Title

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Impacts from Electrification of Space Heating in Residences and Offices: a Simulation of Greenhouse Gas Emissions Across the United States

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ABSTRACT

Greenhouse gas (GHG) emissions from the building sector in 2021 contributed 36% of overall US carbon dioxide (CO_2) emissions according to Energy Information Administration (EIA 2021). The space heating of buildings, a large part of the overall emissions, relies heavily on natural gas. Electrification with a heat pump eliminates onsite emissions from space heating but results in indirect emissions from the electric grid. The generation mix of the electric grid evolves over time and varies widely by geographic location. This study presents a temporal and spatial distribution of the impacts of electrification of space heating in residential and office buildings. A comprehensive analysis was conducted to compare modeled GHG emissions over the operational life of a heat pump and a gas furnace installed between years 2022-2036 in six regions across the US. A residential home and a three-story medium office building were considered in this study and Energy Plus prototype models were used to simulate the energy use for space heating in 99 locations across the continental US. GHG impact calculations accounted for long-run marginal emissions from electricity generation from 2022 to 2050, emissions from natural gas combustion, and emissions from leakage of methane and refrigerant. The population weighted average results in the US for the residential home show a 30 - 68% reduction in 100-Year global warming potential (GWP) emissions for a heat pump over a gas furnace, with savings increasing as the year of the installation is deferred (2022-2036). Similarly, for the medium office building, the emissions change ranged from a 1% increase to 51% reduction. Office buildings show lower GHG emission savings in the initial years because of increase in refrigerant charge from the installation of a heat pump and reliance on electric-reheat in the variable air-volume boxes.

INTRODUCTION

The electricity sector of the United States (US) has been integrating renewables and is progressing forward on the path toward decarbonization. Target dates are set by federal and many state governments to motivate utilities to reduce carbon emissions from the electric grid. However, buildings (residential and commercial) continue to have onsite greenhouse gas (GHG) emissions from fossil fuel use (primarily natural gas). While emissions associated with electricity sales for residential and commercial building operations have decreased since the peak in 2008, emissions from direct fuel use on site are unchanged over the past 30 years (Figure 1). The direct emissions from buildings in the year 2020 equals to 553 million metric tons of carbon dioxide (CO_2), consisting of 230 million metric tons from commercial buildings and 323 million metric tons from

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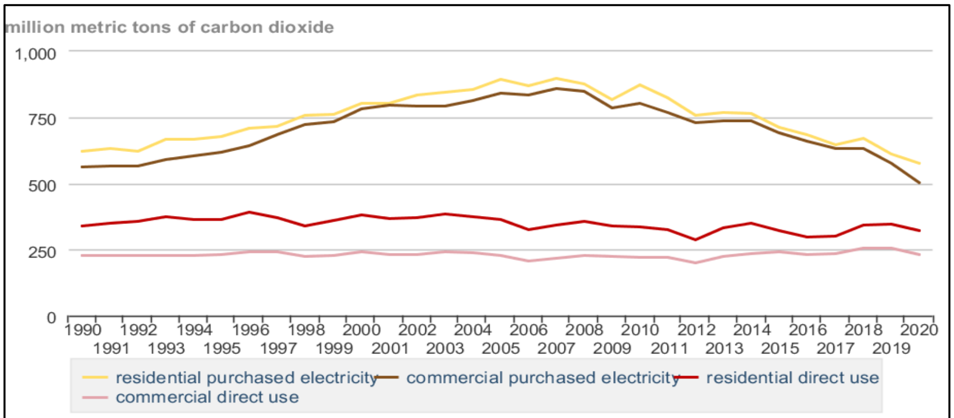
residential buildings (U.S. EIA, 2021) Direct emissions from buildings are predominantly from natural gas (NG) combustion for space and water heating. According to an EIA 2020 report, onsite NG consumption accounts for the major share of the total energy consumption in buildings: 42% in residential and 38% in commercial buildings (EIA, 2021). Electrification of end uses, especially space heating in buildings, is key to reaching decarbonization goals and curbing the impacts of climate change. While electrification of space heating in buildings through energy efficient heat pumps is a potential solution to eliminate onsite emissions, an increase in grid-level emissions due to heat pump electricity use can minimize the overall emission savings in the near term. Thus, a comprehensive assessment of the onsite and grid-level emissions is required for both NG furnaces and heat pumps throughout the lifetime operation of the equipment.

