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Impact of Heating Electrification and Building Retrofit on the Indoor Thermal Environment and Electricity Demand

Retrofitting building stock through heating electrification and energy efficiency improvements is essential for achieving carbon neutrality. Understanding the effects of electrification and efficiency retrofits on building-resident satisfaction and adaptive behaviors is important, as these directly impact retrofitting success, adoption rates, energy consumption, and performance. There is a gap in understanding the combined effects of heating electrification and building efficiency retrofits. Using data collected over 2.5 years, we performed integrated qualitative and quantitative analyses to evaluate the combined effects of heat pump electrification and a roof insulation retrofitting in a 10-unit New York City apartment building. Building-resident satisfaction with each strategy was assessed, and impacts on occupant thermal comfort, energy behavior, indoor thermal environment, and energy consumption were analyzed. Despite perceived challenges and resident skepticism, air source heat pumps (ASHPs) provided adequate indoor thermal comfort. ASHPs were preferred over steam boiler heating for controllability, noise reduction, and improved thermal comfort. Unintended benefits included improved aesthetics, reduced real estate needs, and decreased burn potential. With heat pumps, some residents adopted energy-conservative behaviors while others adopted "comfort-taking" behaviors, prioritizing comfort over conservation. The roof insulation retrofit further improved resident thermal comfort and decreased total building heating energy requirements by 25.3–34.2% and heating peak power requirements by 10.7%. The retrofit also improved ASHP efficiency in previously uninsulated spaces, effectively mitigating heat pump undersizing effects. Combined energy retrofitting strategies could play a key role in ensuring thermal comfort and building energy efficiency toward carbon neutrality.
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Keywords: heating electrification, occupant thermal comfort and behavior, Internet of Things, energy effifiency retrofits, building decarbonization

1 Introduction

Globally, the building sector is the most significant energy-consuming sector, accounting for approximately 30% of final energy consumption [1]. While most energy reduction policies emphasize future building stock, the existing building sector accounts for nearly 40% of all energy and process-related global CO_2 emissions [2], and a large portion of today's existing building stock will continue to exist in 2050, making retrofitting of existing building stock vitally important on the road toward carbon neutrality [3]. Among various building retrofitting strategies, heating electrification has been identified as a critical component to successful deep decarbonization, as electric heating can utilize renewable electricity and tends to be more energy efficient than its fossil-fuel and natural-gas-based counterparts [4–6]. In addition, it is recommended to combine heating electrification with building envelope insulation retrofits to reduce electricity demand and achieve net zero emissions goals [4,7].

In practice, building retrofits require a two-way interaction between the building occupants and building technologies adopted, making it essential to explore both the quantitative and qualitative dynamics involved for better designing future retrofits [8]. Building occupant behavior related to energy consumption plays a critical, yet poorly understood, role in reducing energy use in buildings [9,10]. Occupant adaptive behaviors (e.g., changing clothes, operating windows, and switching thermostat temperature setpoints) are strongly tied to space heating and cooling loads and a building's total energy consumption [11–14]. In some cases, energy consumption can decrease by as much as 60% from a single retrofitting technique, dependent on occupant behavior, while some behaviors may lead to higher energy consumption post-retrofitting [11].

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Retrofitting strategies can also impact various building characteristics, including indoor thermal environment, energy consumption, and peak power demand. A comprehensive building retrofit may reduce energy demand for space heating and hot water energy consumption by 31–39% compared to non-retrofitted buildings while maintaining an acceptable indoor climate for residents [15,16]. Combined appliance efficiency, roof and wall thermal insulation, and water heating system efficiency improvements have demonstrated the potential to reduce annual energy by 52% in new residential homes [17]. Furthermore, wall thermal insulation and air conditioning retrofits may provide up to a 40% decrease in summer peak demand [18].

To maximize retrofit effectiveness, it is necessary to understand the interactions between the energy retrofit and the buildings' occupants and characteristics [19]. Despite the tremendous potential for building retrofits to act as one of the main avenues toward achieving carbon neutrality, their impact is primarily influenced and often limited by activities related to the building occupants. For instance, building occupants' mere perception and interest in heating electrification technologies such as ASHPs contribute to significant uncertainties in their adoption rate [20,21].

This work aims to address gaps in knowledge related to interactions between building energy retrofits, building characteristics, and occupant behavior. More specifically, we aim to contribute to the limited domain of studies assessing (1) building occupants' perception of thermal comfort following energy retrofits, (2) the impact of multiple energy retrofits on building characteristics, (3) the relationships between energy retrofits and peak demand, and (4) the interactions between multiple building retrofits, building characteristics, and building occupants. This work also aims to contribute to the limited domain of studies utilizing the Internet of Things (IoT) to measure these interactions.

In previous work, simulations, predicted mean votes, or the adaptive comfort theory have been used to capture building occupants' thermal comfort and building characteristics rather than direct interviews and measurements [8]. A knowledge gap exists between thermal comfort based on theoretical approaches and actual perceived thermal comfort [22–24]. Resident questionnaires have been used to better understand changes in energy consumption due to building retrofits [16]. Although this adds to the limited domain of existing studies in this area, questionnaires tend to lack in areas such as response validity and reliability. In contrast, methods such as interviews tend to have the advantage [25].

The relationship between retrofits and buildings' peak demand requirements is also poorly understood. Increased electrified heating and cooling can change the magnitude, seasonality, and time of day of historical peaks [26–29]. Knowing the timing of peaks is critical to many transmission-level operations, directly impacting real-time electricity markets, transmission controls, generator dispatch, and generation reserve requirements [20]. Low-cost control strategies have been proposed as retrofitting strategies to minimize peak demand [30] but are limited in practicality as they assume buildings have already been retrofitted with smart heating and cooling technologies. Building subsystems, including heating and cooling, electricity, and occupant activity, are also highly interactive [31]. Still, it is not often that the combined effects of these subsystems are studied together, while considerations of their combined impact on peak demand are even rarer. Monthly peak demand profiles have been simulated to assess the combined effect of retrofits on peak demand [18], but finer temporal granularity is necessary to understand their impact on real-time transmission-level operations. Simulations also tend to oversimplify the actual effects of interactive building subsystems on building energy requirements [11].

To our knowledge, no existing studies have explored the interactions between multiple building retrofits, building occupant thermal comfort, and building peak energy demand requirements. Understanding these interactions will be invaluable on the road to carbon neutrality, as they will play critical roles in determining the impact of retrofits and gauging the extent of future carbon reductions. We use an IoT-assisted integrated qualitative and quantitative research approach to independently evaluate the effects of ASHP heating electrification and improved roof insulation on (1) the occupants of a 10-unit NYC residential building and (2) the building's thermal and energy characteristics.

Acquiring accurate energy and environmental building data is paramount for assessing the impact of building retrofits [32,33]. A promising method of obtaining this data is through IoT devices, which have been successfully used to monitor building characteristics, including indoor temperature and relative humidity [34], occupancy [35], and energy consumption [36]. The benefits of using IoT devices to monitor building characteristics include the low cost of sensors, limited intrusiveness compared to sensors that require manual data retrieval, and the potential for long-term data acquisition. Building data collected from IoT devices has created opportunities for control strategies to reduce energy consumption and has been suggested to assist in making informed decisions regarding new energy-efficient technologies to improve resident thermal comfort and decrease building energy consumption [37]. Still, the use of IoT to assess the impact of building retrofits is minimal, with most works neglecting to evaluate periods of energy retrofits while only measuring either building occupant thermal comfort or building energy consumption exclusively [37]. For this reason, IoT energy and indoor environmental sensors were deployed throughout the studied building to quantitatively capture retrofit impacts on the building's indoor thermal environment, energy consumption, and peak power demand. While existing studies have used IoT to assess building occupant thermal comfort or building energy consumption exclusively for periods either pre- or post-retrofitting, our methodology measures building thermal environments over a period covering both pre- and post-ASHP heating electrification and improved roof insulation, and measures heat pump energy consumption over a period covering pre- and post-improved roofing insulation, minimizing reliance on outsourced data.

Following a clinical trial-based approach, we used direct and frequent interactions with building residents over 2.5 years to rigorously capture the relationships between building occupants and building retrofitting technologies. Previous work has been conducted over shorter durations while interacting with building occupants to a limited capacity through surveys or an intermediary party. Contrary to previous work, our approach utilized a series of semi-structured interviews and pre- and post-retrofit surveys to thoroughly capture building occupant perceptions of thermal comfort and satisfaction with each retrofitting activity. Our work contributes to the domain of occupant-focused building retrofit work, as studies conducted in occupied buildings are limited and often expensive and intrusive [38].

