Decarbonization Beyond Electrification: A Regional Emissions Analysis of Electric versus Gas Supplemental Heating for Heat Pumps

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ABSTRACT

Reducing greenhouse gas (GHG) emissions from building space heating is vital for decarbonizing the built environment. Air source heat pumps (ASHPs) offer a promising low-carbon alternative to gas heating, however their efficiency declines in colder climates, often requiring supplemental heating. While electric supplemental heat is assumed to be more sustainable than gas, this study provides the first comprehensive region-specific analysis across all U.S. grid regions and climate zones to assess long-term decarbonization outcomes. This study quantifies the emissions impact of electric versus gas supplemental heat for ASHPs through hourly whole-building energy modeling using the U.S. Department of Energy's EnergyPlus simulation engine. Models align with ASHRAE Standard 90.1 and represent common commercial building types across the U.S. Historical emissions factors from the Environmental Protection Agency's (EPA) eGRID dataset and forward-looking projections from the National Renewable Energy Laboratory's (NREL) Cambium dataset extend the analysis to 2050. Results show electric supplemental heat yields substantial emissions reductions (~20%) in states like New York and Minnesota but provides only marginal (<2%) or comparable reductions in numerous locations, even with anticipated grid decarbonization. These findings emphasize the need for precision in policy and design decisions as electrification continues to shape the future of sustainable buildings.

INTRODUCTION

Buildings represent the largest consumers of energy and are among the most significant contributors to greenhouse gas (GHG) emissions. In the United States, they account for approximately 70% of electricity consumption, 40% of total primary energy use, and 30% of operational GHG emissions (EIA 2022; EPA 2023). Globally, carbon dioxide (CO_2) emissions from buildings constitute about 37% of total CO_2 emissions (IEA 2021). The decarbonization of the building sector is essential for meeting global climate targets. The adoption of low-carbon heating technologies is pivotal for reducing these emissions. Among these technologies, air source heat pumps (ASHPs), particularly air-to-air heat pumps, are the dominant type of heat pump in North America and have emerged as a cornerstone solution for sustainable space heating (DOE 2024). Combined with the use of renewable electricity sources, ASHPs offer a decarbonized alternative to traditional gas heating systems, thereby supporting the transition to a sustainable built environment (DOE 2023). One critical challenge in deploying ASHPs, particularly in colder climates, is their reduced efficiency during extreme weather conditions. To maintain thermal comfort, supplemental heating is often required. Electric resistance is frequently assumed to be a more sustainable supplemental heating option than gas supplemental heating systems, however this study challenges this mainstream assumption through a comprehensive regional assessment that considers long-term variations in electric grid emissions throughout the U.S.

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Over the past decade, numerous studies have investigated the impact of fully electrifying space heating through ASHP's with electric supplemental heat. However, they overlook the incremental emissions savings potential of ASHP's with gas supplemental heat (dual fuel) when compared to electrifying supplemental heat. Examples of these studies include a recent study by the National Renewable Energy Laboratory (NREL) where nationwide emissions reductions of up to 9% were estimated through full adoption of air-to-air heat pumps with electric supplemental heat across the U.S. residential sector (Wilson et al. 2024). Another recent study investigated the operational emission savings of heat pumps over gas furnaces for U.S. residential heating over a 15-year period. The study demonstrated 38-53% carbon emissions savings through heat pumps (Pistochini et al. 2022). A similar study conducted for Germany demonstrates 39% emissions savings through heat pumps in residential buildings (Bayer 2024). These studies, among others, underscore the significant potential of full space heating electrification through heat pumps with electric supplemental heat (Flores et al. 2024; RMI 2023; Deetjen 2021; CaraDonna 2023), however they do not consider the emissions impacts of dual fuel heat pumps with gas supplemental heating.

Recent studies have begun exploring the emissions impacts of dual fuel heat pumps with gas supplemental heating, but none provide a comprehensive forward-looking analysis for commercial buildings across the U.S. For instance, one study modeled these systems for single-family homes in two California climate zones (Shekhadar et al. 2024). Another examined their use in ASHRAE climate zones 4 and 5 but did not assess their nationwide impact (Landman et al. 2024). A separate study analyzed emissions from dual fuel heat pumps in the Netherlands (Nienhuis et al. 2017), while a more recent study focused solely on residential buildings (Dichter et al. 2020).

This study fills a critical gap in the literature by providing a novel, comprehensive analysis of the emissions impacts of gas versus electric supplemental heating for ASHPs in commercial buildings across the U.S. It simultaneously addresses four key dimensions that have not been explored together in previous studies: (1) an isolated emissions impact assessment of electric versus gas supplemental heating for ASHPs, (2) a nationwide evaluation spanning all U.S. climate zones and electric grid regions, (3) a focus on commercial buildings, which has been largely overlooked, and (4) an analysis incorporating both historical electric grid emissions and forward-looking, long-term grid decarbonization projections through 2050.

