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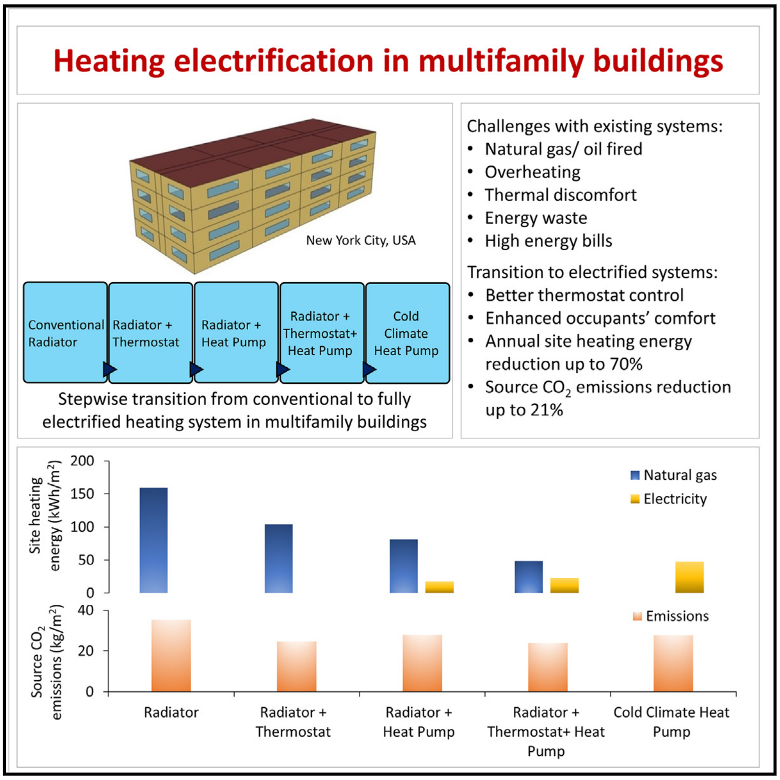
Energy impact of heating electrification in mid-rise multifamily buildings in mixed-humid climates

Graphical abstract



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In brief

The paper investigates a multifamily building in New York City, USA, to evaluate the performance of different heating systems, representing a step-by-step transition from conventional to fully electrified heating systems. The study reveals that transitioning from conventional steam radiators to cold climate heat pumps can reduce annual site heating energy by up to 70% and source CO_2 emissions by up to 21%.

Highlights

- Study on electrification in a multifamily building, New York City, USA, as a case study
- Overheating in apartment units raises indoor temperature up to 8°C above comfort limits
- Compared with steam radiators, cold climate heat pumps provide 70% lower site energy
- This results in 21% reduction in source CO_2 emissions

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Energy impact of heating electrification in mid-rise multifamily buildings in mixed-humid climates

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SUMMARY

Decarbonizing the electric grid in conjunction with electrifying residential heating is a critical step to combat climate change. Heating in multifamily buildings with the existing natural gas-fired central boiler is a complex process that not only leads to overheating in some apartment units but also results in energy waste and high gas bills. In this study, we consider a multifamily building in New York City, USA, to evaluate the performance of five different heating systems, which represent a step-by-step transition from the conventional to a fully electrified heating system, and determine their impact on the site energy consumption and source CO_2 emissions. Results indicate that overheating in a multifamily building can raise the indoor temperature by as much as 8°C above comfortable limits. Transitioning from conventional steam radiators to cold climate heat pumps can reduce annual site heating energy by up to 70% and source CO_2 emissions by up to 21%.

INTRODUCTION

Residential and commercial buildings account for nearly 39% of total energy consumption in the United States.[1] In addition, space heating accounts for 30%–40% of total energy use in US buildings.[2]The US residential building stock includes nearly 23 million multifamily buildings with five or more units.[3] In New York State alone, there are 46,458 residential buildings with four to seven stories built before 1940 and 6,124 buildings built between 1940 and 1978, according to an assessment conducted by the New York State Energy Research and Development Agency (NYSERDA).[4] Most of these buildings are currently heated with hydronic (hot water) or steam radiators that use a central water or steam boiler, usually fueled by "natural gas."[3] Typically, heating energy is not sub-metered for each apartment, so residents do not pay for heating costs individually. This, along with poor thermostatic control of the individual radiators, ultimately leads to higher fuel consumption than is required to meet or exceed the temperature setpoint of the coldest apartment as required by law.[5] This operation not only results in high energy consumption and emissions but also in thermal discomfort for some occupants due to overheating in certain apartments.

According to a report by the US Department of Energy (DOE), overheating leads to an estimated increase in annual energy consumption of nearly 1% per °F above the desired temperature in a home.[6] In addition, overheating in a multifamily building does not occur uniformly but varies from floor to floor and unit to unit. A comprehensive study by Dentz et al.[6] on overheating in water- and steam-heated multifamily buildings showed that the average temperature during the heating season in apartments in these buildings can vary from 71.8°F (22.1°C) to 81°F (27.2°C), with a mean of 76.3°F (24.6°C), which is significantly higher than the desired indoor air temperature of 70°F (21.1°C). This study also shows that the middle floors are generally hotter than the lower and upper floors, causing significant thermal discomfort for tenants and forcing them to open the windows, which further increases heating energy consumption. The energy waste caused by overheating is a major burden for the city, where the natural gas supply is already overloaded during the cold weather season.[7,8]

Controlling overheating in multifamily buildings is a critical technological challenge, not only to meet ambitious emissions targets, e.g., an 80% reduction in New York City by 2050[9] but also for the health and well-being of residents. Several potential solutions to reduce or shift heating energy demand in multifamily buildings have been proposed. For example, Dentz et al.[6] employed an energy management system (EMS) that includes temperature sensors in apartments networked with a central controller that modulates the heating system to control heating energy use in buildings that overheat. Devices such as insulated "radiator" sleeves that distribute heat and prevent overheating and energy waste have also been commercially introduced to thermodynamically moderate the rate of steam condensation in each radiator.[10]

An alternative solution to heat buildings is the heat pump (HP) since it can provide strict thermostatic control for conditioned spaces. Cities around the world, as it is the case in New York City, are introducing regulations to encourage electrification of space heating to meet their decarbonization goals.[11] In New York State, the Public Service Commission recently

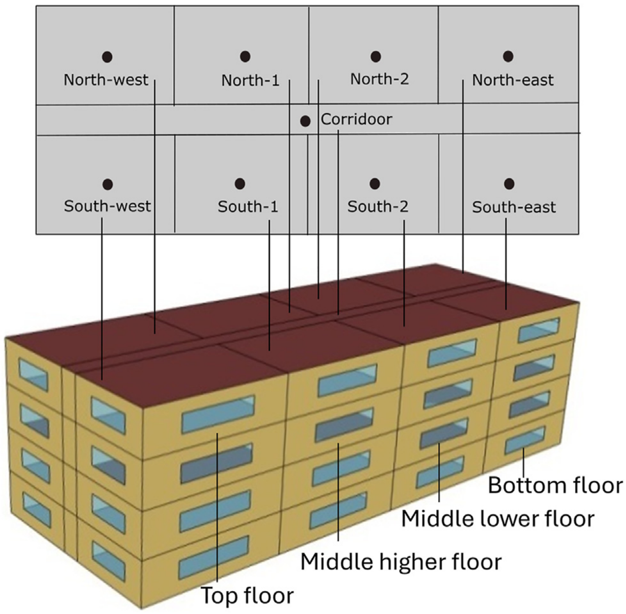

Figure 1. Mid-rise multifamily building model comprising four floors, each with eight apartment homes

mandated a significant increase in energy efficiency measures, with a major focus on HPs.[12] This suggests that a more comprehensive solution to overheating would require a shift from existing systems based on “oil” or natural gas to electric heating.[13] While HPs would give tenants control over the temperature in different apartments, their adoption is likely to be gradual because HPs in multifamily buildings face several challenges, such as high initial investment and lack of awareness among contractors and consumers about the performance of HPs in extremely cold weather.[14] In addition, it is critical to evaluate the impact of converting existing infrastructure to HPs on carbon emissions, energy consumption, peak energy demand, and energy costs. Studies that address these impacts are lacking.