2 Data and Methods

2.1 Building Retrofits. The building used in this study was a 9,690-ft^2 railroad-style residential building located in NYC, a typical residential building style in many large cities within North America. The building consisted of five residential floors with 10 total apartment units, each individually owned by residents, and a shared basement and hallways.

An HB Smith Mills 2500L steam boiler heating system, burning #2 fuel oil, was initially used to heat all apartment units and common spaces of the building. The boiler was programmed to operate at one setpoint temperature during the heating season from 5:30 a.m. to 10:30 p.m. and during nighttime setback periods if the outdoor temperature dropped below -1.1 °C. Steam for heating was transported throughout the building via a system of vertical steam risers and radiators of varying capacities per apartment unit. Each radiator had a manual radiator valve allowing on/off heating control. Total heating capacity varied between apartment units based on the number of radiators, radiator

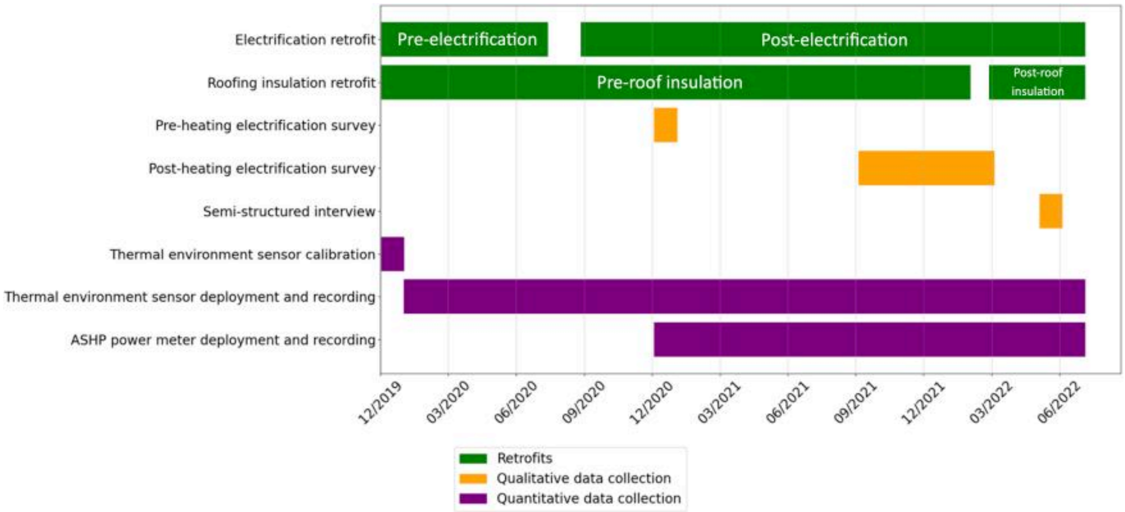

Fig. 1 Project timeline, separated by retrofit strategy and qualitative and quantitative data collection strategies. The durations of study activities are represented by horizontal bars. The case study began in December 2019 with the long-term deployment of 73 IoT thermal environment sensors distributed throughout the building. Sensors remained in place throughout the study, capturing indoor thermal environment and energy consumption variations for three consecutive heating seasons.

sizing, and radiator locations. Some apartment units contained four radiators, while others contained none. To compensate for the varying degree of heating capacity per apartment unit, some residents utilized auxiliary heating sources such as space heaters for additional warmth during the heating seasons. During the cooling seasons, temperature regulation methods varied between window air conditioners (AC), fans, and windows.

As depicted in Fig. 1, the building's steam boiler heating system, which provided heat to all building residents, was decommissioned for building heating in the summer of 2020, and replaced by ductless mini-split electric ASHPs installed in each apartment unit—the first retrofitting focus of our study. Each ASHP system consisted of a 4-port, 3-ton outdoor unit with 3–4 indoor units (IDUs) of varying heating and cooling capacities within each apartment. IDUs were only used within apartment units; no IDUs were installed in common hallway areas of the building. Residents were only responsible for ASHP operating costs. Temperature was recorded during the project's entire duration using IoT sensors distributed throughout the building, further discussed in Sec. 2.2. Finally, in February 2022, the building's roof cavity was insulated with approximately 16 in. of cellulose insulation to increase the thermal inertia of the building with the goal of improved heat retention. This retrofit is the second retrofitting focus of our study, also represented in Fig. 1.

This work refers to the pre- and post-electrification periods as well as the pre- and post-roof insulation periods. Pre-electrification occurs prior to July 2020, while post-electrification occurs after September 2020. The pre-roof insulation period occurs before February 2022, while the post-roof insulation period occurs after February 2022.

2.2 Quantitative Data Collection: Internet of Things-Based Thermal Environment and Power Sensors.

In December 2019, before the building retrofitting, 73 IoT-based temperature sensors were deployed throughout all apartment units, the basement, hallways, and the roof of the building (Fig. 1). Figure 2 is adapted from the building's floor plans and depicts typical examples of IoT sensor locations and pre- and post-retrofit radiator and indoor unit locations, respectively. The MCCI Catena 4618 M201 was selected as the sensing board of choice, given its high accuracy integrated Sensirion SHT35-DIS-F temperature sensor. Sensor enclosures were provided by the sensor manufacturer and were designed to allow for adequate airflow within the device, ensuring accurate environmental readings. Temperature recordings were rated with an accuracy tolerance of ±0.1 °C. Data were automatically recorded in 12-minute intervals for the project's total duration. Maintenance of sensors and battery replacement was coordinated through the cooperation of building residents and with the help of an on-site energy consultant.

Recorded data were wirelessly transmitted to an external database via a long-range wide area network (LoRaWAN) radio-based connection between each device and a single Multitech Conduit, or gateway, installed in one unit within the building. LoRaWAN was selected as the IoT protocol of choice for its low power and long-range capabilities, requiring minimal maintenance from building occupants and minimal network hardware, as data transmission was demonstrated to be highly reliable from just a single gateway. The selection of the LoRaWAN protocol allowed for overall minimal intrusiveness for building occupants throughout the study.

Sensors were placed throughout each apartment unit, typically with one sensor per room, distributed from the northernmost room to the southernmost. Sensors were strategically placed in locations to avoid thermal interactions with heating or cooling sources within each apartment unit, including stoves, windows, refrigerators, and radiators. Additionally, sensor interactions with thermal boundary layers were considered but dismissed, as preliminary testing revealed negligible differences in temperature readings between sensors mounted directly on surfaces and those with an approximate 2-in. distance from the surfaces. Sensor calibration was performed with assistance from the Cornell Animal Health Diagnostic Center (AHDC) in a climate-controlled setting. A high accuracy (±0.05 °C) 5623B Fluke probe and 1521/1522 Fluke calibration thermometer were used for temperature comparisons and calibration. Following the calibration procedure, we observed negligible differences between our sensor readings and AHDC equipment readings, ultimately leading us to trust our recordings without the need for additional calibration adjustments. An example IoT sensor is presented in Fig. 3.

76 MCCI Catena 4618 M201 sensors were distributed throughout all apartment units, with three sensor malfunctions, resulting in 73 sensors for dispersal. A single sensor was placed in the hallway of each of the building's five floors to capture temperature variations in common spaces. Eight sensors were distributed throughout the shared basement using a sensor distribution layout similar to

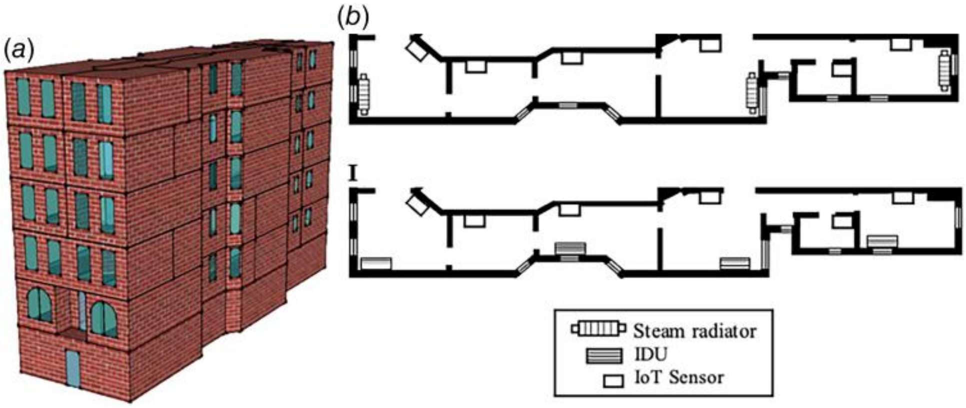

Fig. 2 Model of the studied apartment building (*a*) as well as floor plans depicting typical locations of both IoT sensors and apartment-unit steam radiators pre-electrification (*b*) and IDUs post-electrification (*c*). Room-level and unit-level heating capacities varied both pre- and post-electrification for each apartment.

that depicted in Fig. 2. Outdoor temperature data were obtained from the National Weather Service's (NWS) Automated Surface Observing System (ASOS) [39,40] for the Central Park (New York City) weather station at an hourly interval for the project's duration.