A recent study (Knobloch et al., 2020) has demonstrated that replacement of a fossil fuel space heating system with an electric heat pump would lower emissions in 53 out of 59 regions in the world using the current carbon intensities of the grid. However, the generation mix and carbon intensity of the electricity grid is also highly dynamic and varies widely with time of the day and year. Previous work (Neirotti et al., 2020) demonstrated that accurate assessment of GHG emissions would need accounting for hourly demand of heat pump electricity and the corresponding carbon intensity of the grid.

Several studies (Hirvonen et al., 2019; Roux et al., 2016; Tarroja et al., 2018) have predicted impacts from the electrification of space and water heating in the year 2050 from various locations around the world. The studies utilize a variety of grid models for predicting the emissions and locally available heat pump technologies as a replacement for fossil fuel alternatives. Although 2050 is the target year for a number of government emission reduction policies in the Europe Union and US, emissions over the entire operational life of the equipment should be considered to inform installation decisions. The median service life of a heating equipment can be estimated as 15 years (ASHRAE, 2019). Furthermore, past studies assume the coefficient of performance (COP) and the capacity of the installed heat pump as constant, whereas actual heat pump COP and capacity vary substantially with outdoor and indoor conditions.

The current work contributes to the body of literature by predicting and comparing GHG emissions from combustion and leakage over the operational life (15 years) of gas furnaces (GF) and heat pumps (HP). The GHG emissions are predicted for 99 locations throughout the US from 2022 to 2050 and consist of long-run end-use marginal emissions from electricity generation for new HP installations, emissions from NG combustion in GF, pre-combustion leakage for GF and thermal power plants, and fugitive emissions from refrigerant and NG leakage. Real world heat pump performance curves as a function of temperatures are used in this study to accurately predict the power consumption of the systems. The current study builds on previous work (Pistochini et al., 2022) which predicted major reductions in emissions from residential heat pump installations starting in 2022 to 2036. This study applies the same concept to office buildings as well as the updated grid emissions model from Cambium 2021, a database owned by National Renewable Energy Laboratory (NREL).

The goal of this paper is to provide a comprehensive assessment of the GHG emissions from the replacement of a GF with HP in residential homes and three-story office buildings across the US. The results of the study will inform law makers and researchers about the near-term and long-term implications of HP adoption in two most common building types in the US.



Source: Graph created by the U.S. Energy Information Administration (EIA), based on data from EIA's *Monthly Energy Review*, October 2021, Tables 11.2 and 11.3

Figure 1**:** Direct and Indirect Emissions from Buildings (EIA, 2021)

METHODOLOGY

EnergyPlus models developed by Pacific Northwest National Laboratory (PNNL) were used as starting points for the simulations. Based on specified geometries, material properties, internal gains, and HVAC configurations, a parametric study was conducted, using Python as the high-level programming language. Outputs for electricity and natural gas consumption were generated for each HVAC configuration and each building type.

Residential Building Model

The first model represented a single-family home, Figure 2 (left) using the DOE 2018 prototype model (Mendon & Taylor, 2014). The home was modeled as having one 223 m^2 conditioned zone and a 111.5 m^2 unconditioned attic. The model was updated to be compatible with EnergyPlus 9.4. and modified to accommodate a newer, more accurate EnergyPlus slab heat transfer object. Using ground temperature data from the weather file and user-provided material properties, this object calculates the heat flux through the slab. Two space heating configurations were considered: a fixed-capacity condensing natural gas furnace (GF) with an annual fuel utilization efficiency (AFUE) of 0.96, and a variable speed heat pump (HP) with Heating Seasonal Performance Factor (HSPF) of 10 equipped with backup heating provided by electric resistance heater (Trane Technologies, 2021). As the coefficient of performance (COP) of the air source heat pump approaches 1 at low temperatures, the heat pump was configured such that the compressor was turned off at -18°C. Below that outdoor temperature, heating is only provided by the backup electric resistance. In accordance with common design practice, the heat pump capacity was automatically sized to a safety factor of 1.4 times the 99.6% cooling design day load. Backup electric resistance heat strips (COP of 1) were sized to meet the 99.6% heating design day load. A cycling fan with a total efficiency of 0.4 and a 400 Pa static pressure rise was implemented to distribute conditioned air.

