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Dataset on occupant behavior, indoor environment, and energy use before and after dormitory retrofit

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This paper presents a comprehensive 2-year-long dataset capturing Occupant Behavior (OB) of students living in residential dorms, collected both before and after a complete building envelope and energy retrofit. The dataset is categorized into three data sets: OB, Indoor Environmental Quality (IEQ), and detailed energy usage. OB data includes window and door status, while IEQ data comprises measurements of indoor CO_2, Total Volatile Organic Compounds (TVOC), temperature, relative humidity, and lighting levels. Energy data spans 16 electrical channels in the building, covering stove usage, exhaust hood, lights, refrigerator, plug loads, HVAC (Heating, Ventilation and Air Conditioning) energy consumption by zone, water heater, and Heat Recovery Ventilation (HRV) units (post-retrofit). The study revealed a 77.81% reduction in total HVAC energy usage, 57.70% decrease in infiltration Air Changes per Hour (ACH), and 57.78% reduction in average TVOC concentration. Enhanced thermal comfort during the late summer and early fall transition period led to a 12.33% decrease in window opening frequency and a 34.51% reduction in window opening duration. The building resilience improved significantly as the 'Extreme Caution' hours were reduced by 93.00%. This dataset offers significant value by enabling researchers to quantify key relationships among OB, building energy efficiency, and IEQ, acknowledging the influence of behavior on these outcomes.

Background & Summary

Buildings consume a significant amount of energy over the course of their lifetimes[1]. It is well-documented that the worldwide building sector—comprising residential, commercial, and industrial buildings—accounts for approximately 35% of total final delivered energy globally[2]. In 2018, this sector consumed about 127 exajoules (equivalent to 3050 megatons of oil or 35.27×10^{12} kWh)[3]. HVAC systems are known to consume around 40% of a building's total energy demand[4]. The proper sizing of HVAC equipment plays a critical role in reducing energy consumption. If the equipment is undersized or oversized, it can lead to excessive energy use. The correct sizing is typically determined during the design phase of the building. Former studies have noted that failing to account for OB can result in discrepancies between actual and predicted energy use between 50% to 150%[5–7]. Thus, it is crucial to accurately study and account for the dynamic nature of human behavior and its impact on building energy consumption. It is also important to import this dynamic human behavior into simulation engines to accurately determine the anticipated energy use.

Additionally, previous research has estimated that buildings consume about 40% of the materials entering the global economy and are responsible for generating 40–50% of total greenhouse gas emissions[8]. As the human population is projected to reach up to 10 billion, this consumption trend is expected to continue. Furthermore, it is well-established that people spend about 90% of their time indoors[9], which requires near-constant demand for climate control and exacerbates energy consumption. To mitigate this, governments worldwide are incentivizing retrofits of existing building stock. Retrofitting refers to the adaptation of obsolete building components using modern technologies and features[10]. A 2012 study categorized the building retrofit process into five phases:

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project setup and pre-retrofit survey, energy auditing and performance assessment, identification of retrofit options, site implementation and commissioning, and validation and verification of actual improvements in energy use, thermal comfort, and Indoor Air Quality (IAQ)[11].

Energy efficiency. Numerous studies published in the past have demonstrated that building retrofits lead to a reduction in building energy consumption[12–16]. They emphasized the importance of building retrofit by suggesting that the most effective way to achieve a significant reduction in energy consumption in the building sector is to improve the energy quality of existing buildings. A life cycle assessment case study was conducted for a six-story building at the University of Michigan[17]. The study estimated that the production and transportation of the building materials accounted for 2.2% of the primary energy consumption over the lifetime of the building. The remaining 97.6% of the primary energy consumption was utilized by HVAC systems, lighting, appliances, and general and water services. Hence, in this case, improving energy efficiency had a relatively low impact on embodied energy compared to operational energy use, and from both an embodied carbon and economic perspective, it aligned with the project's energy goals.