By comprehensively addressing the GHG emissions implications of ASHP supplemental heating strategies in commercial buildings, this study contributes novel insights to the literature and underscores the need for precision in policy and system design decisions. The findings emphasize that regional analysis is essential for designing decarbonization strategies that effectively balance environmental benefits and economic considerations. As electrification continues to shape the future of sustainable building systems, tailored solutions for supplemental heating will play a crucial role in achieving meaningful emissions reductions.

METHODOLOGY

This section details the methodology used for modeling the emissions for ASHP supplemental heating scenarios across various building types and U.S. grid regions using physics-based energy simulations. First, we describe the historical and forward-looking emissions factor datasets, followed by the building energy models, modeled scenarios, and emissions savings calculations.

GHG Emission factors

Two open-source datasets of GHG emission factors for electricity were leveraged in the analysis:

Historical Emissions Factors (2014-2022): The Environmental Protection Agency's (EPA) eGRID dataset was used for historical emissions factors from 2014 through 2022 (EPA 2025a). The eGRID dataset compiles historical emissions data from power plants across the U.S., based on actual operational reports of fuel consumption, electricity generation, and direct emissions monitoring. The EPA reports a single annual emission factor for each U.S. grid region, overlooking hourly emissions variations. While this reduces the assessment's thoroughness, the annual values remain highly accurate as they are based on actual measured operational data.

Projected Emissions Factors (2025-2050): The National Renewable Energy Laboratory's (NREL) Cambium dataset provides simulated hourly emissions for various modeled futures of the U.S. electric sector, from 2025 through 2050 (NREL 2023). Cambium supports long-term decision-making through high-resolution future projections of potential grid scenarios. The dataset's hourly emissions factors capture daily grid variations year-round, enhancing the depth and accuracy of the future emissions assessment. Among the various future scenario datasets offered through Cambium, this study leverages the mid-case scenario, which assumes central estimates for inputs such as technology costs, fuel prices, and demand growth. The mid-case scenario excludes nascent technologies and assumes electric sector policies as they existed in September 2023.

The EPA's historical eGRID emissions factors and NREL's projected Cambium emissions factors are available in, and divided into, 18 regions covering the entire U.S, and that align with electric grid system operators. Figure 1 below shows a map of the Generation and Emissions Assessment (GEA) grid regions and their associated names. The analysis conducted in this study spans all GEA regions shown in Figure 1. An emission factor of 117 lb/MBtu (181 kg/MWh) was leveraged for gas consumption across all modeled years and grid regions (EPA 2025b).

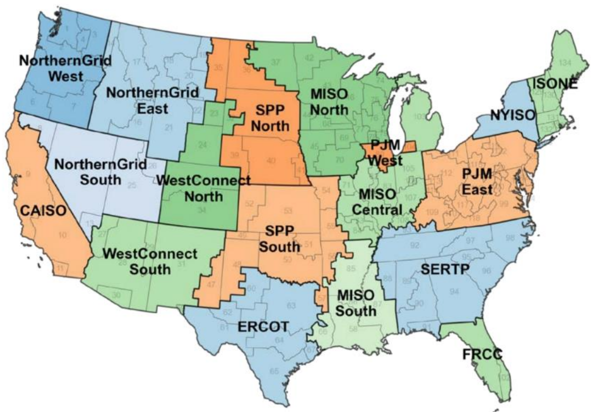

Figure 1 U.S electrical grid regions defined in NREL's Cambium dataset for simulated and projected electricity emission factors (through 2050) and historical emissions factors from EPA's eGRID data (NREL 2023).

Building Models

Hourly whole-building energy models were developed using the U.S. Department of Energy's (DOE) EnergyPlus simulation engine, version 23.1 (DOE 2025). This study focuses on four common commercial building types: Office (125k-ft^2/11.6k-m^2, 4 stories), Multifamily (35k-ft^2/3.3k-m^2, 5 stories), Hospital (240k-ft^2/22.2k-m^2, 5 stories) and School (210k-ft^2/19.5k-m^2), 3 stories). The building models were fully articulated based on ASHRAE Standard 90.1 2004, reflecting existing buildings likely due for an HVAC replacement (ASHRAE 2004). ASHRAE Standard 90.1 assumptions were used to inform model inputs such as internal load definitions, equipment power densities, lighting power densities, and envelope insulation. The DOE commercial building prototype models were used to inform space type definition and allocations (DOE 2025b). Square geometry footprints were modeled for all building types, and typical meteorological year (TMY3) hourly weather files for the representative cities shown in Table 1 were used in the simulation to reflect each of the 18 electric grid regions spanning the U.S.