Office Building Model

The second model, Figure 2 (right) represents a "typical" medium-sized office building constructed in the US in compliance with ASHRAE 90.1-2019 standards (Deru et al., 2011). The modeled building is 8.2 m tall, consisting of three identical floors each divided into a core zone and four perimeter zones. The model has a total conditioned floor area of 10,683 m^2. The building is served by three different Roof top units (RTUs) with respective air handling units (AHUs), one for each floor. Variable air volume (VAV) terminals distribute air into each zone. Variable volume fans are set up in each AHU with a total efficiency of 0.6 and a static pressure rise of 1315 Pa at full speed. The minimum outdoor air flow rate is maintained at 0.08 CFM per square foot. Two space heating scenarios are simulated: a fixed capacity GF and a variable speed HP equipped with a backup electric resistance heater. Performance parameters (i.e. AFUE, COP, capacity factors, performance curves) for the equipment simulated in this building are identical to those used for the residential home. The master thermostats for controlling the GF and the HP are in the core zones of the floors. The VAV terminals in the perimeter zones have electric resistance reheat and operate separately from the GF or HP system to maintain the setpoint.

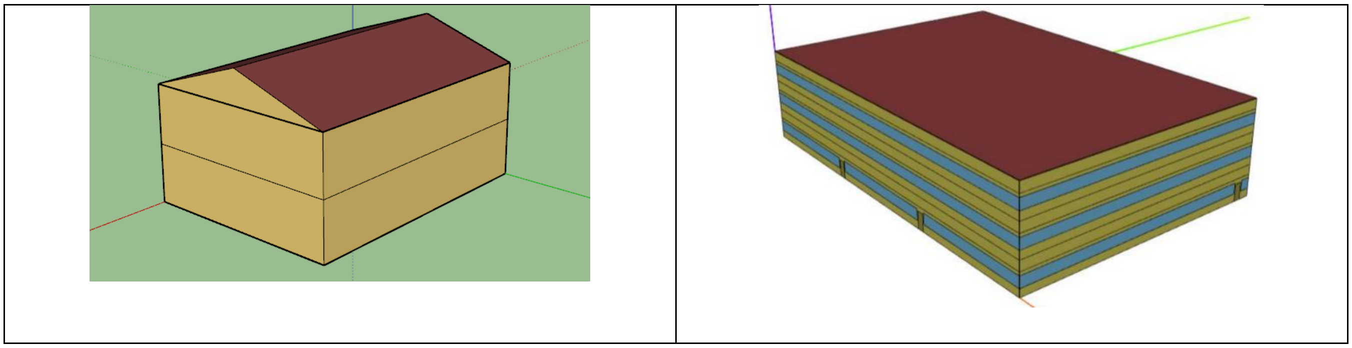


Figure 2: EnergyPlus residential home building model (left), medium-sized office building model (right)

Geographic Scope of Analysis

A total of 99 cities spanning the contiguous US were selected for this analysis. This number was reached by selecting the largest city from each International Energy Conservation Code (IECC) climate region within each of the 48 contiguous states (Pacific Northwest National Laboratory - PNNL, 2015), resulting in 97 cities, and adding two California cities (Sacramento and San Jose) to increase the granularity of the results within that state. The weather files used for the simulation are Typical Meteorological Year 3 (TMY3) weather files. The analysis did not account for potential climate change in the cities simulated. As such, the same weather files were used over the 28-year span of the simulations.

Once emission results were obtained for each climate zone, results were grouped by the following geographic regions: Pacific, Rocky Mountains, Southwest, Midwest, Northeast, and Southeast. Results were weighted based on the population of the County containing the modeled city, as reported in a US Census Estimate (United States Census Bureau, 2010).

Emission Sources

The emission impact from electricity generation was modeled using data provided from the NREL's Cambium project. The Cambium database (Gagnon et al., 2021) predicts, among other variables, hourly long-run marginal emission rates per end-use electricity consumption under different grid development scenarios for the years 2022 to 2050. For each U.S. state, long run marginal emission rates (LRMER) are provided for every even–numbered year (i.e., 2022, 2024, 2026 etc.) between 2022 and 2050, for a total of 15 datasets each of which covers the labeled year and the odd-numbered year that succeeds it. LRMER is used in our analysis for GF replacement with HP as it represents "the emission rate of the mixture of generation that would be either induced or avoided by a long-term (i.e., more than several years) change in end-use demand" (Gagnon et al., 2021). The low-renewable energy cost scenario in Cambium dataset was used as the source of the hourly marginal emission rates for this study. This scenario is in line with present day government-set targets and is less aggressive than a 95% grid decarbonization by 2050 scenario.

To obtain the long run marginal emission result, the electricity consumption for the entire building (or a specific end-use) at a given hour (E_h) is multiplied by the corresponding long run marginal emission factor ($co2\_lrmer\_enduse_h$):

$$m_{CO2\_elec\_annual}\ [kg\ C0_2] = \sum_{h=1}^{8760}\left(E_h\ [kWh] \times\ co2\_lrmer\_enduse_h \left[\frac{kg\ C0_2}{kWh}\right]\right) \tag{1}$$

The Cambium 2021 database, in addition to CO_2 combustion emission factors, provides combined CO_2 equivalent (CO_2-eq) emissions factors which includes an estimate of pre-combustion and combustion emissions in terms of 100-year global warming potential (GWP100). Therefore, the difference between the two factors is used to estimate fugitive CO_2-eq emissions associated with electricity generation in this study.