ASHP energy consumption was monitored for each apartment unit throughout the study. eGauge power meters were used to monitor mean and peak power with 0.5% revenue-grade accuracy at 1-second intervals. Mean power recordings were calculated as the mean recorded power measurement over both 1-minute and 15-minute time windows. Peak power recordings were calculated as the maximum recorded power measurement over the designated time window. One-minute mean and peak power measurements were recorded from July 2021 through July 2022, while 15-minute window power measurements were recorded from December 2020 through July 2022 (Fig. 1).

Baseline boiler energy data were unavailable during the study period due to a lack of metering. For this reason, energy consumption comparisons could not be conducted during the pre- and post-electrification periods. Subsequent sections provide an energy savings analysis only for the pre- and post-roof insulation periods.

2.3 Qualitative Data Collection

2.3.1 Pre- and Post-Retrofit Survey Method. Before occupant data collection, Institutional Review Board (IRB) approval was requested and granted for human participant research through IRB Protocol Number IRB0009283. During the study, occupant data were collected via two surveys and one semi-structured interview. The surveys captured building occupants' perceived thermal comfort and satisfaction before and after heating electrification. The semi-structured interview was used to gain a more unique and personalized understanding of each building occupant's perception of both retrofits. All occupant surveys were designed per ASHRAE 55 standards for long-term thermal environment satisfaction surveys [41]. Participation in surveys and interviews was voluntary, and all questions were optional.

Fig. 3 MCCI Catena 4618 M201 IoT sensor within enclosure base, right. Enclosure cover, left. Seventy-three IoT sensors were distributed throughout the building in all rooms of each apartment unit and building common spaces to capture local thermal environment changes over the entire duration of the study.

As depicted in Fig. 1, the pre-electrification survey was distributed to all 10 residents electronically in December 2020. This thermal environment survey contained 33 questions intended to acquire information regarding occupant information, thermal comfort, experience, satisfaction, adaptive behavioral traits, occupant perception, and knowledge of heating systems. Responses to the pre-electrification survey were received from nine of the 10 units for a 90% response rate. The post-electrification survey (see timeline in Fig. 1) was distributed to residents electronically in September 2021 and contained 51 questions focusing on the occupants' perceived pre- and post-electrification experiences. Due to a 20% occupant survey initiation rate for the post-electrification survey, a supplementary 17-question condensed version of this survey was electronically distributed to residents in March of 2022, which acted as the replacement post-electrification survey, covering all pre-electrification survey sections while targeting key questions on occupancy, temperature settings, setpoint schedules, adaptive behavior, and perceived post-electrification experience.

Responses to the condensed post-electrification survey were received from nine of 10 units for a 90% response rate. For each pre- and post-electrification survey, building occupants were asked to describe their room-specific level of thermal comfort on a 3-point scale. The categorical response "maintained comfort" was assigned to rooms with a positive response for both surveys. The categorical response "comfortable to underheated" was assigned to rooms that demonstrated a positive response for the first survey and a sense of underheating for the second. The categorical response "underheated to comfortable" was assigned to rooms that demonstrated a sense of underheating on the first survey and thermal satisfaction for the second. "Overheated" and "maintained discomfort" categorical responses were excluded as resident survey responses did not reflect them. One apartment unit was excluded from the study due to a change of residence. Three apartments were excluded due to data collection issues, where one apartment already had heat pumps before the study period, residents from one apartment did not respond to survey or interview requests, and one apartment was unoccupied for the post-electrification study period. Table 1 summarizes the structure of the pre- and post-electrification surveys.

Table 1 Summary of question categories compiled for pre- and post-electrification surveys

Section	Question topics
Occupant information	• Apartment number • Number of occupants • Demographics • Apartment occupancy schedule • Estimated room occupancy schedule
Thermal comfort, experience, and satisfaction	• Description of apartment thermal comfort: ○ General ○ Seasonal ○ Daytime/nighttime ○ Localized room level • Description of thermal comfort in common spaces ○ Hallways ○ Basement • Perceived noise levels from heating and cooling • Satisfaction with heating/cooling system's capability of controlling indoor temperature • Perception of technological difficulty with heat pump settings/controls
Adaptive behavior	• Temperature settings and setpoint schedules • Auxiliary heating and cooling sources/actions • Nighttime heating/cooling habits
Perception	• Perception of replacing previous heating/cooling systems with ASHPs • Perceived benefits of electrification
Knowledge	• Environmental conservation • General knowledge of each heating/cooling system

Note: Sections were designed to capture building occupant experiences associated with each heating system holistically.

2.3.2 Semi-Structured Interview Method. To understand resident perspectives of each retrofit in greater detail than that captured through surveys, semi-structured video interviews were conducted in May 2022 with occupants from eight of 10 units, demonstrating an 80% response rate (see timeline in Fig. 1). Each interview ranged from 40 to 90 minutes. Interviews were conducted as naturally progressing conversations but were structured to obtain the following: (1) occupant perception and experience relating to the building envelope energy efficiency retrofit, (2) information omitted from the original post-electrification survey to create the condensed version including more detailed room-specific information on occupancy, thermal comfort, noise, and heat pump controllability satisfaction, (3) additional explanation for responses to both pre- and post-electrification surveys, and (4) explanation for quantitative trends observed from energy and environmental IoT monitoring efforts. Setpoint temperature schedules were obtained from surveys and interviews through detailed questions on temperature settings, time of day for each setting, and estimated duration of use for each temperature setting.

Note that one limitation of the conducted surveys and semi-structured interviews was variation in sample size for responses, given the ability of residents to choose which questions to respond to. Additionally, the objective of the occupant surveys and interviews was not to determine generalized observations for all potential heat pump adopters. Findings from surveys and interviews are extracted and used to diagnose observed trends in measured data. According to ASHRAE 55 standards, when used as a diagnostic tool, thermal environment surveys provide a detailed insight into the building's day-to-day operation through occupant feedback. For such purposes, each response is valuable regardless of the size or response rate of the survey [41].

3 Results and Discussion

3.1 Pre- and Post-Electrification Building-Resident Satisfaction and Experience

3.1.1 Knowledge, Familiarity, and Perception. Building residents' understanding of heating systems has been suggested to impact heating system efficiency levels [42] and would likely affect their experience with system operation and indoor temperature control. Hence, as a part of the pre-electrification survey, building residents were asked about their knowledge of steam boilers and electrified heating systems. Figure 4 shows that of a total of five respondents, 20% were unfamiliar with steam boiler heating, and 60% were unfamiliar with heat pump heating. Thus, many residents would explore unknown territory, transitioning from a heating system they had used for years to one unfamiliar to most residents.