Table 1. Representative Cities that are Modeled for Each Grid Region Across the U.S.

Grid Region	Modeled State, City	Grid Region	Modeled State, City
NorthernGrid West	Washington, Seattle	SPP South	Kansas, Kansas City
CAISO	California, Los Angeles	ERCOT	Texas, Temple
NorthernGrid East	Montana, Helena	PJM West	Illinois, Chicago
NorthernGrid South	Nevada, Las Vegas	MISO Central	Indiana, Indianapolis
SPP North	South Dekota, Pierre	MISO South	Mississippi, Jackson
WestConnect North	Colorado, Denver	ISONE	Maine, Augusta
WestConnect South	New Mexico, Santa Fe	NYISO	New York. Queens
MISO North	Minnesota, International Falls	PJM East	Pennsylvania, Philadelphia
SERTP	North Carolina, Raleigh	FRCC	Florida, Tampa

Modeled Scenarios

The following three space heating system type scenarios were modeled across all 4 building types and all 18 electric grid regions throughout the U.S:

1. **Gas-Fueled Heating Baseline:** Packaged single-zone rooftop air conditioner (PSZ-AC) with direct expansion (DX) cooling and gas combustion space heating. This scenario serves as the baseline throughout the results and reflects system type 3 in Appendix G of ASHRAE Standard 90.1 (ASHRAE 2022). The whole-building emissions savings for scenario 2 and scenario 3 below are compared to this baseline scenario.
2. **Dual Fuel:** Packaged single-zone rooftop, air-to-air heat pumps (PSZ-HP) with DX cooling, electric heat pump heating, and gas supplemental heating. This scenario reflects system type 4 in Appendix G of ASHRAE Standard 90.1 (ASHRAE 2022) with gas supplemental heating.
3. **All Electric:** Packaged single-zone rooftop, air-to-air heat pumps (PSZ-HP) with DX cooling, electric heat pump heating, and electric resistance supplemental heating. This scenario reflects system type 4 in Appendix G of ASHRAE Standard 90.1 (ASHRAE 2022) with electric supplemental heating.

The heat pumps are sized for the design cooling load in scenarios 2 and 3, and the DX cooling performance is identical in all three scenarios. Variable speed supply fans and compressors were modeled for all scenarios. The following system level specifications were detailed in the model for each system type based on commercially available product specifications: Heat pump COP of 3.5 at 47F (8.33C), and COP of 2.335 at 17F (-8.33C), gas combustion coil efficiency of 80%, electric supplemental heat efficiency of 100%, and heat pump compressor shutoff temperature of -10F (-23.33C). Defrost cycles were not considered in this analysis. A total of 216 simulations were produced for this study (18 regions x 4 building types x 3 scenarios = 216 annual, hourly, whole-building energy simulations). In addition, 11 years of electric grid emissions factors from 2014 through 2050 were considered.

Emission Savings calculation:

The primary results of interest in this study include whole-building emission savings of ASHP's with gas supplemental heat (dual fuel) compared to an all-gas space heating solution, and the added whole-building emissions savings associated with electrifying the supplemental heat. The results are presented in two emissions savings calculations outlined in Equation 1 and Equation 2, as shown below. The annual emissions in Equations 1 and 2 are calculated by summing the yearly gas and electricity emissions. Electricity emissions are derived by multiplying the EPA's eGRID annual emission factors (for years prior to 2025) or NREL hourly emission factors (for future years) with the modeled hourly whole-building electricity consumption. Gas emissions are determined using the EPA's gas emission factor, multiplied by the modeled annual whole-building gas consumption.

$$\%\ Emissions\ Savings_{DualFuel} = \frac{Annual\ Emissions_{All\ Gas} - Annual\ Emissions_{DualFuel}}{Annual\ Emissions_{All\ Gas}} \times 100 \quad (1)$$

$$\%\ Incremental\ Emissions\ Savings_{All\ Electric} = \frac{Annual\ Emissions_{DualFuel} - Annual\ Emissions_{All\ Electric}}{Annual\ Emissions_{All\ Gas}} \times 100 \quad (2)$$