Furthermore, the heat pump scenario for both buildings considered GHG emissions resulting from refrigerant leakage. For the residential building scenario, this includes impact of increased air conditioning (AC) adoption (particularly in milder climates where air conditioning is not as widespread). This future projection was achieved using the regression method adopted by Pistochini et al. (2022), mimicking air conditioning adoption to date in the Southeastern United States, since that region has nearly reached 100% saturation (U.S. EIA, 2011). All commercial buildings in the US are usually equipped with AC, so for office buildings, only refrigerant charge increase from switching to a HP is modeled in this study.

$$m_{Ref\_lifetime}\ [kg] = \left(0.06\ \left[\frac{kg}{kW}\right] + 0.28\ \left[\frac{kg}{kW}\right] \times Cap\ [kW]\ \times (1 - f_{ac})\right)\ \times\ f_e \tag{2}$$

The GHG impact of refrigerant leakage was estimated through equation 2 (Pistochini et al. 2022): where 0.06 kg/kW is the additional refrigerant per unit capacity in a heat pump, 0.28 kg/kW is the refrigerant per unit capacity present in an air conditioner, Cap is the nominal cooling capacity of the unitary system as sized by EnergyPlus, f_{ac} is the fraction of homes presently equipped with air conditioning in a given city's region, and f_e is the 15-year lifetime fractional emissions given by equation (3), where y represents the year of installation.

$$f_e = 1.125e^{-0.045(y-2020)} \tag{3}$$

This predictive model assumes reduces in refrigerant emissions over time due to improved manufacturing and refrigerant handling and recovery practices. In addition, substantial decreases in the global warming potential of refrigerants are expected due to increased regulation (U.S. EPA, 2021). Simulation years 2022 and 2024 were conducted with the assumption that the heat pump contains R-410A, which has a 100-year GWP of 1,924 CO_2-eq (Myhre et al., 2014). Installation years starting from 2026 assumed that the refrigerant of choice would be R-32 with a 100-year GWP of 677 CO_2-eq (Myhre et al., 2014), as estimated by (U.S. EPA, 2021).

CO_2 emissions from combustion of natural gas in the furnace were obtained by multiplying the total natural gas consumption for a given year by an emission factor equal to 2.445 kg CO_2 per joule of natural gas consumed(U.S. EIA, 2021).

Behind-the-meter natural gas emissions were estimated at 0.5% of end-use consumption, based on data from the California Energy Commission (CEC, 2019). Furthermore, the heating energy consumed by the gas furnace in each studied city was converted to mass using the heating value for methane of 50 MJ/kg (Moran et al., 2010). Based on this mass, production stage methane emissions attributable to the furnace were calculated for each city based on the relative emissions by state reported by Burns et al. (2021). All natural gas emissions were multiplied by 28 to determine the 100-year GWP CO_2-eq (Myhre et al., 2014).

GHG Impact Assessment

GHG emissions from the above-mentioned sources were calculated for the GF and HP for the 15-year operation of each equipment and combined into same emission categories for comparing the residential home and office building simulations.

- **GF & HP CO_2 Electricity (Air Handler Fan).** Air handler fans are required for air flow and distribution in both building types for both GF and HP operations. The LRMER CO_2 emissions from the electricity generated for consumption of the air handler fans were accounted in this category.
- **GF CO_2 Natural Gas Combustion.** The CO_2 emissions from direct NG combustion onsite at the buildings by the GF were accounted in this category.
- **HP CO_2 Electricity (Compressor).** The LRMER CO_2 emissions from the grid due to the electricity consumed by the compressor of the HP were accounted in this category.
- **GF & HP CO_2 Electricity (Electric Resistance).** Electric resistance heat is used as back up by the HP in both buildings when HP capacity is limited or when the outdoor temperature goes below the equipment operation limit. Besides the HP backup heat, the office building also uses VAV electric resistance reheat coils for both GF and HP in the perimeter zones. The LRMER CO_2 emissions due to the electricity consumed by all the electric resistance heating were combined into this category.
- **GF NG BTM Leakage (GWP 100).** The NG leakage that occurs behind the meter (BTM) were accounted in this category. The leakage was quantified in terms of GWP 100-year kg of CO_2-eq.
- **HP Refrigerant Leakage (GWP 100).** Refrigerant leakage attributed to the additional refrigerant charge of HP in comparison to AC were quantified in this category. For the residential home this category also accounted for leakage due to installation of a heat pump in homes without an AC.
- **GF & HP GHG Leakage (GWP 100).** This category accounts for any leakage of GHG during the production, distribution, and combustion of fossil fuels in thermal power plants to supply electricity to be used by either GF or the HP space heating systems. Besides GHG leakage in the electricity generation, NG consumed by the GF has associated production site leakage, which was also accounted in this category.