Some studies published in the past have reported the measured energy usage changes after retrofit. A study conducted in 240 apartments in Finland and 20 apartments in Lithuania found that the heating energy consumption decreased on average by 24% and 49%, respectively, after retrofit[18]. Another study of multi-family buildings constructed in 1970 in Sweden found that the heating energy savings can vary between 34% and 51% after retrofit[19]. The study mentions that improved windows give the biggest single final energy savings. This may be because of the reduction in infiltration rates through the orifice of the windows. Apart from studies that provide actual descriptive statistics of the energy savings, many studies also focus on sensitivity analysis showing the impact of various design changes on the energy consumption of the buildings[20–22]. A study tried to evaluate the potential of energy efficiency measures in office buildings using nine Energy Efficient Methods (EEMs)[23]. Some of the EEMs explored include adding wall insulation, adding roof insulation, replacing windows U-Factor values, replacing windows Solar Heat Gain Coefficient (SHGC) values, replacing interior lighting with higher efficiency fixtures, and others. An Standard Regression Coefficient (SRC) sensitivity index was developed and applied it to all climatic zones. The study found that replacing windows and office equipment with efficient ones were the best measures to improve the energy efficiency of the office buildings.

Another sensitivity analysis conducted for buildings in Iran found that window size is the most dominant parameter on building HVAC energy consumption and consequently the overall building electricity usage[24]. The study also mentions that the glazing visible transmittance has the biggest influence on the annual lighting in all weather conditions. Similarly, another study tried to assess the best EEMs for hotels in the United Kingdom to make them net-zero (nZEB) buildings[25]. The study found that improving the building fabric and building envelope elements can lower the energy demand. After the building retrofit, the study suggests the inclusion of a renewable/microgeneration system that can help to meet the nZEB target. Another life-cycle assessment study in Sweden found that the use of additional insulation in the walls, replacement of existing windows with more energy-efficient ones and changing traditional mechanical extract ventilation with HRV units are the best ways to reduce the energy demands[26].

Based on the above-mentioned studies, it is clear that building retrofits hold the potential to significantly reduce energy consumption. The primary EEMs differ based on different climatic zones; however, replacing windows and adding more thermal insulation layers are common denominators among all of them. The building's geometry, orientation, height, and window-to-wall ratio (WWR) might also significantly change the energy consumption. Replacing the windows can help to curtail energy usage as it can help to reduce air infiltration. Generally, air leakages occur through the cracks and orifices around the windows, and replacing the old ones can effectively eliminate this problem. Also, optimizing the U-value and the SHGC of the windows based on the climatic conditions can help to increase energy efficiency.

Changes in indoor air quality (IAQ). Prior studies have reported mixed results for IAQ after building retrofit[27–30]. In some homes, if a dedicated mechanical exhaust system is added after retrofit, the concentration of pollutants drops significantly. However, retrofitting buildings by adding new materials can result in an increase in pollutant concentrations, such as NO_2 and formaldehyde, which are counted among TVOCs found indoors. For example, after the retrofit of apartments in Finnish buildings, there was a significant increase in BTEX (benzine, toluene, ethylbenzene, and xylenes) concentration[18]. On the other hand, there was a significant reduction in fungal and bacterial concentrations. In Lithuanian buildings after retrofit, radon concentrations significantly increased. From this observation, it is clear that without the inclusion of an exhaust system, pollutants that tend to be homogeneous with the ambient air tend to increase.

Some past studies also tried to quantify the impact of indoor CO_2 and TVOC concentrations after retrofit. A study in Finnish apartment buildings observed an increase in exhaust ventilation rates in the building with mechanical ventilation from 0.43 hr^{-1} before retrofit to 0.48 hr^{-1} after retrofit[31]. It was observed that the average CO_2 concentrations were 750 ppm before the retrofit, which reduced to 715 ppm after. Additionally, 41% of the occupants were satisfied after the retrofit compared to just 22% before. Another study found that occupant satisfaction with indoor temperature was associated with both retrofit status and IEQ parameters[32]. Positive associations were found between retrofit status and occupants reporting the absence of upper respiratory symptoms. The study also observed that after retrofit, fewer absences were reported from work and schools due to respiratory infections. Another study in different climatic zones of California found that building retrofit improved the thermal comfort conditions, bathroom humidity, and concentrations of carbon dioxide, acetaldehyde, Volatile Organic Compounds (VOCs), and Particulate Matter ($PM_{2.5}$)[33]. However, the results were mixed with formaldehyde concentrations, possibly due to the installation of new materials after the retrofit. Another study in Austria found that building retrofit helped to limit the presence of molds and made a significant difference in IEQ[34].