In this paper, we study heating energy consumption in a pre-1980 multifamily mid-rise building in New York City. Decarbonization of existing multifamily buildings can take many years due to the cost implications and other practical difficulties related to retrofitting an existing occupied building. The transition from the current natural gas-fired boiler system to a fully electrified heating system would therefore require several intermediate steps that need to be explored and evaluated. In this study, we attempt to bridge this technical gap by exploring some of the potential solutions. The main contribution of this analysis can be realized as a step-by-step assessment of electrification in multifamily buildings and its impact of energy and related emissions as the current building stock transition from traditional radiator heating systems to cold climate heat pump (CCHP) technology.

The main objectives of the study are to

- estimate the wasted energy associated with overheating various units and examine the impact on occupant thermal comfort when a gas-fired central heating system with steam radiators is in operation;
- evaluate five different types of heating: (1) radiators only, (2) radiators with thermostatic control, (3) radiators with conventional HP, (4) radiators with thermostatic control and HP, and (5) CCHP that completely replaces the central radiator system; and
- evaluate the impact of preheating and thermal energy storage (TES) to shift peak heating, ventilation, and air conditioning (HVAC) demand from peak to off-peak periods for both gas and electric systems. This process involves sizing a phase change material (PCM)-based TES system to serve the building’s thermal load while meeting thermal comfort requirements.

Although there are techniques such as building weatherization, improved lighting, and appliances that can reduce energy consumption and shift/shave peak energy demand, in this study only the heating systems transitioning from natural gas-fired central boiler heating to distributed CCHPs are considered.

RESULTS

Building descriptions and numerical model

Figure 1 shows the multifamily building used for the simulations in this study. It is a standard pre-1980 prototype building model published by DOE.[15] The building under study has four floors (bottom, lower-middle, upper-middle, and top), and each floor has eight apartments. As shown in Figure 1, these apartments are named according to their location in the building. The gross area of the building is 3,134.5 m^2 (33,739.5 ft^2) with the corridors, and the net floor area of each apartment is 88.3 m^2 (950.5 ft^2).

A standard prototype model was used for the mid-rise multifamily building created for International Energy Conservation Code climate zone 4A.[16] The prototype building models are developed and used by the Pacific Northwest National Laboratory (PNNL) for analyzing the improvements to ANSI/ASHRAE/IES1 Standard 90.1. In this study, additional features were added to the standard model that are commonly found in older buildings.

- The heating system for the standard building model consisted of a unitary packaged terminal system fueled by natural gas. This forced air system was replaced with a gas-fired steam radiator heating system for this study. Recommendations from previous studies by Choi et al.[17] and Dentz et al.[6] were considered when implementing the steam radiator heating system.
- The cooling system of the prototype building consisted of a unitary packaged terminal system. This system was replaced by a window HP at each apartment. This allows for flexible simulation of the heating supplied to the building (1) by radiator only, (2) by a combination of radiator and HP, and (3) by HP only.
- Air infiltration into the units was determined based on a database of blower door evaluations in multifamily buildings conducted between 2011 and 2016 in New York State.[18]
- The plug load values were taken from a previous study[19] that included data from approximately 400 apartments.

Table 1. Energy mix of eGRID subregion NYCW

Energy source	Energy mix (%)	Emission coefficient (kg/MWh)
Natural gas	90.1	202.49
Nuclear	8.7	0
Other fossil fuel	0.5	276.2
Biomass	0.4	0
Oil	0.2	290.1

Table S1 shows the HVAC and load data for the building after the above changes were made. Table S2 provides details about the building envelope components and materials.

HVAC operation modes

In this study, we consider five different HVAC system modes. These modes represent the transition from a traditional steam radiator system without thermostatic control to a modern electric heating system with a CCHP in each apartment along with individual thermostatic control in a mid-rise multifamily building. Each of these heating modes is described in the subsequent sections.

Baseline: Steam radiator without thermostat control (radiator)

The baseline configuration of the heating system, abbreviated as "radiator" in this paper, consists of a steam radiator in each apartment with limited thermostat control. Apartments do not have electrical heating capability in this case. This case represents the current situation in most mid-rise buildings in New York. Minimal thermal control can lead to excessive overheating in apartments where no thermostat is available to regulate heating. To simulate this type of operation, heating throughout the building is assumed to occur based on the thermostat function of the apartment that is, on average, the coldest apartment. This apartment is identified in an annual simulation and then determined regardless of whether it is the coldest apartment at any given time. Using the EMS in EnergyPlus, a control logic is implemented to provide additional heat to each of the other apartments to compensate for overheating due to poor thermostatic control. The EMS control logic is described in the subsequent sections.

Equation 1 shows the heat balance equation used in EnergyPlus to determine the HVAC heating/cooling demand and temperature in a zone at the end of each time step. In this study, it is assumed that each dwelling is a single thermal zone, and the heat balance is calculated for each zone. $\dot{Q}_s$ is the energy stored in the air, walls, and furniture of the zone, $\dot{Q}_{conv,int}$ is the convective internal loads or internal gains from within the zone, $\dot{Q}_{conv,surf}$ is the convective heat transfer from the building's internal surfaces to the zone considering convection and radiation, $\dot{Q}_{inf}$ is the heat transfer due to outside air infiltration, $\dot{Q}_{int,mix}$ is the heat transfer due to interzone air mixing, and $\dot{Q}_{sys}$ is the heat transfer rate from a heating or cooling (HVAC) system.

$$\dot{Q}_s = \dot{Q}_{conv,int} + \dot{Q}_{conv,surf} + \dot{Q}_{inf} + \dot{Q}_{int,mix} + \dot{Q}_{sys} \quad \text{(Equation 1)}$$

The heat transfer rate from HVAC has two components, as shown in Equation 2.

$$\dot{Q}_{sys} = \dot{Q}_{sys,air} + \dot{Q}_{sys,conv} \quad \text{(Equation 2)}$$

The first term $\dot{Q}_{sys,air}$ is the HVAC air transfer, which varies depending on the case (e.g., HP or ceiling diffuser system) where heating or cooling is provided by forced air movement into the zone. The second term $\dot{Q}_{sys,conv}$ is the convective heat transfer, used when heating or cooling is supplied to the zone by natural convection (e.g., steam radiator or baseboard heating system).