RESULTS

The impact of replacing gas-fueled space heating with ASHP's containing gas-fueled supplemental heating (dual fuel) for the modeled office building is shown in Figure 2a. This figure depicts the percentage of annual whole-building carbon equivalent savings relative to the baseline combustion system, spanning from 2014 to 2050. Historically (2014-2022), heat pumps would have marginally reduced whole-building emissions (<2%) annually in 13 of the 18 grid regions, with significant savings (>=10%) in PJM West, Northern Grid West, and ISONE grid regions. PJM West's substantial nuclear energy share (~33%), Northern Grid West's ~50% hydropower energy share, and ISONE's ~40% energy production from non-combustible sources like wind, solar, and hydro contributed to these savings (EPA 2025a). As U.S. grids evolve to leverage cleaner sources of energy, heat pumps, including dual fuel systems, are projected to drastically increase annual emissions savings compared to all-gas heating. By 2050, the most impacted regions include NYISO (over 88% savings), Northern Grid East, SPP North, PJM West, SPP South, MISO North, Northern Grid West, and Western Connect North, with over 20% savings anticipated in whole-building emissions over the next 25 years. The least impacted region is FRCC due to low heating loads, followed by CAISO and Northern Grid South for similar reasons. Figures 2b and 2c show an overlay of the whole-building emissions savings on a U.S. map in 2022, corresponding to the most recently available eGRID emissions data, and for 2050. Figure 3 shows results for the remaining building types, with 2050 results overlaid on a U.S. map.

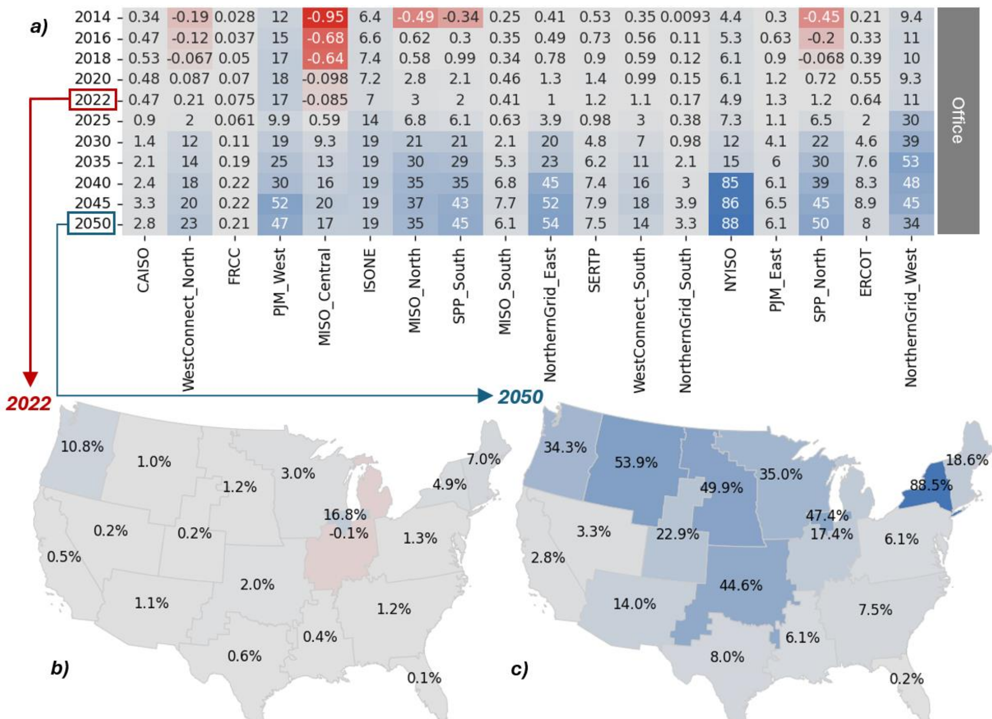

Figure 2 (a) Annual whole-building emissions savings of the modeled office building with ASHP's and gas supplemental heating compared to all-gas heating (b) U.S. map overlay of 2022 emissions savings (c) U.S. map overlay of 2050 emissions savings. *Negative values reflect emissions added, not saved.*