RESULTS AND DISCUSSION

The important results from the simulation of the residential and office building models are presented in this section. The heat pump models simulated in this study include substantial backup electric resistance heat, the use of which is less efficient than heat from the compressor**.** Figure 3 shows the percentage of the annual heating delivered by the HP compressor for both residential and office buildings, with the remaining percentage of heat delivered by electric resistance. A lower percentage of compressor heating is observed in the Midwest region for both residential and office buildings due to the lower average outdoor temperatures which limit HP heating capacity or completely shutting off compressor in extremely cold conditions. The office building can be observed to have lower percentage of compressor heating due to presence of VAV electric resistance heating in the perimeter zones. Thermostat controls along with user supplied set points play a key role in determining the percentage of heat supplied by the heat pump compressor. Initially, the default office building model from PNNL showed less than 20%

utilization of heat pump compressor to supply the annual heating for the US population weighted results. To address this issue, setpoints in the perimeter zones were set 1°C lower than the building core for both GF and HP systems, which prevented the perimeter VAV reheat coils from continuously running during cold outdoor conditions and heat blanketing the building. This decreases the dependence on electric resistance heat for both GF and HP systems and improves the percentage of heating energy provided by the HP compressor to greater than 80% for the US population weighted results.

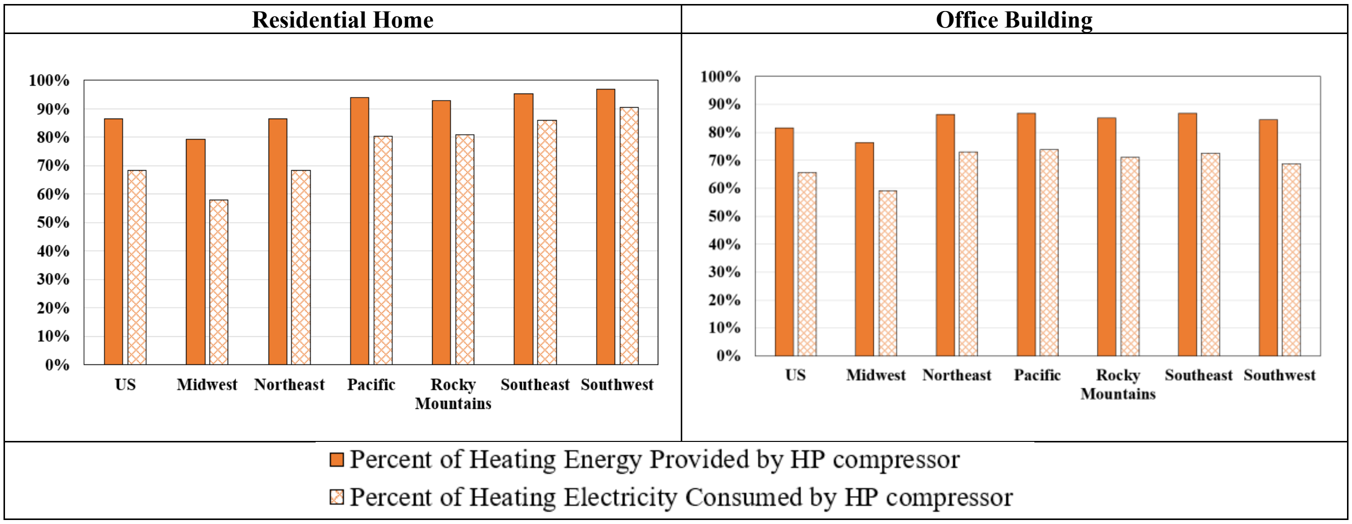


Figure 3: Heating delivered and electricity consumption percentage of heat pump compressor