To model the overheating phenomenon, we assume that the thermostat in the coldest apartment drives the operation of the central boiler. In other words, all the apartments in the building continue receiving the heating energy until the heating setpoint in the coldest apartment is met. As the coldest apartment draws heat from the central system, the heat also gets distributed to other zones that are already warm, leading to overheating in these apartments. To simplify the calculations, we assume that, as the coldest apartment receives heat, the same amount of heating is added to all other apartments. To account for this, the simulation compares the heating load of apartment "i" ($\dot{Q}(i)_j$) and the coldest apartment "c" ($\dot{Q}(c)_j$) at each time step j. If the heating requested by the coldest apartment is higher than the heating requested by the apartment i, i.e., if ($\dot{Q}(c)_j > \dot{Q}(i)_j$), the difference is added to the apartment i as a heat source $\dot{Q}_{hs}(i)_{j+1}$. More specifically, the heat source is added to the $\dot{Q}_{conv,int}$ component of Equation 1 as the HVAC input at the next time step $(j+1)$.

$$\dot{Q}_{hs}(i)_{j+1} = \dot{Q}(c)_j - \dot{Q}(i)_j \quad \text{(Equation 3)}$$

At time step $(j+1)$, the heat balance for the zone i is calculated, and the HVAC heating demand is determined and again compared with the heating demand for the coldest zone c. This process continues for each time step for all zones during the heating months. Therefore, the energy required for the coldest apartment to reach its setpoint is added to the remaining apartments to approximate the overheating behavior of the building. This causes the apartment temperatures to rise above the thermostat setpoint (except for the coldest zone at each time step). The additional heating energy consumed is included in the final simulation results. This modified building model is used as the baseline building for this study. It is ensured that all apartments meet the statutory minimum temperatures of 20°C (68°F) from 6 a.m. to 10 p.m. and 16.7°C (62°F) from 10 p.m. to 6 a.m.

Steam radiator with thermostat control (radiator + thermostat)

The second case, abbreviated as "radiator + thermostat," considers a steam radiator with thermostatic control in each apartment. It is assumed that each apartment is thermostatically controlled by the proper operation of the boiler and distribution system, as well as by additional control mechanisms such as radiator sleeves and thermostats to prevent overheating. Apartments do not have electrical heating capability in this case.

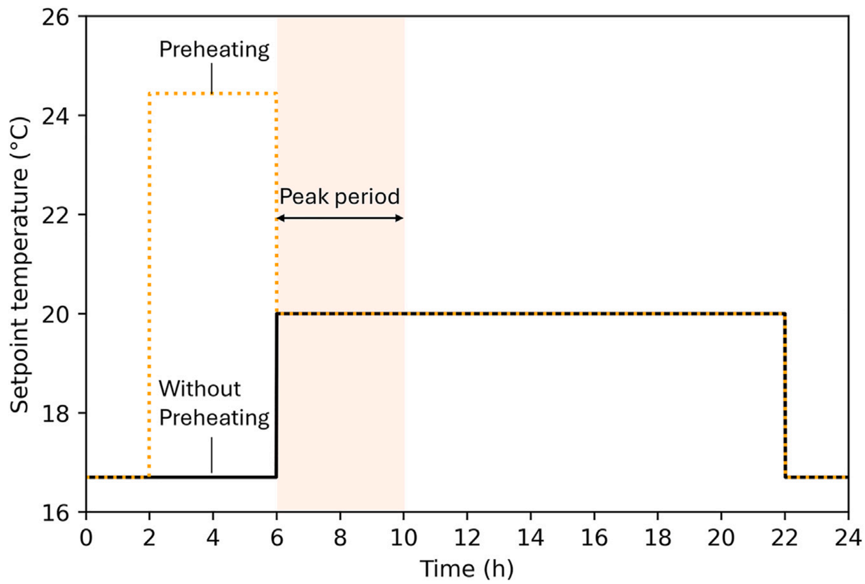

Figure 2. Setpoint temperature profiles for the regular heating and preheating strategy
The shaded area represents the peak period.

Steam radiator without thermostat control and regular HP (radiator + HP)

The third case, abbreviated as "radiator + HP," considers both the steam radiator and a HP for heating. For apartments with a regular HP in cold climates, the regular HP system usually shuts down when the ambient temperature is very low and switches to a natural gas-fired steam radiator heating system.[20] To simulate this scenario, it is assumed that there is a single HP per apartment/household unit; however, heating is provided by the steam radiator when the ambient temperature is below 1.7°C (35°F). The EnergyPlus EMS plug-in is used to control HVAC operation to alternate between steam radiator and HP modes. In steam radiator mode, overheating occurs as described in section baseline: steam radiator without thermostat control (radiator).

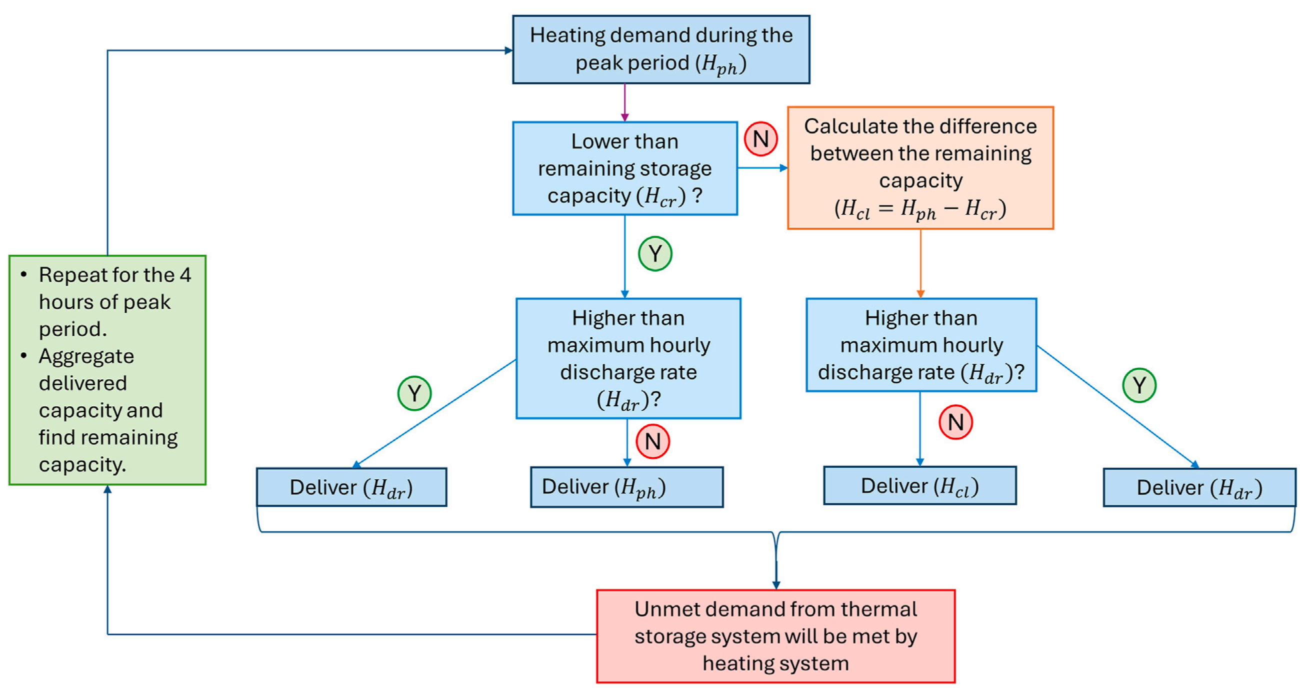

Figure 3. TES assessment for the peak load shaving and shifting of heating load in mid-rise buildings
H_{dr}, maximum discharge rate possible; H_{ph}, heating energy demand during the peak hour (between 6 and 10 a.m.); H_{cr}, remaining thermal energy storage capacity; and H_{cl}, difference between peak hour demand and remaining capacity.

