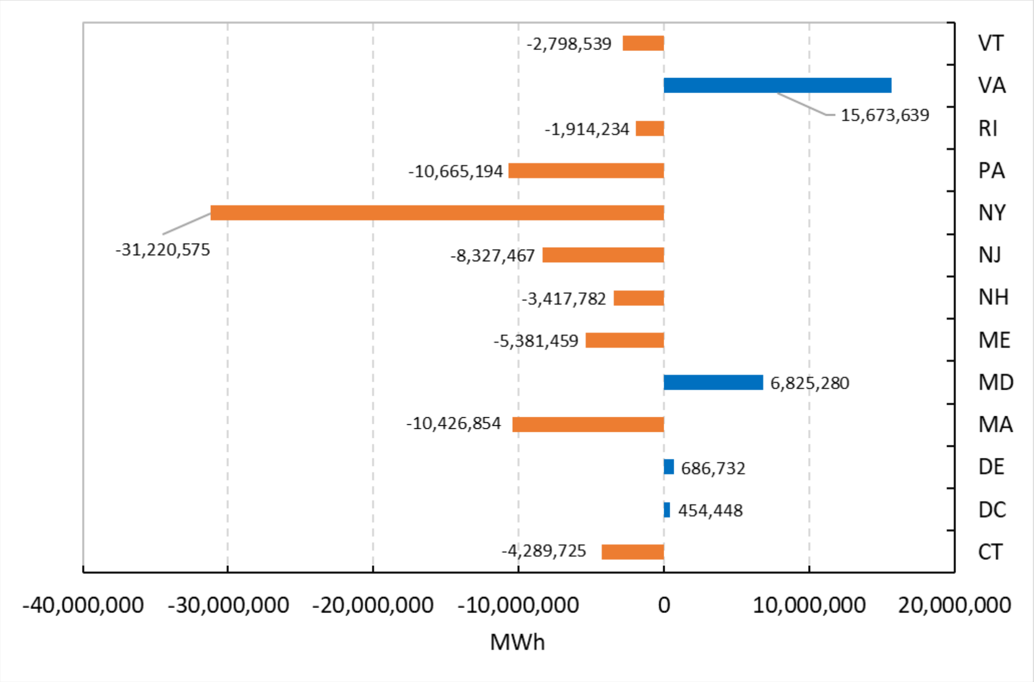

Figure 5: Change in Electricity Consumption, Whole Home Electrification Scenario

In Virginia, Maryland, Delaware, and DC, the Whole Home Electrification scenario reduces overall electricity consumption due to the prevalence of electric resistance space and water heating and central air conditioning in the baseline. Heat pumps 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.

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 remaining 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 11 shows onsite and net (onsite plus power plant-related emissions) emissions reductions from water heating conversions for the entire region. Net emissions are shown for both the current grid and a future grid with 90% lower emissions from power plants. Decreased electricity consumption due to the conversion of inefficient electric resistance water heaters to heat pumps corresponds to greater emissions reductions for the current grid than for the cleaner future grid. Therefore, net emissions reductions for the current grid are larger than those for the future grid.

Table 11: Water Heating Scenario Emissions Reductions, Net and Onsite

Pollutant	**Onsite Annual Tons Reduced**	**Net Annual Tons Reduced (current grid)**	**Net Annual Tons Reduced (future grid)**
NOx	9,376	9,676	9,406
PM	637	667	640
CO_2	11,923,814	12,479,639	11,979,397
SO_2	65	431	102

Table 12 presents net annual changes in NOx, CO_2, PM, and SO_2 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 12: State-by-State Net Emissions Impacts for the Water Heating Scenario

State	**NOx (net tons reduced)**		**CO_2 (net tons reduced)**		**PM (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	492	492	640,321	638,128	28	28	4	4
DC	73	63	103,772	81,913	7	5	11	2
DE	106	78	162,804	98,660	10	6	32	4
ME	205	201	277,015	255,962	9	7	2	2
MD	663	501	1,002,001	639,885	63	41	182	21
MA	981	996	1,189,790	1,276,837	58	64	5	7
NH	206	204	262,355	252,197	9	8	2	2
NJ	1,227	1,312	1,479,513	1,672,114	87	99	-60	2
NY	2,696	2,844	3,247,608	3,602,654	166	196	-10	17
PA	1,849	1,822	2,378,253	2,322,301	127	123	44	16
RI	159	162	192,661	209,038	9	10	1	1
VA	912	624	1,415,673	800,905	92	49	217	25
VT	107	107	127,873	128,803	4	4	1	1
Total	9,676	9,406	12,479,639	11,979,397	667	640	431	102