To understand how building residents felt about transitioning to an unfamiliar heating system, each was asked open-ended questions about their perception of heat pump heating capabilities. In general, most building residents felt confident in the ability of heat pumps to keep their apartment thermally comfortable, with 75% of the eight respondents stating they felt "quite" or "very"

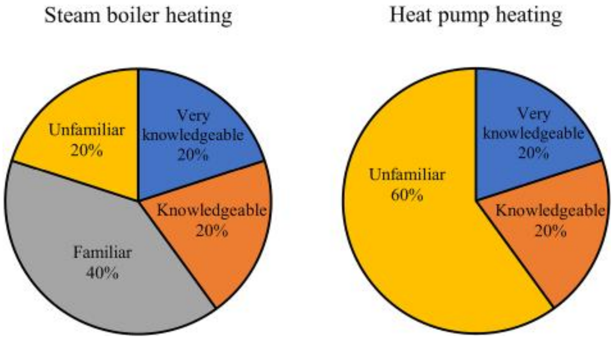

Fig. 4 Summary of qualitative responses to the question, "How knowledgeable are you about steam boiler and heat pump heating?" Categories were ranked using the following order from least familiar to most familiar: "unfamiliar," "familiar," "knowledgeable," and "very knowledgeable." Eighty percent of respondents were at least familiar with steam boiler heating. In comparison, only 40% demonstrated being "knowledgeable" or "very knowledgeable" with heat pump heating. Zero percent responded as being "familiar" with heat pump heating, suggesting that energy efficiency knowledge and heat pump expertise were likely limited among the residents.

confident. 25% of respondents felt less confident for several reasons. One respondent stated:

> I didn't know what to expect [for heating]. Worst case scenario, it would be a better AC system,

demonstrating uncertainty for heat pump heating but optimism for the AC capabilities. Another respondent stated:

> [I am] skeptical because [heat pumps are] expensive and not proven to be adequate for cold climates. Railroad apartments are not ideal for heat pumps,

demonstrating skepticism related to both heat pump heating capabilities and operational costs, as residents were not responsible for any capital costs. Although there was an overall positive perception of electric heat pumps, there remained uncertainty and skepticism due to a lack of personal experience and general knowledge of heat pump performance in both cold climates and railroad-style (i.e., long and narrow) apartments.

To further understand building residents' perception of heating electrification, each was questioned about the primary factors that influenced their decision to convert their heating system. Figure 5 summarizes their responses.

For this pre-electrification survey question, responses were received from eight residents. Each was allowed to choose all options that applied to them. According to Fig. 5, controllability was the most desired characteristic of electric heating selected in 88% of responses, followed by 75% choosing comfort, 63% choosing carbon emissions, and 63% choosing cost as a primary influencing decision to switch to heat pumps. Controllability was likely the most desired characteristic because, pre-electrification, boiler heating was a building-wide shared system operating at set temperatures strictly from 5:30 a.m. to 10:30 p.m., regardless of individualized apartment occupancy schedules or thermal comfort preferences. Additionally, boiler heating was delivered through steam radiators with on/off manual radiator valves, allowing little to no control of temperature setpoints. Heating system noise was the least desired characteristic chosen in only 50% of responses. This is likely because noise was not a significant problem during the pre-electrification period. When asked to summarize noise from boiler operation, 71% of the seven respondents to this question considered noise from boiler operation to be "barely noticeable" or "not noticeable at all."

3.1.2 Satisfaction With System Operation and Indoor Temperature Controllability. Finding controllability to be the most desired attribute of electric heating from the survey, we proceeded to understand how well this desire was fulfilled post-electrification. Residents were asked about heating system temperature control satisfaction on a 5-point scale, with responses summarized in Fig. 6.

As seen in Fig. 6, on a 5-point scale, eight respondents demonstrated a pre-electrification satisfaction of 2.7 and 4.5 with heating and cooling, respectively, compared to seven respondents demonstrating a post-electrification satisfaction of 4.3 and 4.5 with heating and cooling. With the adoption of heat pumps, residents experienced a significant increase in indoor heating controllability, while indoor cooling controllability experienced little change. These trends likely resulted from the fundamental differences between heat pump heating and building-shared boiler heating, as well as the strong similarities between heat pump cooling and window air conditioning.

Regarding utilization of thermal controllability, all residents demonstrated successful adoption of new custom heating and cooling schedules appropriate for their occupancy schedule and thermal comfort preferences. All but one of the seven respondents were very satisfied with the indoor temperature controllability of heat pumps, providing a rating of 4 or greater. The anomalous resident rated controllability as 1 for both heating and cooling. Upon further investigation, it was discovered that the underlying reason for these reported ratings was a lack of roof insulation and heat pump undersizing, discussed further in Sec. 3.3.1. Residents were also asked to compare their experience using each heating system. Without any reference to controllability in the prompt, 75% of the eight respondents mentioned acquiring greater control of indoor temperature and comfort post-electrification, suggesting that electric heating indeed fulfilled the desire to obtain controllability of indoor temperature for a large majority of building residents.

3.1.3 Equipment and Environmental Noise. Equipment and environmental noise associated with indoor heating and cooling can be considered intrusive for some system users. When asked to compare their perception of noise related to each system, 75% of the eight respondents reported heat pump noise as comparable to or quieter than boiler heating noise for heating operation. Residents on the top floor reported increased noise since they were located furthest from the basement boiler and contained the fewest radiator heating units pre-electrification. However, both top-floor residents added that noise did not increase by much and was not intrusive. They stated they were able to adapt to the new sounds and noted:

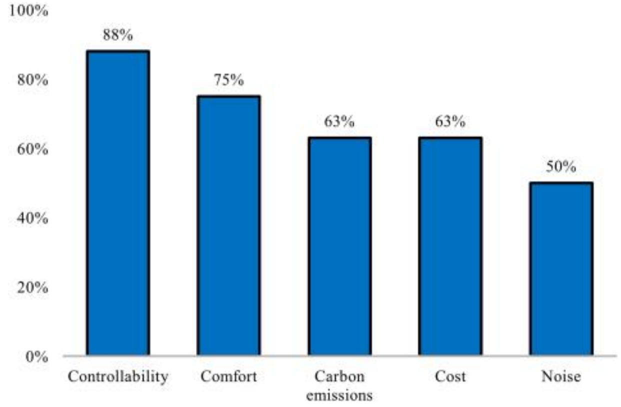

Fig. 5 Summary of qualitative responses to the question, "What are the primary factors that influenced your decision to switch to heat pumps?" Controllability was the most desired characteristic of heat pumps, accounting for 88% of resident responses, while heating system noise reduction was the least desired characteristic, accounting for 50% of resident responses.

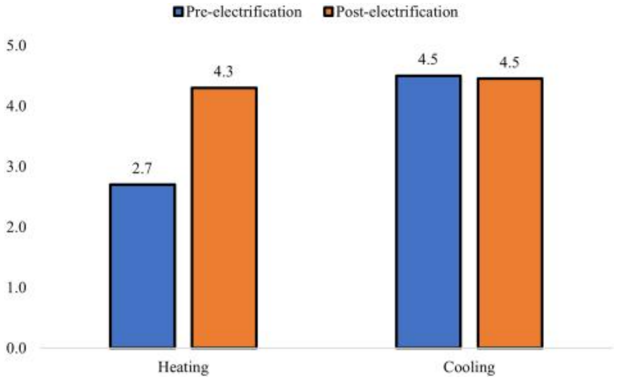

Fig. 6 Summary of qualitative responses to the question, "Please rate the level of control you have over your heating and cooling systems," asked of residents in both the pre- and post-electrification surveys. A significant increase in heating system control satisfaction was observed post-electrification. Cooling system control satisfaction remained unchanged.

> The heat pump is nice and quiet when on.

All residents reported heat pump noise as comparable to or quieter than window air conditioning for cooling operation. Sixty-three percent of the eight respondents reported drastic improvements in noise invasiveness, as window air conditioning units tended to be "very noisy and disturbing." Although most responses concerning heat pump noise were positive, two building residents did report temporary intrusive noise from heat pump operation due to minor condensate pump issues, which were quickly resolved by replacing the condensate pump, indicating an area of improvement for heat pump system planning and installation.

One resident identified reduced environmental noise pollution as an added benefit of electrification. Pre-electrification, this resident tended to open their windows for indoor temperature regulation and stated that after the introduction of heat pumps:

> I'm getting less noise from the street. I can do some work [in my apartment] without noise from outside,

indicating the benefit of reduced environmental noise pollution as a byproduct of electrified heating and cooling.

3.1.4 Operating and Capital Costs. System satisfaction of residents can also largely depend on associated operating and capital costs. When asked about changes to overall heating costs post-electrification, all residents noted that their electricity bills significantly increased, but few understood how these increases compared to previous heating costs. Boiler heating costs for the building were divided equally amongst all residents, independent of individual occupancy or heating schedules. In contrast, heat pump operational costs solely relied on individual energy consumption and were charged within electricity bills, combined with all other electric appliances, making fair heating cost comparisons for residents rather difficult. Though many were unable to compare heating costs directly, residents instead compared pre-electrification electricity bills to post-electrification electricity bills, with two residents quoting that they were "tripling" or "quadrupling" their electricity bills during winter and summer periods of greatest energy consumption. With the deactivation of the boiler, all ground-floor residents noted significant increases in heating expenses during the winter, although one resident acknowledged their tradeoff between cost and comfort, quoting:

> I suspect that once you add everything in, the heat pumps are probably a little more expensive in the winter, but for us, it's worth it. It's a higher value.