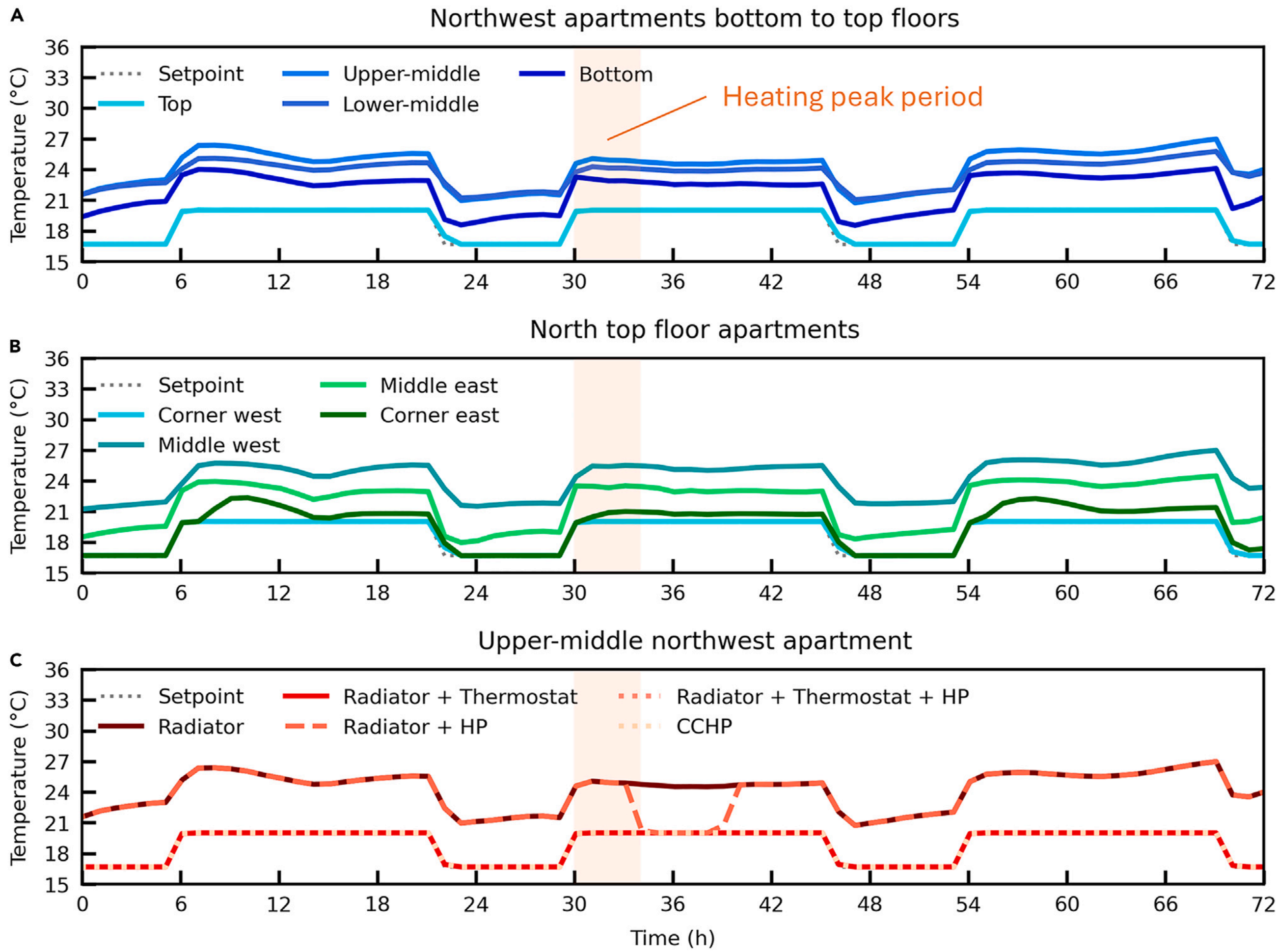

Figure 4. Temperature variations in the apartments

(A) Northwest apartments bottom to top floors, (B) north apartments on the top floor, and (C) upper-middle northwest apartment under various heating modes.

Steam radiator with thermostat control and regular HP (radiator + thermostat + HP)

This case, which includes the radiator, the individual thermostat in each apartment, and the HP, is similar to the previous radiator + HP case, except that the operation of the radiator is now thermostatically controlled in each apartment, as described in section steam radiator with thermostat control (radiator + thermostat). It is essential to include this case, as it is perhaps the most practical way to full electrify the heating system, given that all components are commercially available.

CCHP

The last case described in this section refers to state-of-the-art HPs for cold climates, called CCHPs. In this mode, it is assumed that the HP provides sufficient heating even during extreme cold ambient conditions, and therefore the apartment units do not need any supplementary heating. It is also assumed that each apartment is thermostatically controlled. Lastly, it should be noted that CCHPs may not be available in the quantities and designs needed to fully electrify heating in New York City, or if they are available, prices may still be elevated because they are relatively new.

For all HVAC modes discussed above, site energy demand is reported in kW and site energy use is reported in kWh/m^2 (kWh over total conditioned floor area) for both natural gas and electricity to allow comparison of results.

CO_2 emission calculation

Source emissions were calculated using 2021 electricity generation data by eGRID for the New York City and Westchester (NYCW) subregion and the Eastern Power Grid.[21] These data are provided on the United States Environmental Protection Agency (US EPA) data portal.[22] These data showcase the different fuel sources used for electricity generation in New York City. Table 1 shows the contributions of the different energy sources. The oil, natural gas, and other fossil fuel categories are assumed to contribute to CO_2 emissions at the source. Table 1 also shows the percentage contribution of each energy source and the CO_2 emission coefficients that account for both combustion and pre-combustion emissions. The emission factors were taken from the Cambium Documentation: Version 2021.[23]