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 heat pumps. No other appliances are converted in this scenario. Table 13 shows onsite and net (onsite plus power plant-related emissions) emissions reductions from space heating conversions for the region as a whole. As in the previous scenario, net emissions are presented for both the current and future grid. For all pollutants except SO_2, net emissions assuming the current generating mix were 7-30% lower than onsite emissions reductions alone, due to increased electricity consumption associated with replacement of widespread fossil fuel-fired space heating appliances with heat pumps. For the future grid, net reductions for NOx, PM, and CO_2 were 1-3% lower and SO_2 emissions were 25% lower than onsite emissions reductions alone. SO_2 emissions are driven largely by fuel oil consumption in residential buildings. In the power sector, SO_2 emissions are driven by coal-fired power plants. Net reductions are nearly ten times greater for the Space Heating scenario compared to the Water Heating scenario.

Table 13: Space Heating Scenario Emissions Changes, Net and Onsite

Pollutant	**Onsite Annual Tons Reduced**	**Net Annual Tons Reduced/ Increased (current grid)**	**Net Annual Tons Reduced (future grid)**
NOx	91,461	85,174	90,833
PM	5,222	3,678	5,068
CO_2	120,279,844	99,816,805	118,233,540
SO_2	782	-1,180	586

Table 14 presents net annual changes in NOx, CO_2, PM, and SO_2 emissions on a state-by-state basis for the current and future grid for the Space Heating Electrification scenario. Emission reductions are shown as positive numbers and emission increases are shown as negative numbers.

Table 14: State-by-State Net Emissions Changes for the Space Heating Scenario

State	**NOx (net tons reduced)**		**CO_2 (net tons reduced)**		**PM (net tons reduced/ increased)**		**SO_2 (net tons reduced/ increased)**	
	Current grid	Future grid	Current grid	Future grid	Current grid	Future grid	Current grid	Future grid
CT	5,068	5,294	5,856,212	7,188,064	123	218	12	53
DC	508	470	689,987	603,920	43	38	46	7
DE	985	934	1,293,315	1,180,995	57	51	63	12
ME	2,696	2,974	2,337,046	3,973,549	-54	62	-21	30
MD	5,431	4,784	7,710,915	6,260,662	392	305	755	108
MA	9,555	10,081	10,185,569	13,286,614	314	535	-12	84
NH	2,430	2,605	2,315,030	3,347,832	-6	68	-9	23
NJ	10,156	11,129	12,134,133	14,339,384	650	790	-711	3
NY	24,230	28,007	27,215,310	36,250,215	860	1,612	-510	162
PA	15,169	17,017	18,248,312	22,086,715	752	989	-2,024	-74

RI	1,533	1,629	1,590,057	2,153,687	45	85	-4	14
VA	6,140	4,494	9,309,405	5,797,260	529	283	1,250	152
VT	1,273	1,414	931,515	1,764,643	-28	31	-15	11
Total	85,174	90,833	99,816,805	118,233,540	3,678	5,068	-1,180	586

Emissions Changes: Whole Home Electrification Scenario

The Whole Home Electrification Scenario assumes conversion of space and water heaters, clothes dryers, air conditioning, stoves, and ovens from fossil fuels or electric resistance to heat pumps 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 conversions, such as the installation of induction cooktops, electric ovens, and heat pump clothes dryers. Table 15 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 NOx 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 4,900 to 6,300 tons of PM and more than 135 million tons of CO_2. In the current grid scenario, net emissions reductions are 5% lower than onsite emissions reductions for NOx and 13% lower for CO_2, after factoring in the impact of increased power plant emissions. In the future grid scenario, net emissions reductions are nearly the same as onsite emissions reductions for these pollutants, because we assume fossil fuel power plants have largely been replaced with emission-free electricity generation.