SN	Paper/Year/Reference	Climate Zone	IAQ Changes	OB Changes	Envelope Retrofit	Energy Retrofit
1	Internationale Energieagentur[2]	All Climate Zones			X	X
2	Shaikh *et al.*[10]	All Climate Zones			X	X
3	Du *et al.*[18]	Dfa and Dfb	X		X	X
4	Dodoo *et al.*[19]	Dfb			X	X
5	Shadram *et al.*[26]	Dfc			X	X
6	Pampuri *et al.*[29]	Cfa	X		X	
7	Leivo *et al.*[31]	Dfb	X		X	X
8	Shaughnessy *et al.*[32]	Dfa and Dfb	X	X	X	X
9	Földváry *et al.*[35]	Cfb	X		X	X
10	Coggins *et al.*[36]	Cfb	X		X	X
11	Pandey *et al.*[43]	Dfa	X	X	X	X
12	Jami *et al.*[51]	Csa	X	X	X	X
13	Pérez-Lombard *et al.*[52]	All Climate Zones				
14	Ballarini *et al.*[53]	Cfa, Cfb, Csa, Dfb, Csa			X	X
15	Moran *et al.*[54]	Cfb			X	X

Table 1. Literature Review of residential building retrofit.

Contrary to these findings, a study found that the Air Exchange Rates (AER) decreased in the buildings after retrofit, which increased the building's CO_2 and formaldehyde concentrations[35]. The study further mentions that the energy renovation increased the dissatisfaction levels among the occupants. This reduction in the AER occurred due to the addition of an insulation layer to the building envelope, which was not accompanied by adequate airflow from mechanical ventilation. Thus, the study suggests integrating additional ventilation units in the buildings to ensure that the IAQ stays at adequate levels. Another study in Ireland mentions that only 30% of the time, the bedroom data met the standards for CO_2[36]. This suggests that the rooms are under-ventilated after retrofit. The study also indicates that the median formaldehyde concentrations of 25.4 and 20.7 ug/m^3 were detected in living rooms and bedrooms, respectively, originating from the new building materials used for construction. Finally, the study emphasizes that since the retrofitted homes did not meet the minimum performance requirements stated in Irish Regulations of 2019, the ventilation rates should be increased. Similar observations were recorded by a study that examined the ventilation rates in schools[37]. The study mentioned that increasing the airtightness of the building envelope by reducing the infiltration of outdoor air can have a negative effect on the IAQ of a building. There are few studies that have attempted to gather data of all building system components and OB at the same time. For example, while the ASHRAE Occupant Behavior Database contains extensive data, none of its datasets compare energy and environmental changes before and after retrofits[38]. A promising two-year dataset from Harvard University documents energy, environment, and system operations for an ultra-low energy office building, but it is limited to a single office building[39]. A summary of literature discussing the impact of various retrofit strategies in residential buildings implemented in different regions worldwide is presented in Table 1.

From our literature review, it is evident that most studies on building energy efficiency and IAQ after retrofitting focus on residential apartments and offices in Europe, particularly in Scandinavian countries. Research on residential dormitories is almost non-existent. Additionally, many studies do not account for changes in OB after retrofitting and tend to focus on a limited number of building system parameters. To the best of our knowledge, no previous studies on residential dorms have compared and contrasted such a comprehensive set of variables before and after retrofitting.