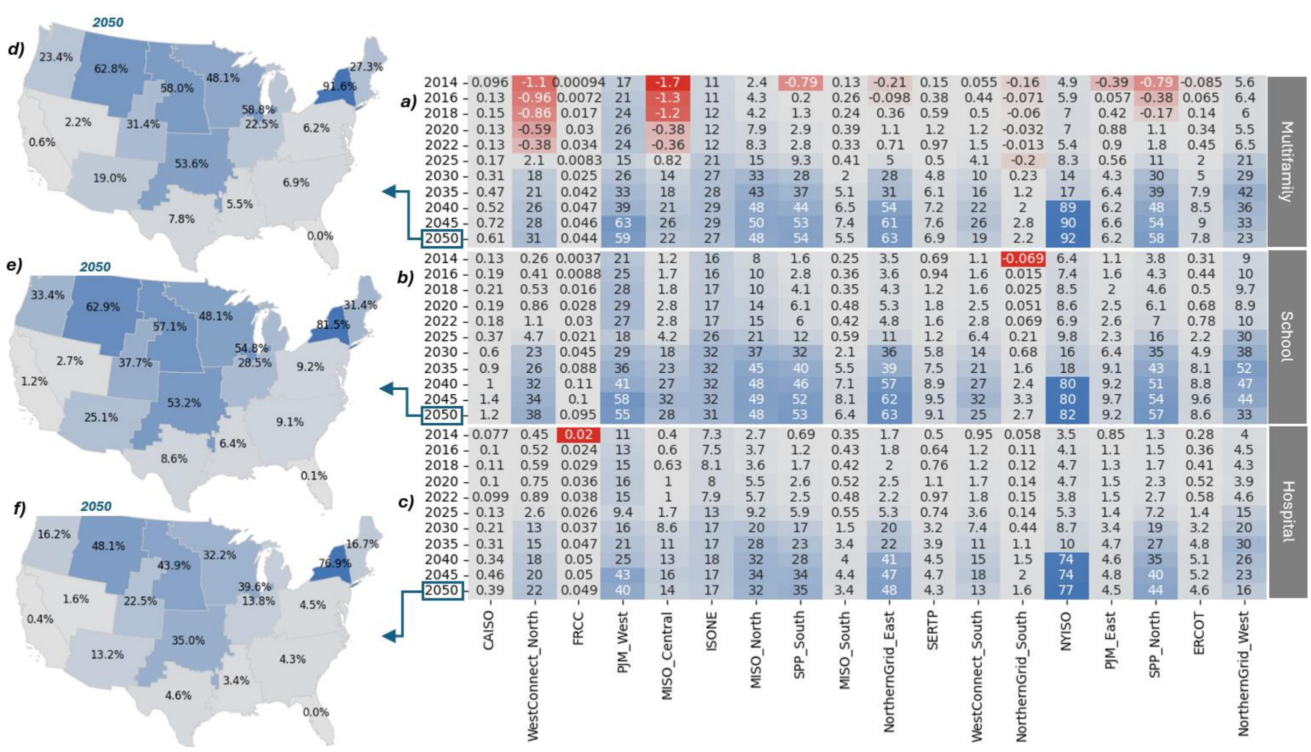

Figure 3 Annual whole-building emissions savings from ASHP's with gas supplemental heating compared to all-gas heating for the modeled (a) multifamily (b) school and (c) hospital building types (2014-2050). U.S map overlay of 2050 emissions savings for the modeled (d) multifamily (e) school and (f) hospital building type.

While trends in Figures 2 and 3 are similar, the magnitude of impact varies between buildings due to differences in heating load profiles and magnitude of heating loads. NYISO is the most impacted region, with 77%-92% modeled whole-building emission savings in 2050 from dual fuel heat pumps compared to gas space heating. The sharp increase in 2040 is driven by New York’s 100% zero-emissions electricity target by 2040 and the statewide net zero emissions target by 2050 under the Climate Leadership and Community Protection Act (NYSERDA 2025). From 2025 onward, MISO North, SPP North, and SPP South are among the top regions impacted by dual fuel heat pumps, due to their significant wind power contributions, which make up roughly 40% of their total energy mix by generation in 2023, with projected increases through 2050 (EPA 2025a).

The results in Figure 4 show the additional percentage of whole-building annual emissions savings for the modeled office building, year-over-year, across all grid regions through a transition from dual fuel to all-electric heating. The additional impact of electrifying the supplemental heating on annual emissions is minimal in most U.S. regions. In 12 of the 18 grid regions, the added percentage of annual emissions savings from switching to electric supplemental heating, compared to gas, is less than 2.7% through 2050. In FRCC, the impact is negative due to the small run time, marginal efficiency benefit of electric resistance heat (100% efficient) over gas (80% efficient), and the smaller projected fraction of renewable sources through 2050 compared to other grid regions. FRCC is projected to have 50% renewable energy generation by 2050 (EPA 2025a). The most impacted regions are MISO North, SPP North, Northern Grid East, PJM West, followed by SPP South and NYISO. MISO North and SPP North result in more than 10% in added whole-building emissions savings in 2050.