Table 15. Whole Home Electrification Scenario Emission Changes, Net and Onsite

Pollutant	**Onsite Annual Tons Reduced**	**Net Annual Tons Reduced/Increased (current grid)**	**Net Annual Tons Reduced (future grid)**
NOx	108,326	103,087	107,802
PM	6,308	4,924	6,170
CO_2	141,773,232	123,749,771	139,970,886
SO_2	904	-172	797

Table 16 shows net annual emission reductions for the Whole Home Electrification scenario for each state. Each state would have substantial annual NOx and CO_2 emissions reductions in this scenario. In the current grid scenario, net SO_2 emissions decrease in six states and increase in seven states, due to greater electricity generation from power plants. 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 provide power for heat pumps. In other states, the reductions in SO_2 emissions from heating oil combustion largely offsets 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 2020/2021 grid emissions and does not account for the cleaner grid that will occur as states decarbonize electricity. Because of this, the future grid scenario is likely more representative of 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 one state. 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	**NOx (net tons reduced)**		**CO_2 (net tons reduced)**		**$PM_{2.5}$ (net tons reduced /increased)**		**SO_2 (net tons reduced/ increased)**	
	Current grid	Future grid	Current grid	Future grid	Current grid	Future grid	Current grid	Future grid
CT	5,980	6,192	7,116,621	8,367,505	176	266	22	61
DC	632	570	871,786	734,156	54	46	72	10
DE	1,188	1,096	1,590,591	1,382,615	74	62	111	18
ME	3,101	3,368	2,916,986	4,486,219	-37	75	-15	34
MD	6,594	5,673	9,469,193	7,402,157	496	371	1,066	144
MA	11,350	11,866	12,563,587	15,604,057	430	647	4	98
NH	2,826	2,995	2,839,188	3,835,814	11	82	-4	26
NJ	12,467	13,523	14,998,520	17,393,083	817	969	-763	13
NY	29,406	33,199	33,802,947	42,878,768	1,199	1,955	-476	199
PA	18,598	20,257	22,772,929	26,218,853	986	1,199	-1,780	-29
RI	1,824	1,919	1,974,895	2,533,086	63	103	-1	16
VA	7,651	5,535	11,644,181	7,130,173	676	359	1,604	193
VT	1,470	1,609	1,188,347	2,004,401	-21	38	-12	13
Total	103,087	107,802	123,749,771	139,970,886	4,923	6,196	-172	797

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.[68]

Table 17 shows changes in emissions due to increases and decreases in electricity generation in the Whole Home Electrification scenario on a state-by-state basis. As previously discussed, electricity-related NOx emissions decrease in DC, DE, MD, and VA but increase for the other states in the current grid scenario.

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

Table 17: Whole Home Electrification Scenario Electricity Generation-Related Emissions Changes

State	**NOx (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	-236	-24	-1,389,871	-138,987	-99	-10	-43	-4
DC	68	7	152,922	15,292	9	1	68	7
DE	103	10	231,085	23,109	14	1	103	10
ME	-296	-30	-1,743,593	-174,359	-124	-12	-54	-5
MD	1,024	102	2,296,707	229,671	138	14	1,024	102
MA	-573	-57	-3,378,301	-337,830	-241	-24	-104	-10
NH	-188	-19	-1,107,361	-110,736	-79	-8	-34	-3
NJ	-1,174	-117	-2,660,626	-266,063	-169	-17	-862	-86
NY	-4,215	-421	-10,084,246	-1,008,425	-840	-84	-749	-75
PA	-1,843	-184	-3,828,805	-382,881	-237	-24	-1,945	-195
RI	-105	-11	-620,212	-62,021	-44	-4	-19	-2
VA	2,351	235	5,015,565	501,557	352	35	1,567	157
VT	-154	-15	-906,727	-90,673	-65	-6	-28	-3
Total	-5,238	-524	-18,023,462	-1,802,346	-1,384	-138	-1,076	-108

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 18 lists total annual NOx, 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, NOx 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 18: 2020 NOx, CO_2, $PM_{2.5}$, and SO_2 Emissions from Residential Wood Burning in the Region

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

Ozone Season NOx 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 NOx is reduced by nearly 17,000 tons in the Whole Home Electrification scenario. In every jurisdiction, at least one ton of NOx per ozone season day could be mitigated with a conversion of fuel-burning appliances to heat pumps. In the largest state

(NY), nearly 30 tons of NOx could be reduced per ozone season day, assuming there are 153 days in the ozone season.