About this study. Our study on residential dorms is unique, as it investigates changes in IAQ, energy efficiency, thermal comfort, and OB both before and after retrofitting. In total, two identically constructed buildings each containing eight units were studied for two years, out of which one building (8 units) were retrofitted. Nearly every building component use was measured, including window states, energy use from HVAC systems in each zone, stoves, exhaust hoods, plug loads, lighting, water heaters, and refrigerators. IEQ parameters such as indoor CO_2 concentrations, TVOC levels, indoor temperature, relative humidity, and lighting were also measured. Additionally, occupant window and door operations were recorded. Both pre- and post-retrofit measurements were taken over two semesters, providing at least eight months of data covering all major seasons of the year.

Methods

Overall methodology. This study was reviewed and approved as exempt by the Syracuse University Institutional Review Board (IRB #21–396) under Category 2 of the federal exemption categories defined in 45 C.F.R. 46. The IRB granted a waiver of informed consent because the study involved analysis of de-identified data, and no identifying or sensitive personal information was collected from participants. The residential dorms, constructed in 1972, were retrofitted as part of the Net-Zero Living Lab project funded by the New York State Energy Research and Development Authority (NYSERDA). In total, we analyzed 16 residential dorm units, 8 of which underwent deep energy retrofitting. Before the retrofit, the buildings were heated using baseboard electric heaters, and there were no cooling systems in place. Data from various building components, including HVAC

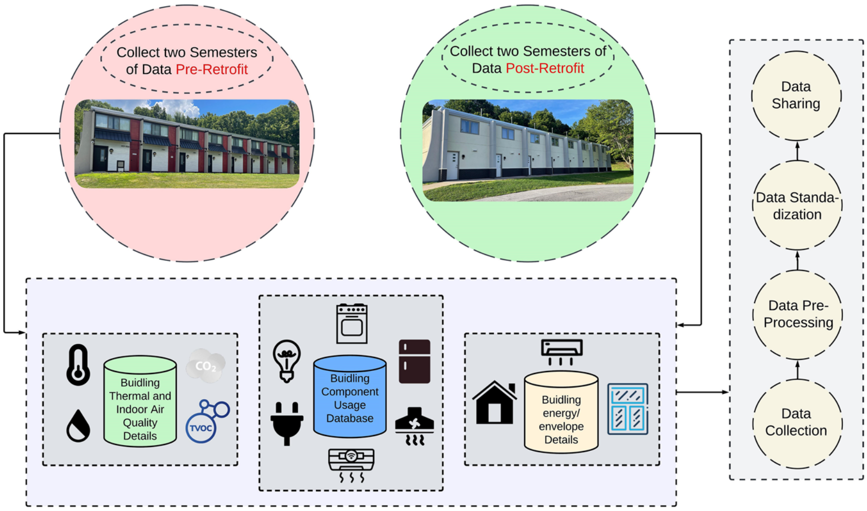

Fig. 1 This figure presents the overall methodology followed in the manuscript. It illustrates that data related to three broad building components—IEQ, Power Usage, and OB—were collected for both pre- and post-retrofit buildings. The data was then pre-processed, standardized, and shared.

systems, stoves, refrigerators, exhaust hoods, lights, plug loads, energy/heat recovery systems, and water heaters, were recorded using power meters. OB data related to door and window operations were collected using contact sensors, which measured the opening and closing states of fenestrations. IEQ parameters, such as indoor temperature, relative humidity, illuminance, CO_2 concentration, and TVOC concentration, were also measured. All of these data were recorded over two semesters (August 2021 – May 2022). In the summer of 2022, the buildings underwent retrofitting using state-of-the-art methods, as described in the sections below. The baseboard heaters in the living rooms were replaced with multi-speed split Air-to-Air Source Heat Pump (ASHP) systems with rated Coefficient Of Performance (COP) of 4.20. The same parameters mentioned above were measured for an additional year (August 2022 – May 2023). The sensors were installed in the dorms with the approval of Institutional Review Board (IRB # 21–380). The students of the dorms were informed about this study before sensor installation. After data collection, the raw data were standardized using pre-processing techniques. Finally, the data were shared via a GitHub portal after receiving the necessary permissions from the university. This dataset is also used to compare and contrast the differences in all the parameters mentioned, which is explained in detail at the end of this paper. The overall methodology is illustrated in Fig. 1.