The contributions to overall CO_2-eq emissions from various emission categories per unit of floor area are shown in Figure 4 as stacked bar charts by installation year for both GF and HP. The left three bars and right three bars correspond to GF and HP installations respectively in years 2022, 2028, and 2036 for residential (top) and office (bottom) buildings. For the residential home GF installation, CO_2 from NG combustion is the major component of the overall CO_2-eq emissions. Furthermore, emissions from residential home GF are constant, whereas emissions from office building GF decrease in the future installation years. This is because a significant portion of the office building GF emissions comes from the electricity used by the air handler fan and VAV electric resistance heaters, and as the electric grid becomes cleaner with time the emissions drop. In a residential home, the emissions from the air handler fan electricity are negligible in the GF scenario as compared to the HP scenario due to the higher temperature (80°C) heat from NG combustion which allows the fan to operate for a shorter duration to heat up the home. This difference between GF and HP air handler fan operation is not noticeable in office building because in a commercial building the fan is also used to meet the ventilation requirement of the building and cannot shut off when the thermostat setpoint is met.

Although the overall emissions from the office building are higher than the home, the total emissions per unit floor area from the home are an order of magnitude higher than the office. This is because single family homes have higher heating loads per unit of floor area attributed to a high surface to volume ratio of the building and 24-hour run-time of the heating equipment. In contrast, the office building is only heated during occupied hours and has a lower surface to volume ratio.

Refrigerant charge in AC or HP is determined by cooling capacity of the application and is similar for residences and offices for per unit floor area. For installation year 2022, refrigerant emissions are 3.0 kg CO2-eq per m2 of floor area for the office and 3.9 kg CO2-eq per m2 of floor area for the home. Thus, the emission contribution from refrigerant leakage is similar in magnitude for both building types, however the refrigerant emissions in the office building are a large percentage of total emissions due to the low heating loads. In the home, the increase in refrigerant emissions is a clearly outweighed by the beneficial reduction in heating emissions; in the office this trade-off is less clear. The refrigerant leakage emissions in CO2-eq drops off between 2022 to 2028 installation year because of a projected transition to R-32, a lower GWP refrigerant, and because of projected reduction in fugitive refrigerant emissions. Overall, electrification of buildings with higher space heating loads (either because of climate or building type or both) will achieve greater CO2-eq reduction impacts that outweigh increased use of refrigerant. Electrification of space heating in homes is a clear priority for achieving GHG reduction goals.