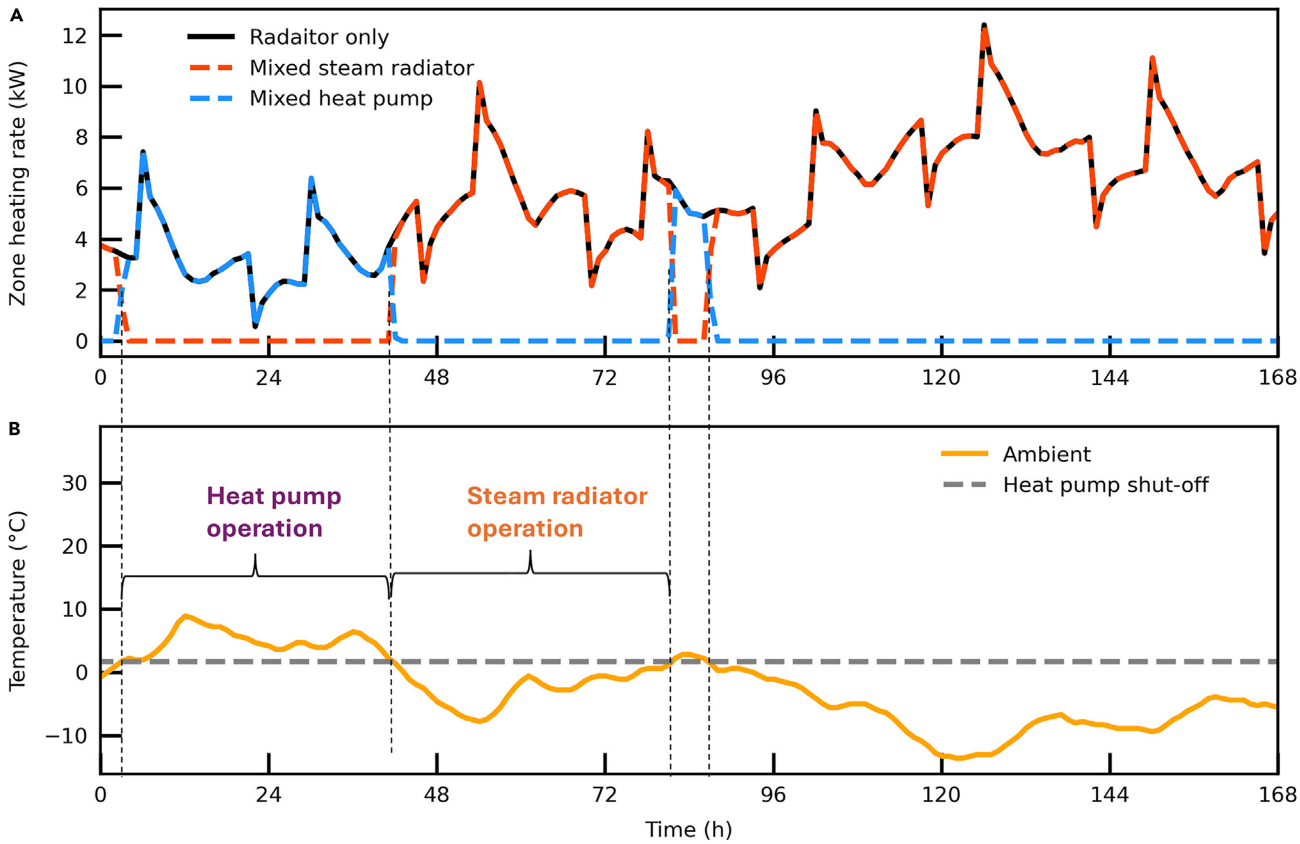

Figure 5. Zone heat transfer rate at the bottom northwest apartment

Two heating modes: radiator with thermostat control and radiator with thermostat control and regular heat pump.

(A) Zone heating rates under the two modes and (B) ambient temperature and the cutoff of the heat pump.

To calculate the emissions with respect to the current building, we first calculate the annual source energy consumption of the building. The site-to-source conversion factors published by Deru and Torcellini[24] were considered in this study to convert the natural gas and electrical HVAC energy to the source values. This annual source energy is then apportioned to each fuel source based on the energy mix shown in Table 1. Emissions from the energy produced by each fuel source are calculated using the emissions coefficients shown in Table 1. Finally, the emissions from each fuel type are summed to determine the source emissions for the building.

Heating demand and peak shaving

The following assumptions, consistent with local utility and New York regulations, were made to determine the heating demand and evaluate the various strategies to avoid and shift peak loads for the current building[25]:

- the heating season is between October 1 and May 31;
- peak heating demand is between 6 and 10 a.m.;
- during the daytime (between 6 a.m. and 10 p.m.), the indoor temperature is maintained at a minimum of 20°C (68°F); and
- during the nighttime (between 10 p.m. and 6 a.m.), the indoor temperature is maintained at a minimum of 16.7°C (62°F).

Demand modulation using preheating

One possible method to reduce heating demand during peak periods is to use thermostatic control to preheat apartments during off-peak periods. The inherent thermal mass of the apartment walls, furniture, and appliances, as well as the zone air, stores thermal energy that can be consumed during peak periods. An important factor to consider is the thermal comfort of the occupants. Therefore, the increase in the heating setpoint during off-peak hours should be within a comfortable range. In this study, a preheat off-peak temperature of up to 24.44°C (76°F) was investigated. Figure 2 shows the regular and preheat setpoint temperatures during the day. Both profiles meet the requirements of the New York City Housing Preservation and Development (HPD) Department.[26]

Demand modulation using TES

TES is a method to store energy for both heating and cooling during off-peak hours. Thermal energy can be stored as sensible, latent, or thermo-chemical storage. Latent thermal storage is

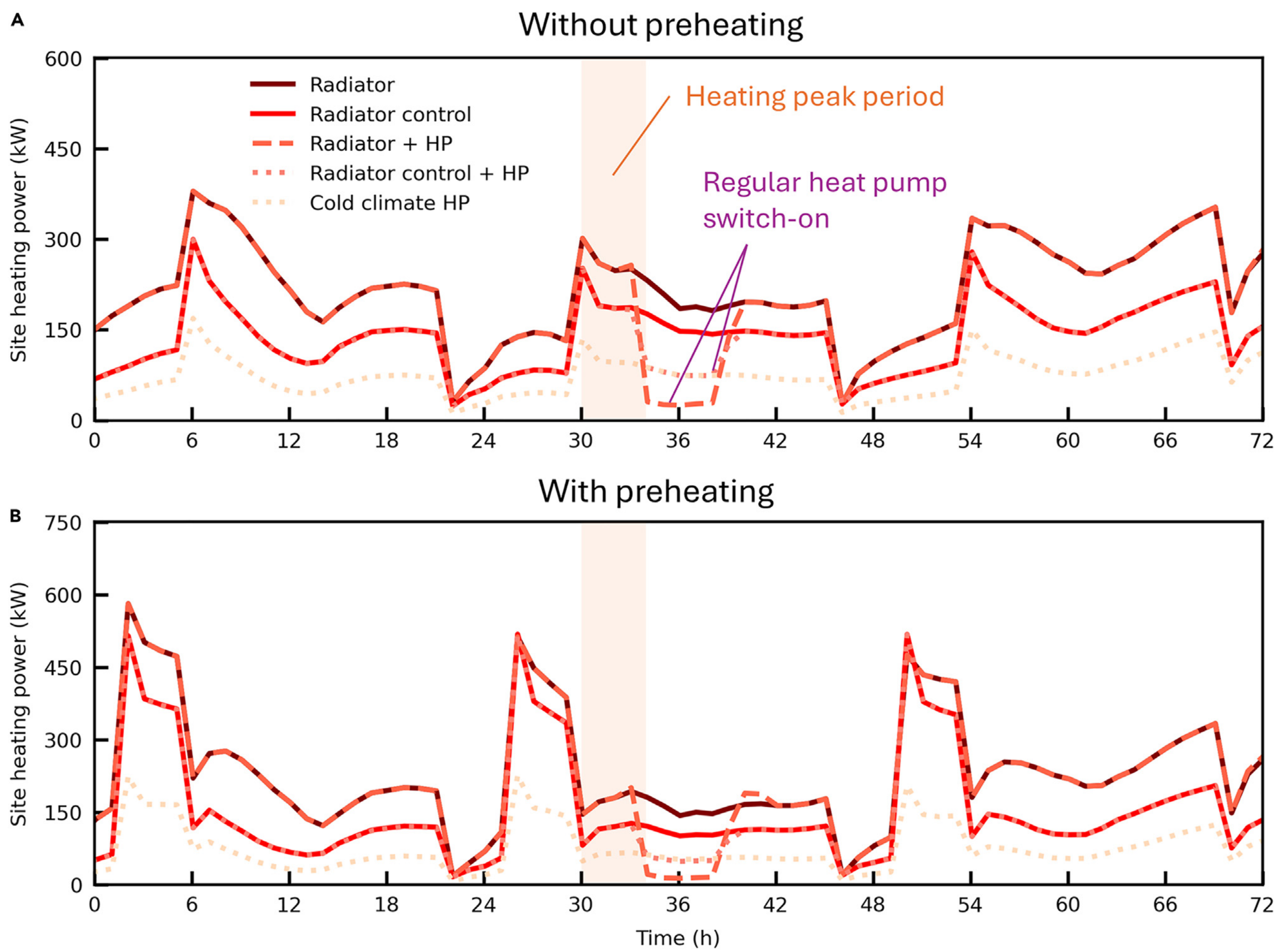

Figure 6. Total site heating power for 3 days (February 3–5) in winter

Different heating modes: radiator mode (radiator) without individual thermostat control, radiator with individual thermostat control (radiator + thermostat), radiator without individual thermostat control but with regular heat pump (radiator + HP), radiator with individual thermostat control plus regular heat pump (radiator + thermostat + HP), and cold climate heat pump (CCHP).