Forty-three percent of the seven respondents noted significantly greater electricity bills in the winter, consistent with what would typically be expected, while 29% of these seven identified the summer as the period with the most significant electricity bill increases. Those who identified the summer as the season with the most considerable electricity bill increases previously relied on electric space heating in the winter, possibly causing winter heating electricity prices to be comparable. One of these residents stated:

> Last year, [my summer electricity bill] was very expensive because I used it a lot. Before the heat pump, I would deal with my windows. I would open my windows. My [summer electricity bill] was $75, now it's [between] $200 [and] $250.

This suggested electricity price increases may have been overlooked in favor of increased thermal comfort and convenience.

Taitem Engineering conducted an energy cost and rate structure analysis to understand the impact of electrification on whole-building energy costs [43]. Through their analysis, they discovered that annual pre-electrification heating, cooling, and domestic hot water energy costs totaled $11,858, while post-electrification costs decreased by 10.3% to $10,632, for a total annual savings of $1,226. While the operating cost reductions were promising, the authors also noted that the analysis did not include annual maintenance costs, which they suggested could total approximately $1,000. This additional cost could counteract most of the annual energy savings, which would imply minimal differences in operating costs between the two systems. These findings may have differed from residents' perspectives because they may have focused on the negative perception of increased electricity prices due to electrification and overlooked the elimination of steam boiler heating costs.

Relating to capital costs, one resident quoted:

> Heat pumps [capital costs] are very expensive and may not be feasible without a subsidy.

As a part of this case study, residents were only responsible for heat pump operating costs. For the broader adoption of heat pumps, this highlights a cost concern. Without decreased capital costs or increased subsidized electrified heating programs, residential adoption of heat pumps may be limited, especially for those considered low-to-middle-income.

3.1.5 Unintended Benefits of Heating Electrification. In addition to anticipated attributes of the heating electrification conversion, resident interviews revealed many unintended benefits. For one, heat pumps were found to require less real estate and equipment, with individual IDUs capable of heating and cooling from a single piece of equipment mounted on the wall or floor. The eliminated need for separate heating and cooling equipment, such as window air conditioning and radiators, which one resident stated as being:

> [radiators were] ugly and took up too much space,

in addition to the elimination of auxiliary heating and cooling sources, freed space in apartment units. This feature of reduced real estate is especially beneficial for heating system conversions in apartment units where space is limited, such as those included in this case study.

Additionally, one resident stated:

> I distinctly remember burning myself [on the pre-electrification steam riser].

Steam risers ran vertically through the building from the basement boiler to the fifth floor to provide heat. They could reach high temperatures and were often exposed to residents, posing potential burn risks to some and physically burning others. This resident was pleased to find that while operating IDUs, they were relieved of these troubles, providing additional system satisfaction.

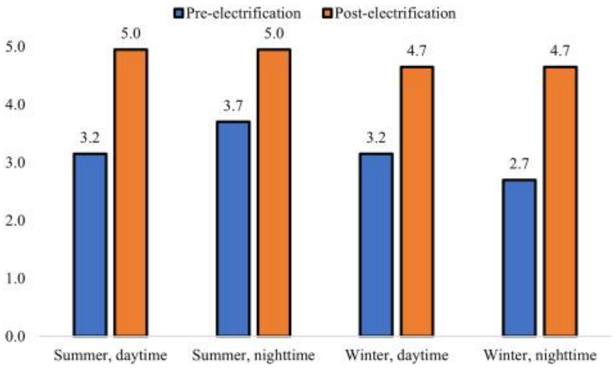

Fig. 7 Summary of qualitative responses to the question, "How would you rate your overall thermal comfort during the day and night in both the summer and winter?" Results demonstrated that post-electrification thermal comfort increased for all seasons and times of the day.

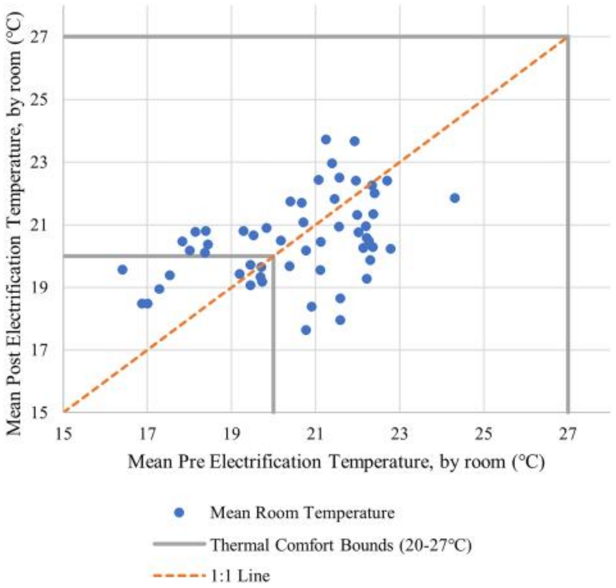

Fig. 8 Comparison of mean pre- and post-electrification room temperatures across 55 rooms throughout all 10 apartment units. Eighty percent of rooms remained within ASHRAE 55 thermal comfort bounds. The 11 rooms outside of the band are identified by the boxed region in the lower left of the plot. Post-electrification, eight of these 11 rooms maintained or increased their mean temperature to be closer to the band.

3.2 Heat Pump Impact on Building-Resident Thermal Comfort and Behavior

3.2.1 Impact of Electrification on Room-Specific Thermal Comfort and Mean Temperature. The effect of heating electrification on indoor thermal comfort was assessed by asking residents about their seasonal and daily thermal comfort satisfaction, as shown in Fig. 7.

As seen in Fig. 7, it was discovered that for the seven respondents, electrification increased thermal comfort on a 5-point scale for all seasons and times of day, with daytime summer satisfaction increasing from 3.2 to 5.0, nighttime summer satisfaction increasing from 3.7 to 5.0, daytime winter satisfaction increasing from 3.2 to 4.7, and nighttime winter satisfaction increasing from 2.7 to 4.7. Introducing indoor temperature controllability to building residents significantly contributed to heat pump system satisfaction. Quantitative thermal environment measurements for each apartment unit were recorded to complement thermal comfort survey responses.

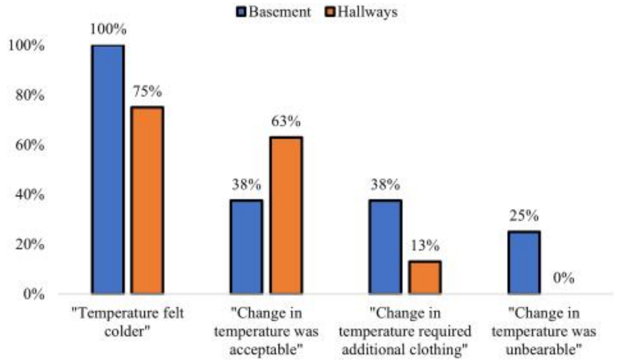

Fig. 9 Summary of resident responses to thermal comfort in the basement and hallways. Open-ended responses were synthesized into categories represented on the *x*-axis, reflecting post-electrification changes in thermal comfort compared to pre-electrification levels. Responses were quantified based on the percentage of resident responses received for each synthesized category.

Figure 8 quantitatively analyzes mean room temperatures across 55 rooms throughout all 10 residential units within the building. Mean pre-electrification temperatures for each room are compared to mean post-electrification temperatures. Rooms appearing above the 1:1 line demonstrate an increased mean post-electrification temperature, while those below the 1:1 line demonstrate a decreased mean temperature. According to ASHRAE 55 standards [41], acceptable indoor operative temperatures for human occupancy range from approximately 20 to 27 °C, indicated by the solid lines in Fig. 8. We observe that, independent of the direction of change of mean temperature for each room post-electrification, 80% of rooms remained within the acceptable temperature range.