Location and climate. The residential dorms in this study are located at a university in Syracuse, New York, USA. Syracuse has a Köppen climate classification of 'Hot-summer humid continental (Dfa)' and is known for having one of the highest average snowfalls in the country, averaging 115.6 inches annually. The summer season lasts approximately four months, from May to September, with an average high temperature of 72 °F. July is the hottest month, with an average high of 82 °F. Winter lasts about three months, from December to March, with daily high temperatures typically below 41 °F. January is the coldest month, with an average low of 18 °F and a high of 32 °F. Figure 2 illustrates the average monthly weather parameters in Syracuse.

Building information. The eight-apartment, townhouse-style dormitory was constructed in 1972. There are two townhouse blocks analyzed during this study (16 individual apartments/dorms), one of which underwent a deep energy retrofit. The building has a total conditioned space of 5,500 ft^2 (510.97 m^2), distributed over two floors. The first floor, which includes each unit's living room and kitchen, accounts for 3,000 ft^2 (278.71 m^2) of this space. The second floor, comprising two bedrooms, a bathroom, and a hallway, has a conditioned space of 2,500 ft^2 (232.26 m^2). Each apartment is designed to host two students and is located at an elevation of 700 ft (213.36 m) above sea level.

Before the retrofit, the building featured three-layered walls: (i) a 2×4 wood frame with 3.5 inches of fiberglass batt insulation, (ii) precast concrete with 1 inch of closed-cell extruded polystyrene (XPS) insulation, and (iii) precast concrete extruded demising walls. The building originally lacked a cooling system, as the city predominantly experiences cold weather, and students usually do not reside on campus during the summer. The apartments were equipped with electric baseboard heaters with a rated COP of 1. Additionally, the pre-retrofit building had windows with a U-value of 0.64 and a SHGC of 0.61, and the doors had an R-value of 2.27. There were no Photo-Voltaic (PV) panels or HRV units installed initially.

After the retrofit, the building's walls were upgraded to five layers: (i) a 2×4 wood frame with 3.5 inches of fiberglass batt insulation, (ii) precast concrete with 1 inch of closed-cell extruded polystyrene (XPS) insulation, (iii) 3 inches of Exterior Insulated Finishing Systems (EIFS), (iv) Tremco NewBrick, and (v) 7/16" Oriented Strand Board (OSB). The entire enclosure was insulated using EIFS. The retrofit also included the installation of a heat pump system with an effective average COP of 3 (rated COP = 4.20) that provides both heating and cooling. Double-pane casement windows with low-E coating were installed, featuring a U-value of 0.28 and an SHGC of 0.40. New fiberglass-insulated exterior doors were installed with an R-value of 10. The building was