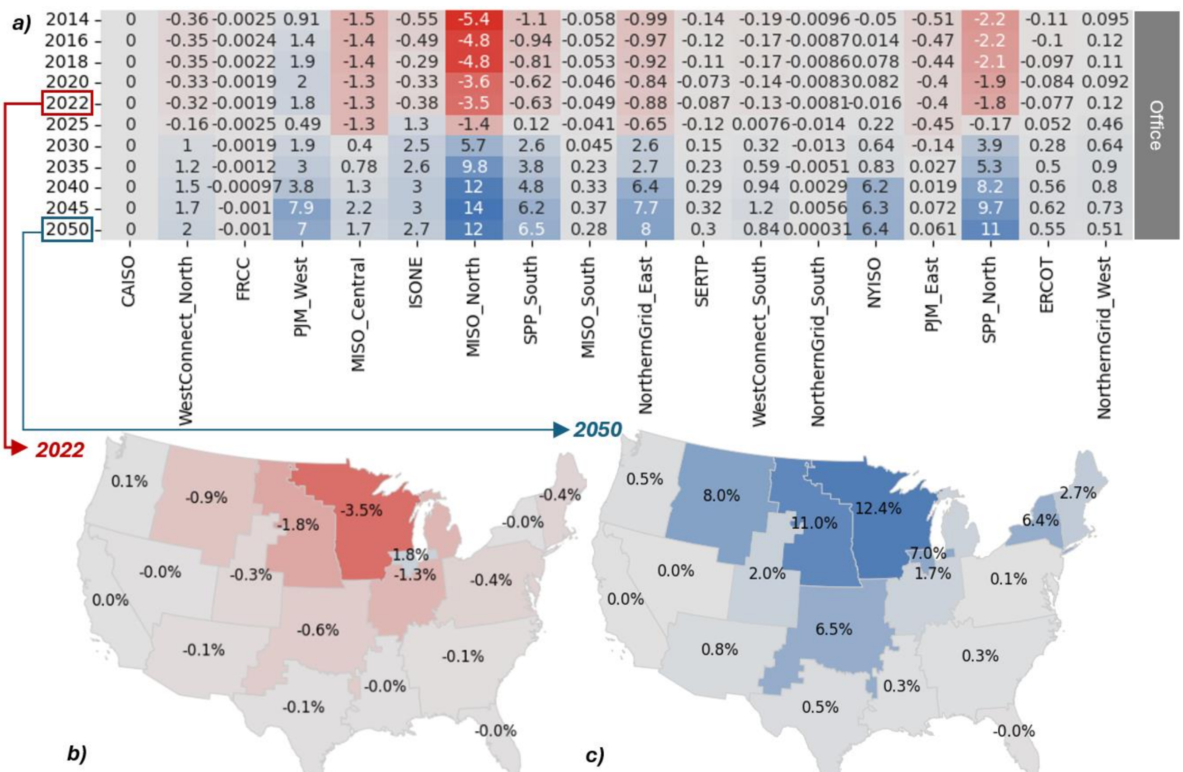

Figure 4 (a) The added percentage in annual whole-building emissions savings for the modeled office building, year-over-year, across all grid regions, through a transition from ASHPs with gas supplemental heating (dual fuel) to ASHP’s with electric supplemental (all-electric) heating (2014-2050) (b) U.S. map overlay of 2022 incremental emissions savings (c) U.S. map overlay of 2050 incremental emissions savings.

Similar trends are observed for the remaining building types, as shown in Figure 5, with MISO North and SPP North remaining among the top positively impacted by a full transition to electrification through ASHPs with electric resistance supplemental heating compared to dual fuel ASHP’s with gas supplemental heating. However, buildings in many U.S electrical grid regions have marginal (<1%) difference in emissions savings from electric resistance supplemental heating compared to gas fueled supplemental heating through 2050.