The boxed region in the lower left of Fig. 8 highlights the 11 rooms that fell outside this range during both the pre- and post-electrification periods. Due to electrification, eight of these 11 rooms maintained or increased their mean temperatures closer to the acceptable range, demonstrating the positive impact of electrification on thermal comfort from the general perspective of ASHRAE standards. Collectively, 95% of the 55 rooms analyzed remained within the ASHRAE suggested thermal comfort range or increased their mean temperature toward the suggested range. We proceed to understand the impact of electrified heating on thermal comfort specific to the building residents in this study by combining our qualitative and quantitative findings.

Table 2 summarizes the thermal environment changes for the five units from which both complete qualitative and quantitative thermal comfort data were obtained. Results demonstrate that the overall adoption of electrified heating proved to be thermally beneficial for most respondents. Thermal comfort was maintained or improved in 93.9% of the 15 rooms post-electrification, despite a preconceived uncertainty of the capabilities of electrified heating from 25% of the eight respondents and the perceived challenges

Table 2 Qualitative thermal comfort findings and measured thermal environment findings recorded from temperature sensors are summarized below for each apartment unit

	Qualitative and quantitative findings					
	Underheated to comfortable		Maintained comfort		Comfortable to underheated	
Apartment unit	# of rooms	Change in mean temperature (°C)	# of rooms	Change in mean temperature (°C)	# of rooms	Change in mean temperature (°C)
A	3	+1.8	2	+1.0	0	–
B	0	–	10	−2.0	0	–
C	4	−0.8	2	−2.7	0	–
D	2	+2.1	2	+2.1	2	+2.4
E	6	+1.7	0	–	0	–

Note: Qualitative responses resulting in or originating from a state of "overheated" are excluded, as no resident responses reported feeling overheated. The number of rooms that were qualitatively observed to experience each thermal comfort change is presented first, followed by a quantitatively measured change in mean temperature.

of maintaining thermal comfort in a railroad-style apartment. Thermal comfort declined in two rooms of the apartment unit that experienced troubles due to poor roof insulation and heat pump undersizing, discussed further in Sec. 3.3.1. Seventy-three percent of the 15 rooms demonstrating thermal comfort changes of "underheated to comfortable" were associated with a mean temperature increase greater than or equal to 1.7 °C. The remaining 27%, all obtained from one apartment unit, were associated with a mean temperature decrease of 0.8 °C. The resident from this unit stated:

> With the heat pumps, you can put them on whenever you want, so it's always comfortable,

suggesting they directly correlate their thermal comfort with their newfound thermal controllability. The observed decrease in apartment-level mean temperatures within this unit can be attributed to adopting new adaptive behaviors related to thermal controllability, including using zoned climate control, which was once very difficult to implement with steam boiler heating. Findings from this unit suggest that measuring temperature alone can be insufficient for assessing the impact of heating electrification, demonstrating the necessity of qualitative observations.

For qualitative responses categorized as "maintained comfort," 75% of these 16 rooms experienced a decrease in mean temperature greater than or equal to 2.0 °C, while the remaining rooms demonstrated mean temperature increases of 1.0 °C and 2.1 °C. Variations in the magnitude and direction of measured indoor temperature changes could be largely attributed to factors including changes in room-level heating capacities and new adaptive behaviors brought forth by introducing improved indoor temperature control.

Residents from one unit responded with "maintained comfort" in all rooms despite observing a mean apartment temperature decrease of 2.0 °C. In this unit, thermal controllability was exercised through new adaptive behavioral traits, namely occupancy-based heating schedules and nighttime temperature setbacks. These residents decided to take an energy-conscious approach to their indoor space heating strategy by using energy-conservative setpoint temperatures between 20.0 and 22.2 °C and adopting a zoned climate control strategy, only operating IDUs in occupied rooms while deactivating units in unoccupied rooms. They also adopted the adaptive behavioral trait of deactivating all IDUs when the apartment was unoccupied. During the night, these residents adopted an energy conservation strategy similar to that used pre-electrification—they deactivated all IDUs when sleeping, much like the nighttime temperature setback strategy used by the shared steam-heating system. Adopting these adaptive behaviors and increasing control of the indoor thermal environment post-electrification contributed to the apartment units' overall decrease in mean temperature while still allowing for thermal comfort to be achieved in all rooms.

3.2.2 Adopted Comfort-Taking Behaviors. In addition to the several energy-conservative behaviors adopted with the introduction of heat pumps, several "comfort-taking" behaviors [42] failing to conserve energy were observed. While survey responses showed that 75% of the eight respondents powered off IDUs in unoccupied rooms, 88% of the eight respondents powered off all IDUs when their apartment was vacant, and 80% of the five respondents utilized nighttime setbacks and did not use their IDUs at night, there was a minority of residents that continuously operated all IDUs in every room regardless of the time of day, room, or apartment occupancy schedules. These residents were located on the ground floor of the building. Resident interviews revealed that ground-floor residents experienced decreased floor temperatures after deactivating the boiler for space heating in the basement. To combat reduced floor temperatures, some ground-floor residents took an energy-conscious approach by wearing warm house slippers when at home. In contrast, others adopted indoor climate comfort-taking behavior, rarely deactivating any IDU at any time throughout the day. These residents prioritized their control of maintaining thermal comfort over incurring additional heating expenses, quoting:

> It's so hard to compare them. We can control them [the heat pumps]. We couldn't control the heat from the basement [with steam radiators], so we're not unhappy [with higher heating costs].

Manual radiator valves on steam radiators provided little control of temperature setpoints. Furthermore, a single, often inadequate temperature setpoint was established for the building's shared heating system. The introduction of electrified heating allowed these residents to set personalized indoor temperature setpoints and adopt a setpoint schedule capable of meeting their thermal comfort needs.

Further potential comfort-taking effects were discovered through resident interviews. When asked about thermal comfort characteristics for individual rooms, some residents reported adopting the strategy of operating IDUs at higher setpoint temperatures in more occupied or larger spaces or rooms with floor units instead of wall units to increase the rate of achieving thermal comfort. One resident adopted the strategy of briefly heating all rooms regardless of occupancy to quickly warm the entire apartment, then deactivating IDUs in unoccupied spaces. Another resident adopted comfort-taking behavior from the luxury created for them during summer cooling periods. Pre-electrification, they would often open windows to regulate temperature. Still, post-electrification, they became very comfortable with and reliant on heat pump cooling, significantly increasing cooling costs to the point where they stated:

> I think I need to control myself.

Optimal heating and cooling strategies had yet to be identified for many residents. One resident stated:

> I have to think about what is the best temperature for my apartment, for example, when the weather is 90 deg. I have to know how to manage that. I have to put attention to that. Do I put it to 65? Or lower? I don't know that yet,

demonstrating their uncertainty in identifying suitable temperature setpoints for corresponding outdoor temperatures. This resident adopted a trial-and-error temperature regulation strategy, testing through experience which temperature setpoints were ideal for various outdoor temperatures. Another resident quoted:

> I should stress that one question we had that we never answered to ourselves … in terms of conservation, [is] 'is it better to have far away setpoints but very low ones at night or close ones so that the machines don't have to work as hard when they go back to the high one?' and we never got an answer to that question. We just followed our comfort level,

suggesting this resident was concerned with identifying an optimal heating strategy but needed to understand how different heating patterns affect energy consumption. Without this information, this resident resorted to a comfort-taking strategy, basing temperature setpoints primarily on maintaining thermal comfort. These uncertainties suggest that for optimal user satisfaction and to maximize potential energy savings benefits from heat pumps, new heat pump adopters should be provided additional information on temperature regulation strategies to ensure they make more informed decisions regarding heat pump temperature setpoints and schedules.

3.2.3 Thermal Satisfaction and Experience in the Basement and Common Areas. In addition to understanding the impact of electrified heating in occupied spaces, it is important to understand the implications of removing heating in shared spaces and common areas of the building. Pre-electrification, the common basement was indirectly heated by boiler operation. Post-electrification, boiler operation was terminated for building heating, only operating for domestic hot water heating, significantly decreasing total boiler jacket losses. Figure 9 summarizes resident responses to the question, “During the heating season, how did your overall thermal comfort from when the boiler operated compare to when the heat pumps operated while in the hallways of the building and the basement?”

From Fig. 9, survey responses revealed that post-electrification, all eight respondents found the basement area to feel colder. Responses to this temperature decrease varied. Thirty-eight percent of these eight respondents thought it was an acceptable change, as they rarely spend time in the basement. Another 38% of these respondents adapted to the change by wearing heavier clothing when entering the basement to conduct activities such as doing laundry. Twenty-five percent of these respondents felt the basement became too cold or unbearable on the coldest winter days.