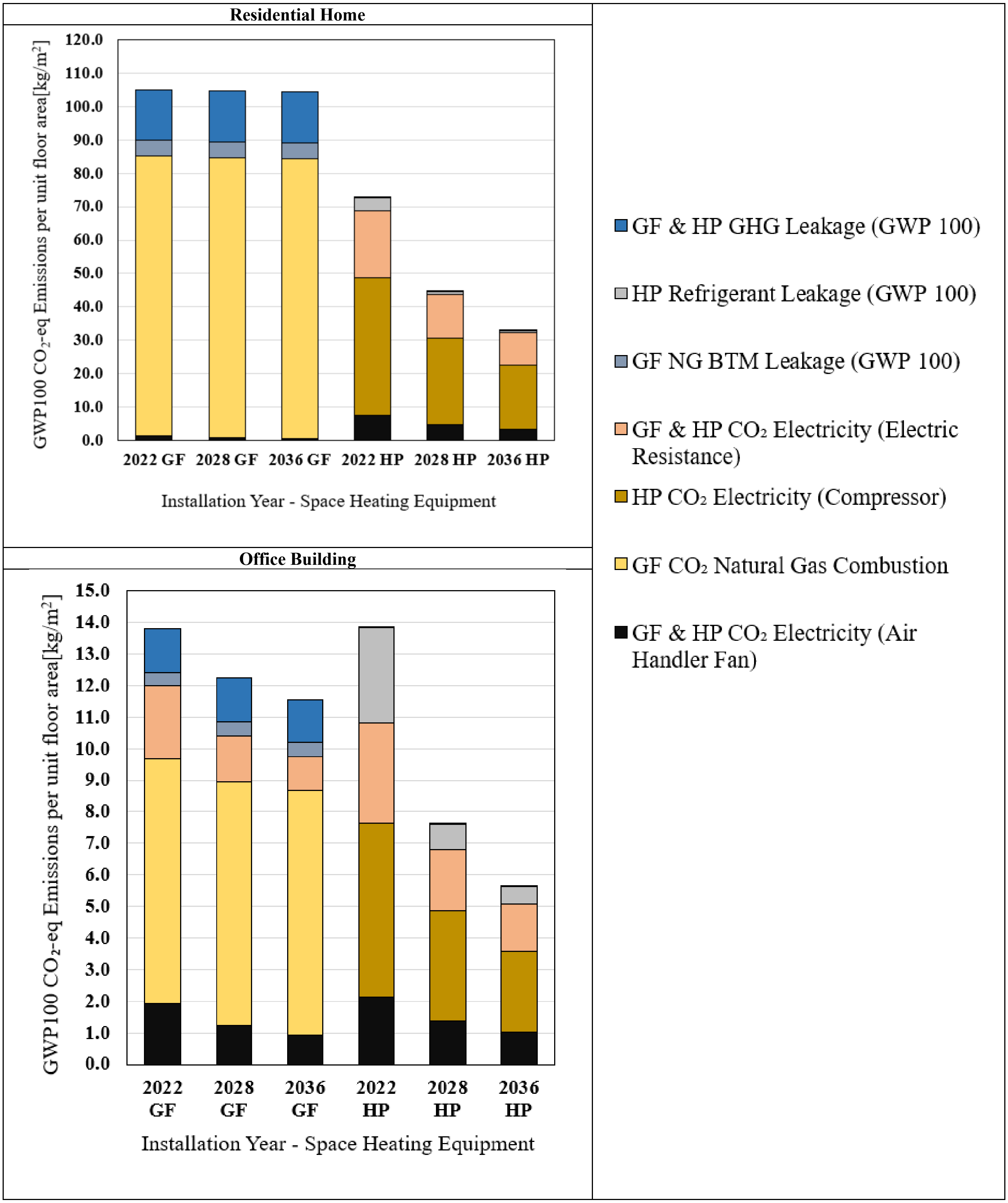
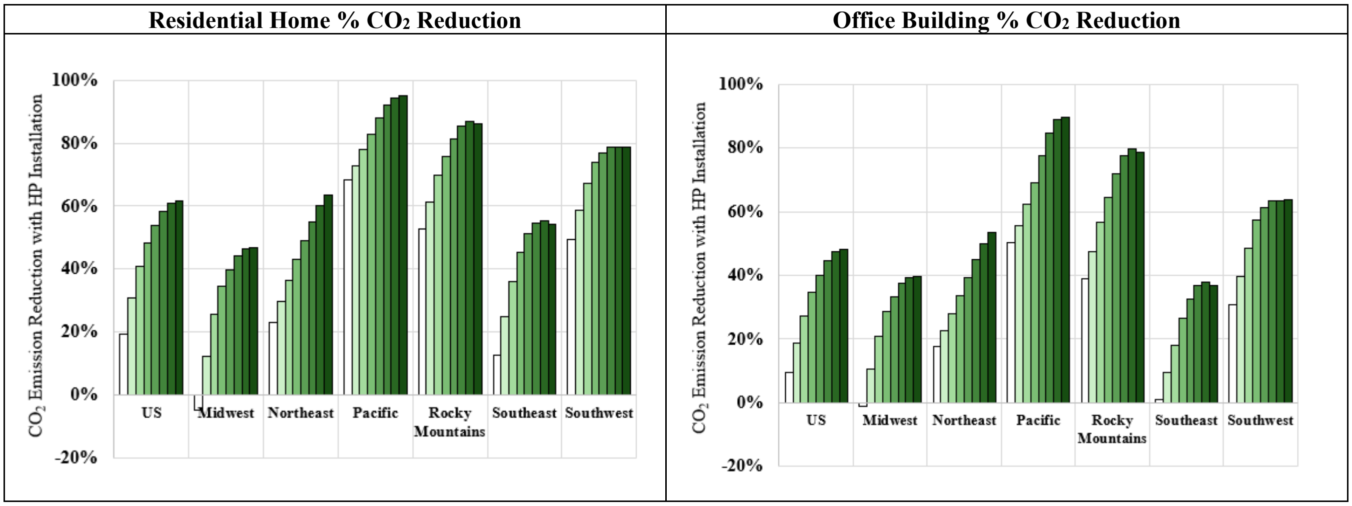


Figure 4: US Population weighted emission categories per residential and office building in GWP100 CO_2-eq

Figure 5 shows the regional population weighted percentage reduction in emissions when a GF is replaced with a HP. The top charts show direct CO_2 emission reduction without accounting for any fugitive GHG emissions for both building types. Residential homes show higher CO_2 emissions reduction (19% to 62%) than that of office (10% to 48%), with reductions increasing in future installation years. The Pacific region shows the highest direct CO_2 reduction, whereas Midwest region shows the lowest CO_2 reduction for both building types. The bottom charts show the emissions reduction after accounting for all fugitive emissions from refrigerant and NG leakage in terms of GWP100 CO_2-eq. Accounting for all emission categories, installation of HP for residential homes results in 30% to 68% CO_2-eq reduction and for office buildings a 1% CO_2-eq increase to 51% CO_2-eq reduction with reductions increasing in future installation years. Pacific, Southwest and Southeast regions show an increase in emissions in the initial years from the replacement of GF with HP. This is due to both lower heating loads and substantial increase in refrigerant emissions in these regions due to use of R410a till 2026, which is a high GWP refrigerant.