(A) Without preheating and (B) with preheating. The shaded area represents the peak hours of the second day (6 to 10 a.m.).

attractive because of its high thermal storage capacity compared with sensible thermal storage.[27] PCM is a type of latent TES that has been used both actively and passively to store thermal energy for building applications.[28,29] Charging active PCM systems with cheap off-peak energy has been widely studied.[30,31] Solar heating,[32] hydronic radiant floor systems,[33] and HPs[34,35] are some of the common heat sources for charging PCM storage in the literature.

In this study, we assume that a PCM thermal storage system is charged by a CCHP.[36] It is assumed that CCHP could meet the setpoint in all the apartments, even during extreme cold conditions without the need for any supplementary natural gas heating system. Furthermore, several assumptions are made when sizing the PCM thermal storage system:

- the storage system is charged during off-peak hours and is available at 100% capacity at the start of the peak period each day.
- the efficiency of the storage system operation is 1. Therefore, there are no thermal losses when charging and discharging the PCM storage, and there are no standby losses (losses from unused storage).
- the goal of this study is only to estimate the size of the TES systems; therefore, the detailed thermophysical characteristics of the PCM are not modeled here.
- the size of the storage system is based on the hourly demand during the 4-h peak period from 6 to 10 a.m.
- each apartment in the building would reach the setpoint at 20°C during the peak period, first by the energy supplied by the PCM storage system and then by activating the HP system.
- PCM stores and releases the same amount of energy during melting and freezing (no hysteresis) and has a total phase change enthalpy of 250 kJ/kg.[37] PCM is also assumed to have a density of 2,070 kg/m^3, typical of an inorganic salt hydrate PCM.

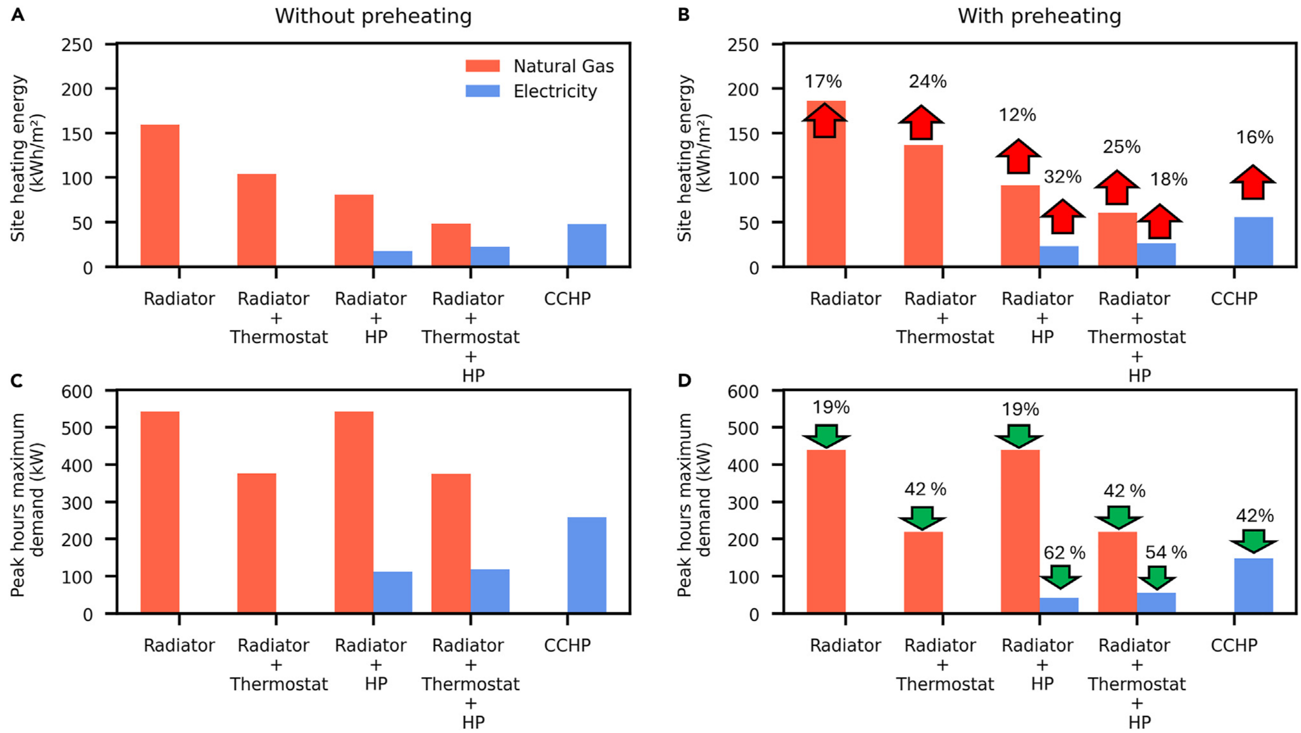

Figure 7. Annual site energy consumption and the peak hours maximum heating demand from 6 to 10 a.m
(A) and (C) without preheating, (B) and (D) with preheating at 24.4°C for 6 h.

- a single TES system is available for each apartment.

The discharge of stored energy from the TES system is limited by the maximum capacity and the maximum hourly discharge rate. Figure 3 shows the algorithm used to evaluate the heat delivered by the storage system for each hour during the peak period. The algorithm assumes that the energy delivered by TES every hour is determined by the minimum of the desired discharge capacity and the available capacity and the maximum discharge rate. This process is performed for the 4-h peak period of each day. The sum of the delivered heat during the 4 h of the peak period determines the daily used capacity of the TES and thus the peak demand shifted by the TES system. In addition, the ratio between the total annual sum of the heat supplied by the TES system and the total heating energy required during the peak hours determines the total capability of the storage system to shift heat demand. This analysis is performed for different combinations of storage capacity and maximum discharge rates for the building.

Zone temperature and overheating

Figure 4 shows the zone temperature of the different apartments in the building for 3 days during the winter (February 3–5). Figure 4A shows at the vertical axis the average temperature of the apartment at the northwest corner (bottom floor to the top floor) when the steam radiator is operating without individual thermostatic control. The shaded area indicates the peak hours (6 to 10 a.m.) when heating demand is highest in the morning. The top floor apartment in the northwest corner of the building is the coldest of all apartments, followed by the bottom floor apartment. This observation is consistent with previous studies, for instance Dentz et al.,[6] which reported that the lowest average temperature occurs in either the bottom or top floor apartments, while the middle floor apartments have relatively higher temperatures.

Figure 4B shows the zone temperature along a horizontal axis on the north side of the top floor when the apartments are equipped with steam radiators but without individual thermostatic controls. Temperatures are lower in the corner apartments than in the middle apartments. This is to be expected because the exterior envelopes of the corner apartments are more exposed to the outdoor environment than those of the middle apartments.