Table 19: Annual and Ozone Season NOx Reductions for the Whole Home Electrification Scenario

State	Annual NOx Reduction (net annual tons – future grid)	Ozone Season NOx Reduction (net tons – future grid)
CT	6,192	929
DC	570	855
DE	1,096	164
ME	3,368	505
MD	5,673	851
MA	11,866	1,780
NH	2,995	449
NJ	13,523	2,028
NY	33,199	4,980
PA	20,257	3,038
RI	1,919	288
VA	5,535	830
VT	1,609	241
Total	107,802	16,938

In addition to assisting states in meeting the NAAQS for ozone, the NOx reductions resulting from the efficient electrification of residential buildings would assist some 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 criteria pollutant emissions. This is especially relevant to this study since wintertime nitrates have been increasing in recent years and are becoming a more important contributor to poor visibility.[69] NOx emissions impede visibility by contributing to secondary formation of nitrates. From this analysis, we can see that a substantial amount of NOx 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 in this report 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 and eventually reaches 90% lower electricity-related emissions (as compared with today) by 2045.

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[69] 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.

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 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 air conditioners and window air conditioning is replaced with heat pumps, in 2035, approximately 40 million net annual tons of CO_2 would be reduced regionwide. In 2040, that number would rise to 80 million tons reduced each year. By 2045, over 120 million tons of CO_2 from residential homes would be eliminated. 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 and a 90% cleaner grid.

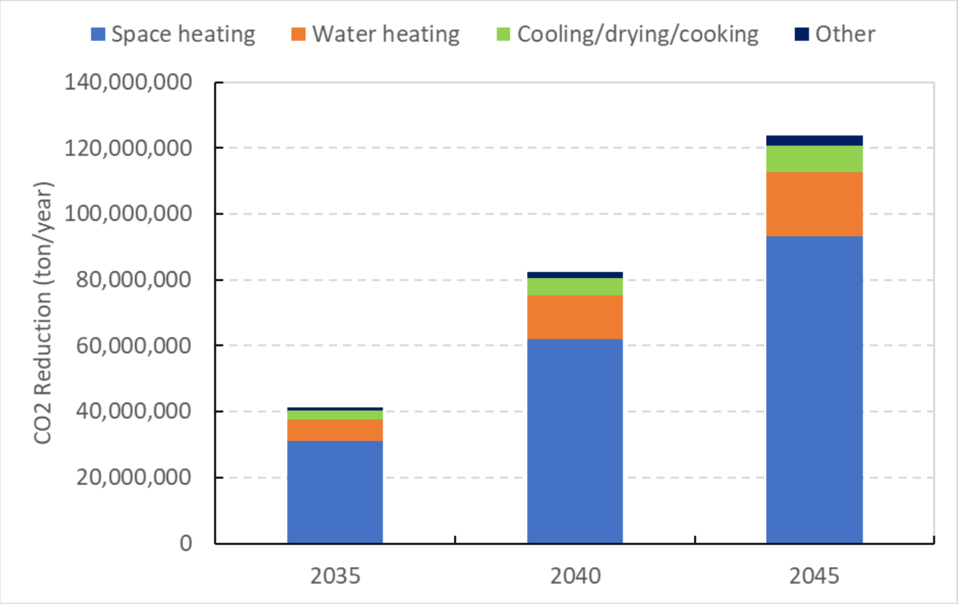

Figure 6: Annual CO_2 Reductions in the Whole Home Scenario Assuming Replacement at the End of Useful Life

We also estimated NOx emission reductions for the phase-in scenario. As seen in Figure 7, reductions reach approximately 38,000 tons in the OTC states by 2035, 70,000 tons in 2040, and over 100,000 tons annually by 2045.