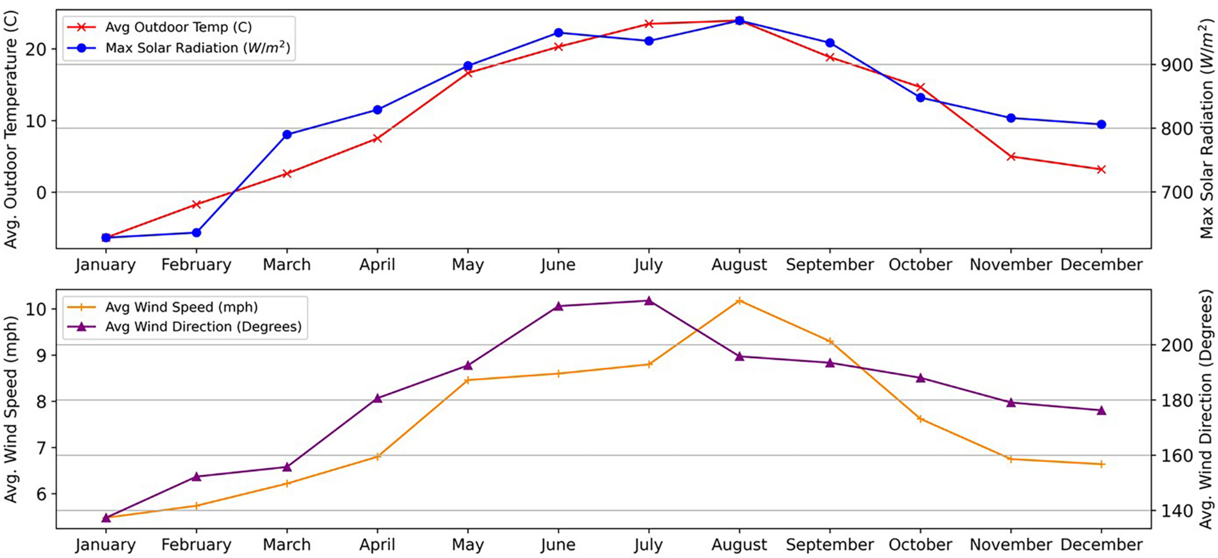

Fig. 2 This figure shows the monthly averages of outdoor weather parameters, including outdoor temperature, solar radiation, wind speed, and direction, at the data collection site.

SN	Parameter	Before Retrofit	After Retrofit
1	Year of Construction	1972	2022
2	Total Conditioned Space	5500 ft^2	5500 ft^2
3	Walls	3 Layered Walls (Exterior to Interior): *Layer 1:* Precast concrete with 1 inch closed-cell extruded polystyrene (XPS) insulation (R-4.53) *Layer 2:* 2 × 4 wood framed with 3.5 inch of fiberglass batt insulation (R-8.55) *Layer 3:* Precast concrete extruded demising walls	5 Layered Walls (Exterior to Interior): *Layer 1:* 3" Exterior insulated finishing systems (EIFS) (R-5.60) *Layer 2:* TREMCO NewBrick *Layer 3:* Precast concrete with 1 inch closed-cell extruded polystyrene (XPS) insulation *Layer 4:* 7/16" Oriented Standard Board (OSB) (R-0.27) *Layer 5:* 2 × 4 wood framed with 3.5 inch of fiberglass batt insulation.
4	Heating Units	Yes (Electric Baseboard Heater)	Yes (Heat Pump and Electric Baseboard Heater)
5	Cooling Units	No	Yes (Heat Pump)
6	HVAC (COP)	1.0	3.0 (effective)
7	PV Units	No	Yes (40–50 kWh PV Array)
8	Windows Type and Material	Metal-framed, thermally broken, double-pane (non-Low-E, non-argon) sliding windows.	Double-pane Casement Windows with low-E coating
9	Window (U Value)	0.64	0.28
10	Window (SHGC)	0.61	0.40
11	Doors (R Value)	2.27 (Insulated Metal Door)	10 (Fiberglass External Door)
12	Heat Recovery Ventilation Systems	No	Yes (LUNOS E2)

Table 2. Changes made before and after retrofit[43].

also equipped with two 40–50 kWh PV arrays and LUNOS E2 HRV Systems, with each apartment having two HRV units operating on an alternating cycle in which one circulates fresh outdoor air inside and the other discharges exhaust air outside.

Some building components remained unchanged, including the lighting system, domestic water heating system, kitchen and bathroom exhaust fans, baseboard heaters in the bedrooms, roof, and fascia. The details of the changes before and after the retrofit are described in Table 2, and images of the building before and after the retrofit are shown in Fig. 3.

Sensor information. We used three broad types of sensors to collect data from the residential dorms: (i) door/window contact sensors, (ii) ambient monitoring sensors, and (iii) power meter sensors. The details of these sensors are provided in Table 3.