Figure 4C shows the zone temperature of the middle to upper floor of the northwest apartment for the five different heating modes: (1) radiator-only mode (radiator), (2) radiator with thermostat control (radiator + thermostat), (3) radiator with regular HP (radiator + HP), (4) radiator with thermostat control and regular HP (radiator + thermostat + HP), and (5) CCHP. The highest temperature is observed for the case with the steam radiator but without individual thermostat control. Moreover, the temperature curves of radiator and radiator + HP almost overlap, except for the second day between 10 a.m. and 3 p.m. when the HP is turned on. The radiator + thermostat, radiator + thermostat + HP, and CCHP lines closely follow the setpoint line of the thermostat and lie on top of each other meeting the setpoint. On many winter days, especially during peak hours, much of the heat output is provided by the steam radiator. For example, on the 3 days shown here, the HP turns on only on the second day, from 10 a.m. to 3 p.m., when the thermostatic control is

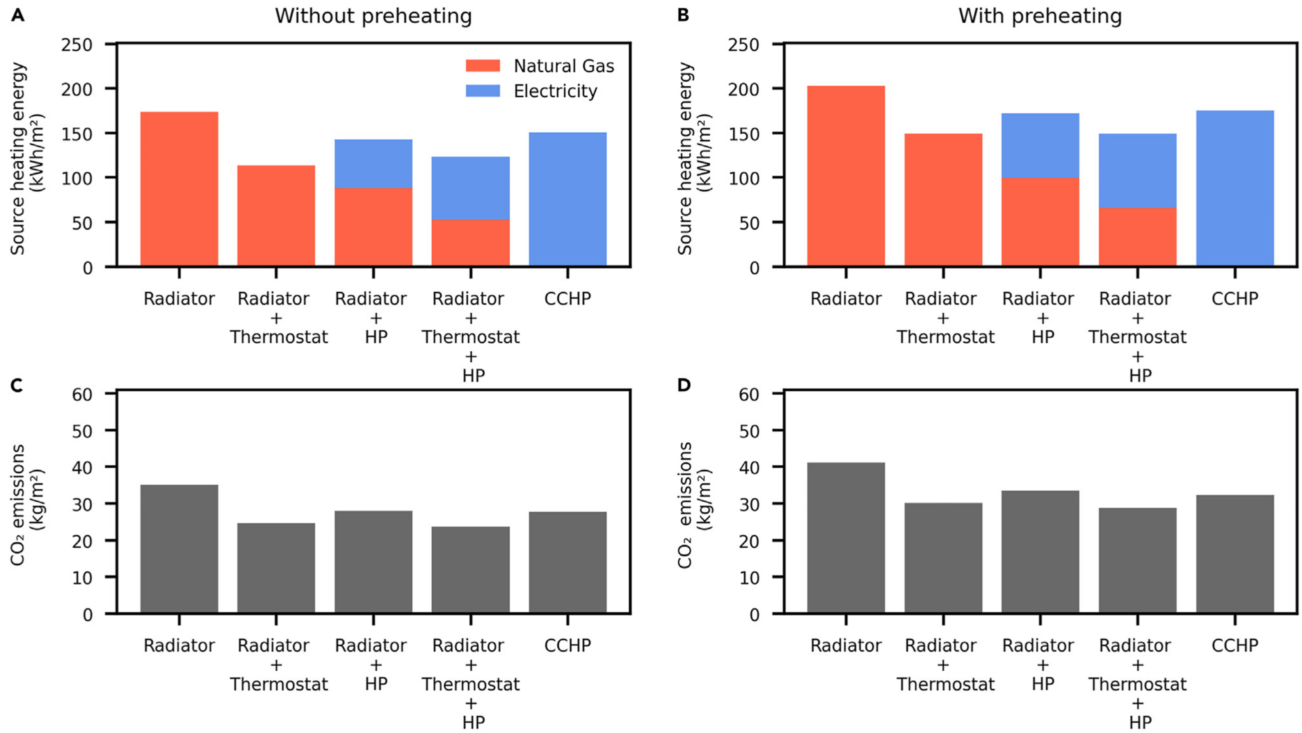

Figure 8. Annual source heating energy consumption of the building and related source CO_2 emissions
(A) and (C) without preheating, (B) and (D) with preheating at 24.4°C for 6 h.

turned on. At all other times, uncontrolled heating is observed. As expected, when the HP is on, the temperature closely adheres to the thermostat setpoint.

In the absence of individual thermostat control, we have observed a temperature rise of up to 8°C above the setpoint in some apartments. This exceeds a reasonable level of thermal comfort for most occupants and, in practice, is likely to result in tenants opening apartment windows even on cold winter days, further increasing heating energy consumption.

Site heating energy use

Figure 5A shows the zonal heat transfer rate in the bottom northwest apartment under the two heating modes: radiator + thermostat and radiator + thermostat + HP. Figure 5B shows the outdoor temperature that determines operation of the HP. In radiator + thermostat + HP, the HP is only on when the outdoor temperature is above 1.7°C (35°F); when the outdoor temperature is below 1.7°C (35°F), heating is provided by the radiator. The total heat transfer to the zone air remains the same in both cases because the two systems serve the same thermal load. The black solid line shows the heating rate provided by the radiator alone (radiator + thermostat) when the temperature is appropriately controlled by the thermostat. The dashed lines lying on the black solid line in this figure show the case of a radiator with thermostat control and a regular HP (radiator + thermostat + HP). The red dashed line shows the cases where heating is provided by the radiator (radiator mode), and the blue dashed line shows heating by the HP when the outdoor temperature is above 1.7°C (35°F) (HP mode). The two systems, radiator and HP, together cover the heating load while alternating between the two systems, which is managed in these EnergyPlus simulations using EMS. This approach is used in the calculation of the combined heating energy profiles in the following sections.

Figure 6 shows the variation in site heating energy consumption for the different modes of heating modes studied. The shaded area shows the peak hours of heating energy from 6 to 10 a.m. on the second day. Figure 6A shows the heating modes without preheating, and Figure 6B shows the heating modes with preheating at 24.4°C for 6 h (based on the preheating schedule in Figure 2). The radiator and radiator + HP lines coincide unless the HP turns on. Due to the lack of thermostat control, the heating output in these two cases is higher than in the other cases. The radiator + thermostat and radiator + thermostat + HP lines also match, unless the HP turns on, because the only difference between the two cases is the presence of the HP. The CCHP line is lower than the other cases.

As expected, the heating demand requirement is highest for the steam radiator without individual thermostat control. When the steam radiator without individual thermostat control is used with the regular HP, the radiator system turns off during the day as the ambient temperature warms up. This results in a decrease in site energy consumption. The same phenomenon occurs when the steam radiator with thermostat control is used with the regular HP. The power consumption of the HP after the radiator is turned off is lower in the case where there is no

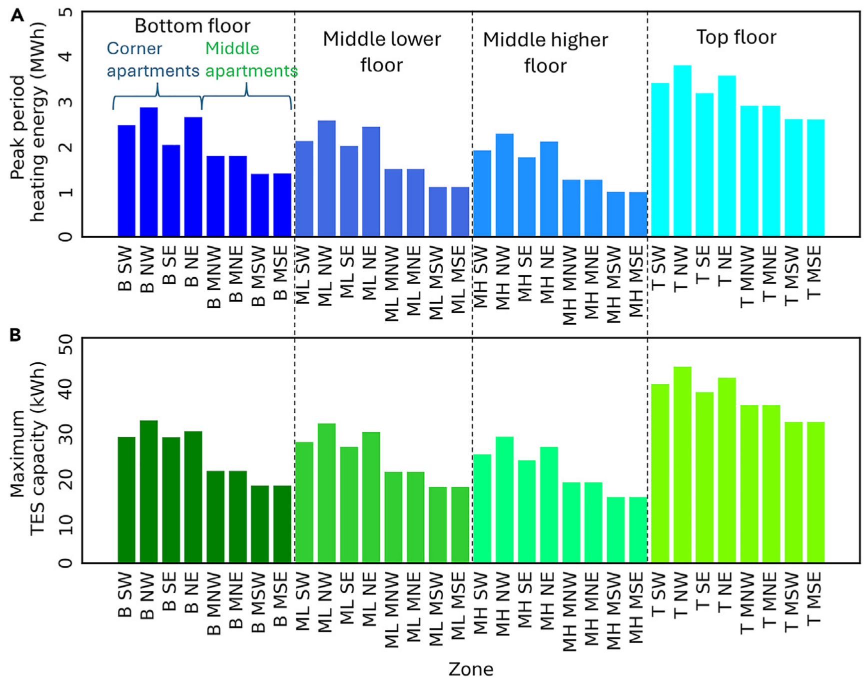

Figure 9. Heating energy and TES capacity

(A) Heating energy demand during the peak hours for each apartment, and (B) PCM maximum TES capacity needed to fully shift the HVAC heating energy requirement from peak hours to non-peak hours.

thermostat control than in the case where there is a thermostat control. This is due to the apartment being warmer without thermostat control due to overheating. The CCHP shows the lowest heating demand due to the complete electrification of the heating system with very stringent control of the thermostat setpoint.