Prior to the heating conversion, the first floor’s hallway also contained a radiator unit, providing heating to the shared spaces of the building. Post-electrification, hallway radiator heating was discontinued and was not replaced by heat pumps. When asked to describe changes in hallway thermal comfort, 75% of the eight respondents reported feeling colder post-electrification, with 63% of these eight respondents adding that the temperature change was not a problem or barely noticeable since less time is typically spent in these spaces. Thirteen percent of these respondents adapted to the hallway temperature decrease by wearing additional layers of clothing.

More residents demonstrated acceptance of the hallway temperature changes than those experienced in the basement, likely because the basement was less insulated and further from resembling the thermal properties of a habitable space. After the heating system conversion, residents generally found temperature decreases in common areas acceptable or adapted to the changes with additional layers of clothing. Experiences on the coldest days demonstrated the potential need for additional insulation and air-sealing in the basement and possibly alternative heating sources in poorly insulated common spaces, suggesting this consideration for future building heating conversions.

3.3 Pre- and Post-Roof Insulation: Effect of Roof Insulation on Thermal Comfort, Energy Consumption, and Peak Demand.

On February 5, 2022, the building in this case study underwent an envelope upgrade in which approximately 16 in. of cellulose was added to the roof cavity for improved thermal insulation. The impacts of improved roof insulation on resident thermal comfort and heating power and energy requirements are discussed as follows.

3.3.1 Changes to Thermal Comfort and Indoor Thermal Environment due to Improved Roof Insulation.

Section 3.2.1 identified a resident who rated heating and cooling controllability far less than any other resident and experienced a post-electrification decline in thermal comfort within their apartment unit. Further investigation revealed that this dissatisfaction was due to a lack of roof insulation that caused the installed heat pump to be undersized. Each IDU within the building was sized appropriately according to dimensional requirements and thermal load sizing. Building residents were aware of the lack of existing roof insulation affecting the thermal performance of the building, and, as part of their building energy efficiency improvement efforts, they decided to install roof insulation shortly after the building electrification process. Given that this was projected to be a temporary thermal performance problem, a lack of roof insulation may not have been accounted for in determining proper IDU sizing, therefore causing temporary IDU undersizing on parts of the top floor. As a result of this temporary IDU undersizing, the resident quoted:

> [The] living room is hot in one section. In another section, it’s cold. And that’s the section walking to the bathroom

as well as,

> In terms of heat or cold, it’s not enough for that area because it’s an open living room and kitchen. It’s a large space. I think they didn’t take that into consideration.

Due to introducing a single IDU for temperature regulation of the living room and kitchen areas and removing portable space heating, the effects of having no roof insulation were more noticeable to the resident. To avoid additional electricity costs, this resident relied solely on ASHP heating rather than auxiliary space heating. Fixed IDUs could no longer address uneven temperature distributions and underheating problems previously solved by portable space heaters. When asked about how overheating is addressed in their apartment during the summer, this resident stated:

> I’m on the top floor, and the top floor is getting very, very hot, to the point that I have to put my personal things in the refrigerator like my lipstick, candles, creams, you know, because it’s getting too hot [and they start to melt]…We’ll see what happens this summer.

A lack of roof insulation can lead to overheating during cooling months. Before the improved roof insulation, this resident reported extreme overheating and poor indoor temperature regulation. When asked if overheating remained a problem after roof insulation improvements, they quoted:

> No, it’s fine. [The indoor temperature] has gotten better.

Experiences from this resident suggest that optimal resident thermal comfort can be better achieved through integrated building retrofitting approaches instead of relying on a singular retrofitting approach.

Temperature improvements resulting from roof insulation upgrades were observed quantitatively using recorded indoor temperature data. Indoor temperature trends were compared for periods of pre- and post-roof insulation upgrades. Several factors could potentially skew a yearly comparison of indoor thermal environment, including varying outdoor temperatures from one period to the next—a colder winter might require warmer indoor temperatures to maintain thermal comfort, changes in building occupant thermal preferences and adaptive behavior, and changes in thermal characteristics of the building envelope.

Using Kolmogorov–Smirnov two-sample tests for goodness of fit and survey and interview responses, periods were identified that would minimize the dependence of indoor temperature differences on these factors. February 5th to April 15th of each year demonstrated similar occupancy characteristics and adaptive behavior from this resident. It also demonstrated very similar outdoor temperature distributions, shown in Fig. 10(*a*), with a p-value of 0.106. Statistically, $p < 0.05$ would require rejecting the null hypothesis that the two distributions are identical. Finding $p > 0.05$ provided statistical support for the claim that the null hypothesis could not be rejected. For these reasons, this period was used to compare indoor temperatures, as depicted in Fig. 10(*b*).

Figure 10(*b*) suggests that the temperature within the apartment unit rarely achieved the mean IDU setpoint temperature during the pre-insulation period. The flattened curve resembled a uniform distribution, suggesting similar probabilities of experiencing a mean apartment temperature anywhere between approximately 16 °C and 22 °C for this time, despite the average IDU temperature setpoint being 20 °C. Additionally, the greater pre-insulation temperature density is found to the left of the desired setpoint temperature, suggesting that much of the apartment experienced frequent underheating. Post-insulation, it was found that the setpoint temperature was far more likely to be achieved, noted by increased indoor temperature density near the mean IDU setpoint. This trend suggested optimal thermal comfort could be achieved by adding roof

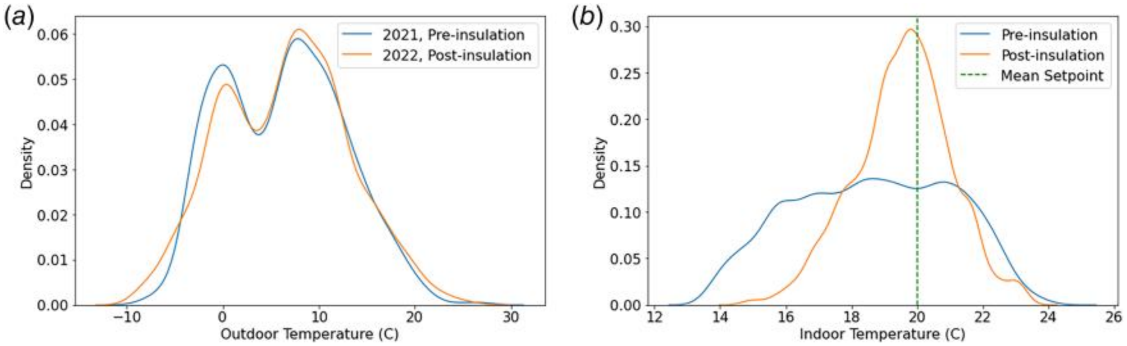

Fig. 10 (*a*) Kernel density estimation of outdoor temperature from February 5th to April 15th of 2021 and 2022. (*b*) Kernel density estimations of indoor thermal environment pre- and post-roof insulation. The mean recorded temperatures of all rooms were used to determine the mean pre- and post-insulation temperatures. The mean of all occupant-reported IDU setpoint temperatures from this resident determined the mean setpoint temperature.

insulation. Because a lack of roof insulation resulted in the heat pump system effectively operating as undersized, heating electrification alone frequently failed to allow indoor temperatures to achieve the intended IDU setpoint levels. Indoor temperatures were only able to achieve intended levels in all rooms through combined heating electrification and improved roof insulation and only through these combined efforts did this resident report their greatest level of indoor thermal comfort.

3.3.2 Impact of Improved Roof Insulation on Building Heating and Cooling Energy Consumption. It was discovered that improved roof insulation significantly impacted the building's average heat pump heating and cooling energy requirements. Resident interviews revealed that seven of nine, or 78%, of the apartment units maintained similar occupancy and adaptive behavioral trends throughout the study. This section focuses on these units to isolate the impact of roof insulation and minimize the impact of changing occupancy trends and behavior on energy consumption.