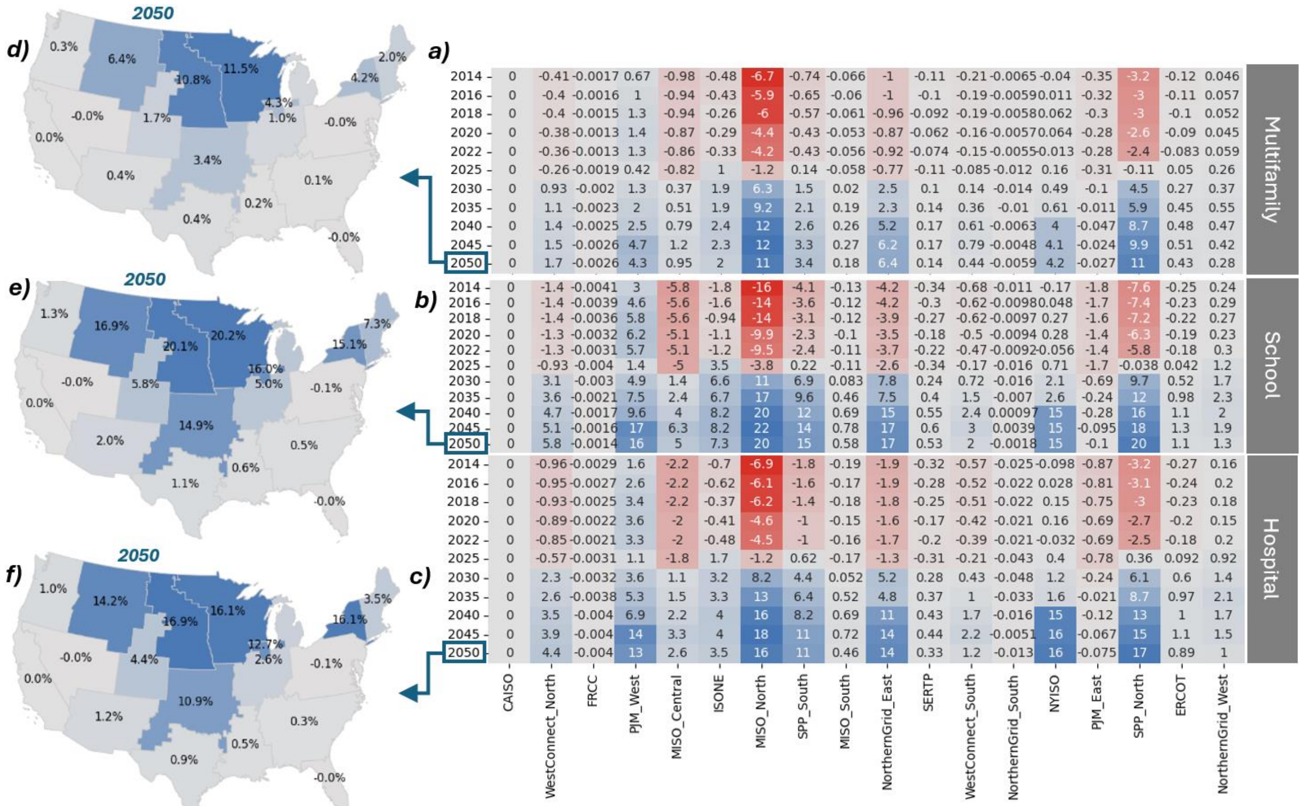

Figure 5 The added percentage in annual whole-building emissions savings, year-over-year, across all grid regions, through a transition from ASHPs with gas supplemental heating (dual fuel) to ASHP's with electric supplemental (all-electric) heating (2014-2050) for the modeled (a) multifamily, (b) school, and (c) hospital building types (2014-2050). U.S. map overlay of the 2050 incremental emissions savings for the modeled (d) multifamily, (e) school, and (f) hospital building types.

The year-by-year visibility into annual emissions reductions, provided through Figures 2-5, offers insights into the impacts of heat pumps and supplemental heat options as the U.S electric grid evolves with time. However, assessing these technologies and supplemental heat options over the lifespan of typical HVAC equipment presents a more realistic design scenario and offers an alternative perspective on their emissions impacts. Figure 6 presents a 15-year assessment (2025-2040) of ASHP's with gas supplemental heating, along with the added savings from electrifying the supplemental heat. Figure 6 offers designers, building owners, and utility incentive programs an assessment of emissions reductions for systems adopted today, considering the anticipated grid evolution over the next 1.5 decades.

While NYISO shows the largest impact from both heat pumps and electric supplemental heating over the next 25 years (2050), its cumulative impact over the next 15 years, corresponding to the typical lifespan of a heat pump system installed today, is minimal (<2% savings) ahead of the NYISO 2040 and 2050 electricity and statewide zero emissions targets. Conversely, the impact of electric supplemental heating compared to gas is greatest in MISO North, although for most building types it results in less than a few percent in added emissions savings, with a maximum of 5.8% in added savings for the modeled school building type. For at least half of the grid regions across the U.S., electric supplemental heating offers less than 1% in added whole-building emissions savings across all investigated building types compared with gas supplemental heating over the life of the equipment. These results highlight the critical importance of equipment selection decisions made today, over the expected lifespan of equipment.