Figure 6B shows that preheating minimizes the peak heating load. For example, when the steam radiator is not thermostatically controlled, a maximum heating demand of 310 kW is observed during the peak period (day 2). When the preheating strategy is implemented, the maximum heating demand during the peak period decreases to 203 kW, which is a 35% reduction in the peak load. Because the maximum energy demand now occurs between 2 and 6 a.m., preheating allows us to shift the peak demand from the peak period to the off-peak period.

Annual heating energy and heating demand during peak hours

Figure 7 shows the site (end use) heating energy consumption and the demand during the peak hours. Figures 7A and 7B show the annual site heating energy use of the building (thermal energy for radiator and electrical energy for the HP). Red color bars show the contribution of radiator heating, and blue color bars show the contribution of HP electricity. From the radiator to CCHP case, end use energy consumption decreases when the radiator and HP energy are added together. Preheating the building increases the total end use heating energy consumption for each scenario. Annual heating energy consumption increases by 16%–24% for the scenarios analyzed.

Figures 7C and 7D show the maximum value of heating energy demand (thermal for radiator and electrical for the HP) during the 4 h of the peak period in the year. As expected, the highest heating demand is observed for the steam radiator without individual thermostat control. When the radiator and HP are operating together, two peaks occur, one for the radiator and one for the HP. These peaks occur at different times. When the steam radiator is used together with the regular HP, the natural gas demand remains high because at low ambient temperature (<35°F/1.7°C), the heating is still provided by the radiator. The CCHP has the lowest peak energy demand.

In all cases, preheating results in a reduction of the maximum energy demand during the peak period. In the first case with the radiator without individual thermostat control, the maximum demand during the peak period decreases by 19% when preheating is used. When the operation of the radiator is thermostatically controlled, the reduction of the maximum demand for natural gas during the peak period is 42%. The reduction of the peak demand due to preheating for the steam radiator + HP without individual thermostat control is 19% of natural gas and 62% of electricity. The steam radiator + HP with individual thermostat control yields reduction in peak demand by 42% of natural gas and 54% of electricity. Lastly, the CCHP provides 42% reduction in peak electricity demand.

In this section, we look at the energy consumption at the source and the associated CO_2 emissions. We consider emissions associated with energy used for HVAC space heating. Figures 8A and 8B show the source heating energy use related to the building. Red bars show the contribution of radiator heating, and blue bars show the contribution of HP electricity.

Figures 8C and 8D show the annual aggregate source CO_2 emissions per building conditioned floor area based on source energy consumption. These emissions were calculated using the methods described in section CO_2 emissions calculation. Without preheating, when transitioning from uncontrolled radiator operation to CCHP operation, CO_2 emissions are reduced by 21%; a similar amount is observed with preheating. The highest reduction in CO_2 emissions (35%) is observed for the case of the radiator with thermostatic control. Full electrification of heating leads to a lower reduction of CO_2 emissions compared with thermostat control. This is because the corresponding network is heavily dependent on fossil fuels. From the variant without preheating to the variant with preheating, the emissions values for the five given heating modes increase between 14% and 18%.

Peak shaving with thermal energy storage

Figure 9A shows the heating energy demand (MWh) for the HVAC system during peak hours for each apartment summed annually without considering overheating. We assume that this heating energy is supplied by the CCHP (heating mode 5). The top floor has the highest heating energy consumption during peak hours, and the upper-middle floor has the lowest heating energy consumption. The corner apartments on each floor have a relatively higher heating demand than the middle apartments because more heat is lost to the environment. The total annual heating demand for the building, including all apartments, is 69.1 MWh during peak hours.

Figure 9B shows the maximum TES capacity required for each apartment. This TES capacity ensures that the heating energy demand of the apartment during peak hours can be fully shifted to non-peak hours for all days. The highest TES heating energy demand for an apartment during peak hours is 43.7 kWh in the northwest corner apartment on the top floor. To provide this required heat, an active PCM storage system of 629 kg is required, assuming that the PCM has a latent heat of 250 kJ/kg, which is typical for salt hydrate PCMs.[38] Furthermore, assuming a salt hydrate PCM with a mass density of 2,070 kg/m^3, the required volume of the TES system would be ~0.3 m^3. This is a large volume that might be difficult to accommodate in crowded apartments in large cities such as New York. However, the storage can be divided into several smaller units based on the number of CCHP units in the apartment, since it is assumed that each energy storage unit is charged using the CCHP unit.

DISCUSSION

This study examined the energy consumption for space heating in a pre-1980 multifamily mid-rise building in New York City for five different types of heating. The key observations of the study are summarized below.

- When steam radiators in a mid-rise building are controlled by a single thermostat in the coldest apartment in the building, overheating occurs in the other apartments, resulting in a temperature increase of up to ~8°C above the thermal comfort range. This also results in 35% higher natural gas consumption in the building compared with a case where all apartments are strictly thermostatically controlled.
- If the steam radiators are completely replaced with CCHPs, the site energy consumption for heating can be reduced by 70% annually. Through this conversion, CO_2 emissions associated with building heating decrease by 21% compared with the baseline building. Appropriate thermostat control for all apartments alone can reduce CO_2 emissions by 35%.
- Preheating the building to 24.44°C (76°F) for 6 h, before peak hours, shifts natural gas demand and reduces demand during peak hours by up to 42% if each apartment has individual thermostat controls or uses a CCHP. However, while preheating shifts peak, there is an annual energy loss of 16%–24%.
- The capacity of a PCM-based thermal storage system to shift the peak heating energy demand of the building when fully electrified by CCHPs was quantified. It was found that it may be difficult to implement the same size PCM storage for each apartment because heating energy demand varies from apartment to apartment; implementing one or two sizes of TES units based on the heating demand during peak hours is a more practical approach.

Electrification of heating in mid-rise multifamily buildings and the addition of other technologies, such as thermal storage, can shift peak energy demand. The extent to which CO_2 emissions and peak demand are reduced can vary from building to building, depending on the year of construction and location.

RESOURCE AVAILABILITY

Lead contact

Further information and requests for resources should be directed to and will be fulfilled by the lead contact, Ravi A Kishore (ravi.kishore@nrel.gov).

Materials availability

This study did not generate any new materials.

Data and code availability

The published article includes all data generated and analyzed during this study.

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AUTHOR CONTRIBUTIONS

R.A.K. and S.W. conceived the idea and carried out the modeling and simulations. R.A.K., S.W., and C.B. conducted the data analysis and discussions. C.B. and M.V.A.B. supervised the research. All authors contributed to the writing and revision of the manuscript.

DECLARATION OF INTERESTS

The authors declare no competing interests.

SUPPLEMENTAL INFORMATION

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