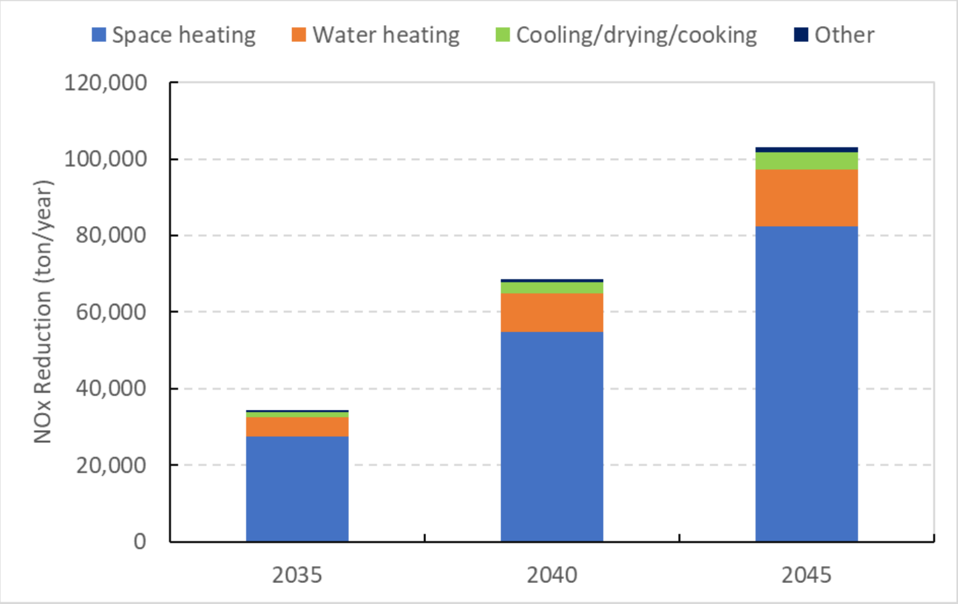

Figure 7: Annual NOx Reductions in the Whole Home Scenario Assuming Replacement at the End of Useful Life

Conclusions

Substantial reductions in criteria pollutant and GHG emissions can be realized in the region through residential building electrification. Whole home electrification provides the greatest reductions in fossil fuel consumption and NOx and CO_2 emissions. Space heating electrification alone 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 (DC, DE, MD, and VA), 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 heat pumps.
- 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 induction cooktops would result in 103,000 tons of NOx, nearly 5,000 tons of $PM_{2.5}$, and 124 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; heat pumps can reduce this substantially.

- Converting fossil fuel and electric resistance water heaters to heat pump water heaters would reduce over 12 million tons of CO_2 and 9,000 tons of NOx annually.
- Ozone season NOx emissions would be reduced by nearly 17,000 tons over the 153-day ozone season each year across the OTC states with whole home electrification, and the NOx savings from water heating electrification is particularly valuable during the ozone season.
- For the region as a whole, assuming a 2020/2021 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 4% for NOx, 12% for CO_2, and 21% for $PM_{2.5}$, before factoring in that electricity grids are likely to get cleaner over time.
- Assuming the grid gets 90% 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 - 1% for NOx, 2% for $PM_{2.5}$, and 1% for CO_2.
- With the introduction of a zero-emission standard in 2030 for newly installed appliances and phased replacement of household appliances at the end of their useful life, CO_2 could be reduced in the region by 40 million tons in 2035, 80 million tons in 2040, and over 120 million tons in 2045, assuming a transition to a cleaner grid over the same time period. Using the same phase-in assumptions, NOx emissions could be reduced in the region by 38,000 tons in 2035, 70,000 tons in 2040, and over 100,000 tons in 2045.

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.

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 IRA and IIJA 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 is based on an analysis of 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.

Assess Health Benefits of Residential Building Electrification

Future research could use EPA's Co-Benefits Risk Assessment (COBRA) or another model to evaluate the health benefits of residential building electrification. COBRA provides county-level changes in health outcomes resulting from primary and secondary $PM_{2.5}$ emissions reductions or increases. We could also consider conducting a more granular analysis of health impacts associated with localized increases in power plant emissions resulting from additional electricity generation in the residential electrification scenarios. This analysis may require the use of a different model.

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. In addition, a health benefits analysis of wood heating could be compared to the residential fossil fuel COBRA analysis described above.

Commercial Building Emissions Analysis

NREL has developed a commercial building stock model (ComStock™)[70] 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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[70] For more information on the ComStock model, *see* https://www.nrel.gov/buildings/comstock.html.