As depicted in Fig. 11, linear relationships were observed between daily heat pump energy consumption and outdoor temperatures measured as heating degree days (HDD) and cooling degree days (CDD), respectively, using recorded eGauge energy data described in Sec. 2.2 and NWS outdoor temperature data obtained from 12 months pre-roof and 12 months post-roof insulation, also described in Sec. 2.2. Base temperatures for calculating HDD and CDD, which are outdoor temperature thresholds below and above which the building needed heating and cooling, respectively, were found using Ref. [44], which tests regressions of energy data against degree days with different base temperatures to find the ones that give the best statistical fit. For our study, we used Ref. [44] to test linear regressions of our collected eGauge energy data against degree days with various base temperatures and determined that the optimal pre- and post-insulation heating base temperatures were 14.0 °C and 15.5 °C, respectively, while the optimal pre- and post-insulation cooling base temperatures were both 21.0 °C. It was expected that post-roof insulation, the heating and cooling base temperatures would decrease and increase, respectively, but these trends were not observed, likely due to variations in resident adaptive behaviors.

Comparing the linear regression slopes (9.89 ± 0.28 kWh/°C day pre-insulation versus 6.93 ± 0.24 kWh/°C day post-insulation) in Fig. 10(*a*) reveals that energy requirements per heating degree day decreased by 25.3–34.2%, suggesting significant heating energy savings. For cooling, comparing the linear regression slopes (5.64 ± 0.30 kWh/°C day pre-insulation versus 5.09 ± 0.24 kWh/°C day post-insulation) in Fig. 10(*b*) reveals a 0.2–18.4% decrease in energy requirements. Normalized, day-weighted energy consumption was also calculated by determining the ratio of total daily heat pump energy usage to both total heating degree days and total cooling degree days. It was determined that the pre-insulation normalized, day-weighted energy consumption was 10.89 kWh/°C day for heating degree days and 7.27 kWh/°C day for cooling degree days. Post-insulation, these values decreased to 7.44 kWh/°C day and 6.35 kWh/°C day, respectively, representing 31.7% and 12.7% decreases in normalized, day-weighted energy consumption post-roof insulation. This again reflects the need for integrated building energy retrofitting techniques.

To fully exploit the benefits of heat pumps, improved roof insulation is necessary, as it can increase building thermal inertia, allowing heat pump retrofits and building residents alike to operate more thermally efficiently. As a result, heat pumps required less energy to maintain thermal comfort, and building residents

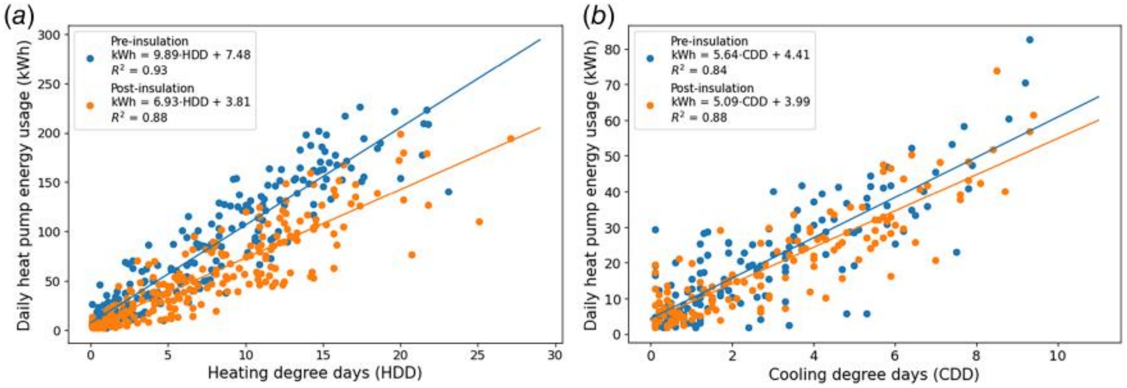

Fig. 11 Daily total heat pump energy usage compared to (*a*) HDD and (*b*) CDD. For both heat pump heating and cooling, building-wide decreases in total heat pump energy usage per heating/cooling degree day are observed.

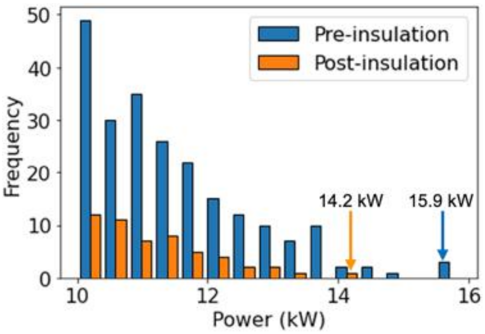

Fig. 12 Histograms representing the frequency of occurrences of the building's total heating demand requirements exceeding 10 kW during a 15-minute interval, pre- and post-roof insulation. Decreases in magnitude and frequency of peak heating requirements post-roof insulation are observed.

were less reliant on heat pumps as the sole contributor toward achieving thermal comfort. Additionally, as shown in Sec. 3.2.2, heating electrification alone could create comfort-taking behavior, likely increasing building energy consumption. Combined with added roof insulation, some of these increases in energy consumption could be mitigated, allowing these building retrofits to achieve their intended energy efficiency goals.

3.3.3 Impact of Improved Roof Insulation on Building Peak Demand. In addition to impacting average energy requirements, it was discovered that adding roof insulation also affected peak heating power demand requirements for the building. Figure 12 depicts this impact.

The pre- and post-insulation periods selected for Fig. 12 were identical to the comparable periods specified in Sec. 3.3.1—February 5th to April 15th of each year—to minimize differences in external measurement conditions. The analyzed apartment units were an aggregation of the seven units previously identified to maintain similar occupancy and adaptive behavioral trends throughout the study. Figure 12 depicts the magnitudes and frequencies of peak heating electricity demand occurrences, showing that the occurrences for heating electricity demand exceeding 10 kW decreased by 73% post-insulation compared to pre-insulation. Additionally, the highest heating electricity demand saw a reduction of 10.7% from 15.9 kW pre-insulation to 14.2 kW post-insulation, demonstrating improved building insulation's compound effect on aggregate demand requirements.

As discussed in Sec. 3.3.1, heating electrification without adequate thermal insulation can result in equivalent heat pump system undersizing, which can negatively affect thermal comfort for residents most affected by building envelope inadequacies. Heat pump undersizing can also increase peak heating demand requirements [45] and total system energy consumption [46], which could overload existing grid infrastructure and potentially create grid imbalances. A combined building energy efficiency approach could minimize grid impact due to peak demand requirements [47] and improve resident thermal comfort and experience, helping to further promote the adoption of ASHP systems.

4 Conclusion

This paper presents the evaluation of a combined energy retrofitting case study, using an integrated qualitative and quantitative approach to analyze the effects of a heating electrification conversion from steam boiler heating to ASHPs and roof insulation retrofitting in a 10-unit NYC apartment building. Our findings suggest that despite most residents being unfamiliar with ASHP systems, electrified heating was preferred over steam boiler heating for controllability, noise reduction, and overall thermal comfort in all living and shared spaces. Added benefits included improved aesthetics, reduced real estate, and decreased potential for accidental burns. It was also discovered that the roof insulation retrofit improved resident thermal comfort and ASHP efficiency in previously uninsulated spaces, effectively mitigating the effects of potential ASHP undersizing. The roof insulation retrofit decreased total building heating energy requirements by 25.3–34.2% and cooling energy requirements by 0.2–18.4%. Roof insulation also reduced building peak power requirements, decreasing the magnitude of peaks by 10.7% and the frequency by 2.2%, demonstrating the importance of combined energy retrofitting strategies. Results suggest that integrated energy retrofitting techniques could play a key role in ensuring thermal comfort and building energy efficiency on the road to carbon neutrality.

Despite resident accounts of increased electricity costs from ASHP systems, a detailed comparison of associated capital costs still needs to be performed. Resident interviews revealed concern for lifetime heating system capital costs. ASHP systems were thought to have a lifetime of 20 years, while the building's boiler was replaced approximately every 40 years, with the steam system providing heat to the building for over 100 years. It may be expected that ASHP systems provide greater thermal comfort and controllability at the expense of greater capital costs, given the lifespan of steam boiler systems, but detailed lifetime tradeoff and capital cost analyses are left for future work. Additionally, being that ASHP equipment was expected to be replaced more frequently than steam boiler equipment, there was concern over the lifetime environmental impact of each heating system. A life-cycle assessment of each heating system to reveal total environmental impacts is left for future work. Lastly, total and peak pre-electrification power requirements were not measured, leaving a quantified comparison of building power requirements for future work.

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Conflict of Interest

There are no conflicts of interest.

Data Availability Statement

The datasets generated and supporting the findings of this article are obtainable from the corresponding author upon reasonable request.

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