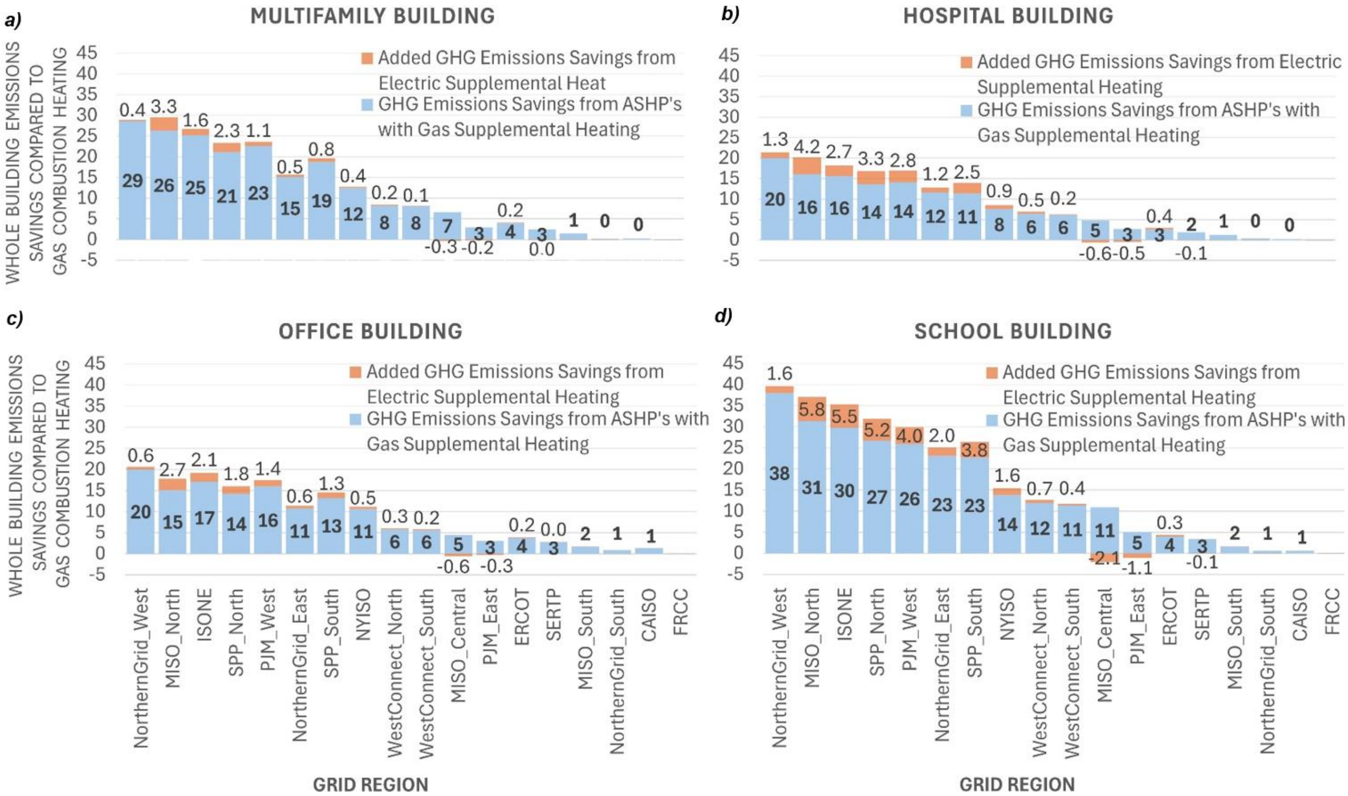

Figure 6 Modeled whole-building emissions savings over a 15-year period (2025-2040) from ASHPs with gas supplemental heating compared to gas-fueled heating, and the incremental increase in savings from electrifying the supplemental heat for the (a) multifamily (b) hospital (c) office and (d) school building types.

The accuracy of this study is limited by Cambium's reported hourly emissions data and EPA's historical, eGRID, annual emissions factors. The study also focuses on commercially available heat pumps with shut-off temperatures of -10F (-23.33C), which may reduce as technologies advance, and does not consider the impacts of heat pump defrost cycles on emissions. This research also assumes Cambium's mid-case future electrical grid scenario. Future work could expand this research by exploring a cost analysis between supplemental heat options, additional future electric grid scenarios through the Cambium dataset, and include more building types and vintages.

CONCLUSION

This study highlights the significant potential of ASHP's, including those with gas supplemental heating, in reducing whole-building emissions as U.S electrical grids transition to cleaner energy sources. While historical assessments (2014-2022) show minimal annual savings (<2%) in many electrical grid regions, future projections (2025-2050) indicate substantial increases in emissions savings, especially in regions with high renewable energy contributions. NYISO, Northern Grid East, SPP, PJM West and MISO North are among the most impacted grid regions by 2050, with annual whole-building emissions savings of 32%-92% through ASHP's with gas supplemental heating compared to all-gas heating systems. However, regions like FRCC exhibit limited benefits due to lower heating loads and lower projected renewable energy shares. The study also demonstrates that electrifying supplemental heating offers minimal additional emissions savings in many grid regions throughout the U.S. (<2% savings through 2050). Regions most impacted by the electrification of supplemental heat include MISO North and SPP North, with at least 10% in added whole-building emissions savings through 2050 for all investigated building types. These findings highlight the critical region-specific and long-term impacts of equipment selection decisions made today throughout the U.S.

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