CONCLUSION

A comprehensive GHG emissions simulation from space heating was conducted for residential home and office building types in the US. Direct CO_2 emissions from NG combustion and electric generation were analyzed and predicted for gas furnace (GF) and heat pump (HP) operating over a life of 15 years across the continental US. The US population weighted result shows for residential homes 19% to 62% reduction and for office buildings 10% to 48% reduction in direct CO_2 emissions from replacement of GF with HP, with reductions increasing from 2022 to 2036 installation years. Fugitive emissions of NG leakage from production site and behind the meter, refrigerant leakage from HP use, and other GHG emissions from electricity generation were also accounted in this study. In the near-term, installation of HP in office buildings could lead to increase in emissions mainly due to increased use of refrigerant R410A. This signifies the importance of transition to lower GWP refrigerants, especially in large equipment, to lower overall emissions from electrification. Future work is required to accurately estimate refrigerant emissions in HP RTUs. Emissions from NG combustion in GF and production site leakage of NG remain high and steady throughout future, whereas emissions from electricity will keep dropping due to increased penetration of renewables.



Residential Home % CO_2 Reduction

Office Building % CO_2 Reduction

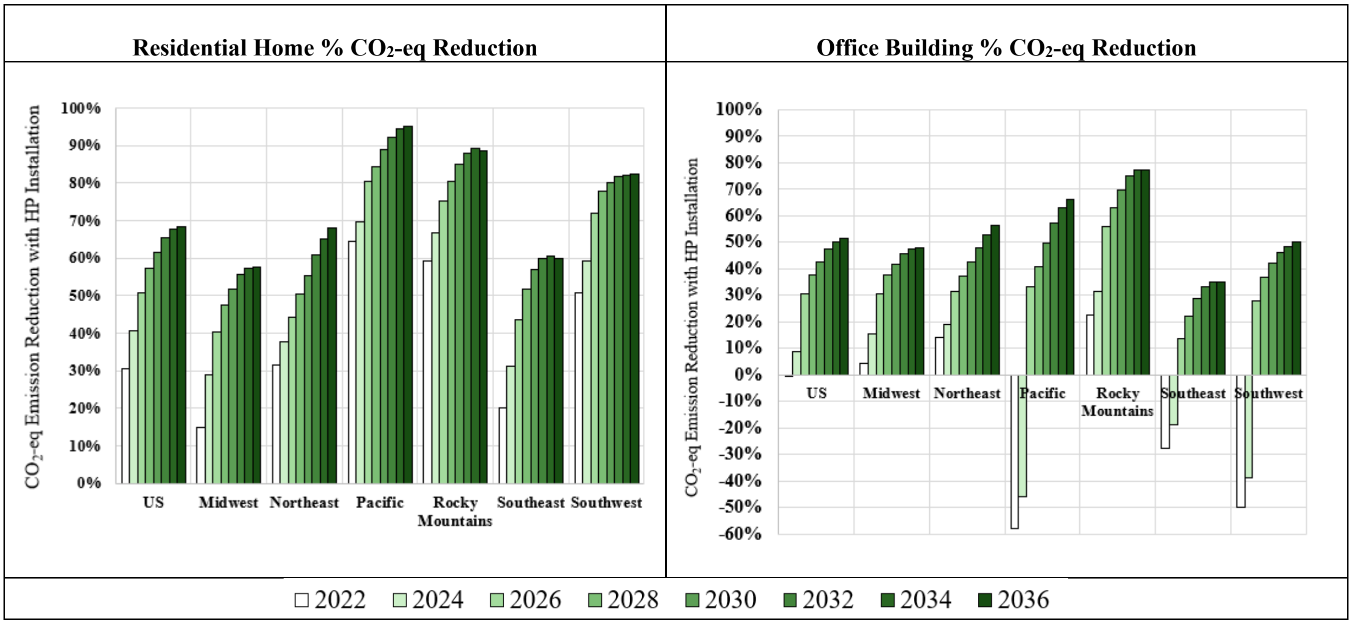


Figure 5: Regional population weighted average results for percent emission reduction by installation year for CO_2 (top), GWP100 CO_2-eq (bottom) in residential home (left) and office building (right)

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