The door/window contact sensors and ambient monitoring sensors are wireless and connect through a LoRa (Long Range) gateway. LoRa employs strict protocols for data transfer and provides greater security compared to a regular Wi-Fi network. For the power meters, we used a local network via Ethernet to transmit data through the ONSET platform. These power meters logged electricity usage from various electrical equipment using 14 different channel slots available on the sensor. For instance, they recorded data from the refrigerator, stove, plug loads, lighting, water heater, and HVAC system in each zone. Images of the sensors are shown in Fig. 4, and the details, including the model number, measured values, accuracy, and resolution, are presented in Table 3.

Fig. 3 This figure displays front and rear images of the buildings before and after the retrofit. It highlights design changes as well as the installation of heat pump outdoor units on the back of the building.

Sensor Name	Manufacturer/ Model	Measurement	Accuracy	Resolution
Wireless Door/Window Sensor	Netvox (R311A)	Open/Close	NA	NA
Ambience Monitoring Sensor	Milesight (AM107)	Temperature	0 °C to +70 °C (+/− 0.3 °C), −20 °C to 0 °C (+/− 0.6 °C)	0.1 °C
		Humidity	10% to 90% RH (+/− 3%), below 10% and above 90% RH(+/− 5%)	0.5% RH
		Light	±30%	1 lux
		CO_2	±30 ppm or ±3%of reading	1 ppm
		TVOC	±15%	1 ppb
		Barometric Pressure	±1 hPa	0.1 hPa
Power Meter	ONSET (EG1430 Pro)	Power Usage Data	NA	1 sec

Table 3. Sensors used for data collection[43].

These sensors were installed at various locations within the building. Each residential dorm has three windows, requiring three window contact sensors—two facing south and one facing north. Additionally, each dorm features three indoor doors and one outdoor door, all monitored using contact sensors. The IAQ sensor is positioned in the living room, while the power meter sensor is securely housed in a closed metal box near the power circuit box. Figure 5 illustrates the sensor installation locations within the residential dorms.

The data underwent strict pre-processing steps, during which it was cleaned and anonymized. Any identifying features of the sensors were deleted to comply with the university's privacy policy. The detailed data pre-processing procedures included the following steps:

i. A few data points were not recorded by the sensors due to hardware errors. These were removed from the dataset.
ii. Any voids in the continuous data were filled using a linear interpolation method.
iii. The names of the columns were standardized for clarity and consistency.
iv. The data measured by the Ambient Monitoring Sensors were initially recorded at a five-minute resolution and were linearly interpolated to a minute-level resolution.
v. The raw data for window and door states were recorded as ON/OFF by the sensors, labeled as 0 and 1, respectively. These sensors recorded timestamps when the state of the fenestrations changed, and the data were systematically interpolated to minute-level resolution to depict the fenestration state for each minute.
vi. Uniform timestamps in the format "yyyy-mm-dd hh:mm" were defined for each dataset to ensure consistency, as all data were recorded at a minute-level resolution.
vii. Each dorm is assigned a unique identifier that cannot, under any circumstances, be used to identify or retrieve personal information about the occupants. All data and metadata descriptions have been thoroughly reviewed to ensure the absence of any personal information.

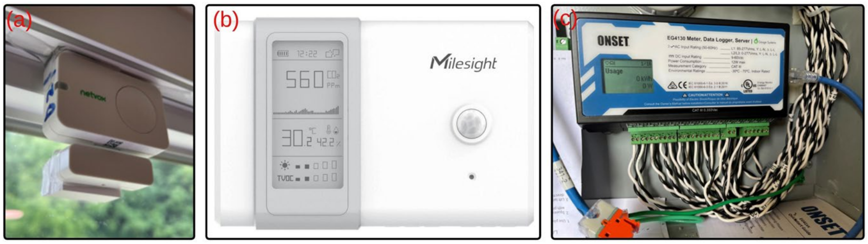

Fig. 4 This figure shows the three types of sensors used to measure window state, IEQ, and energy consumption by power circuit channels. (**a**) depicts window/door state sensors, while (**b,c**) show IEQ and power meter sensors, respectively.

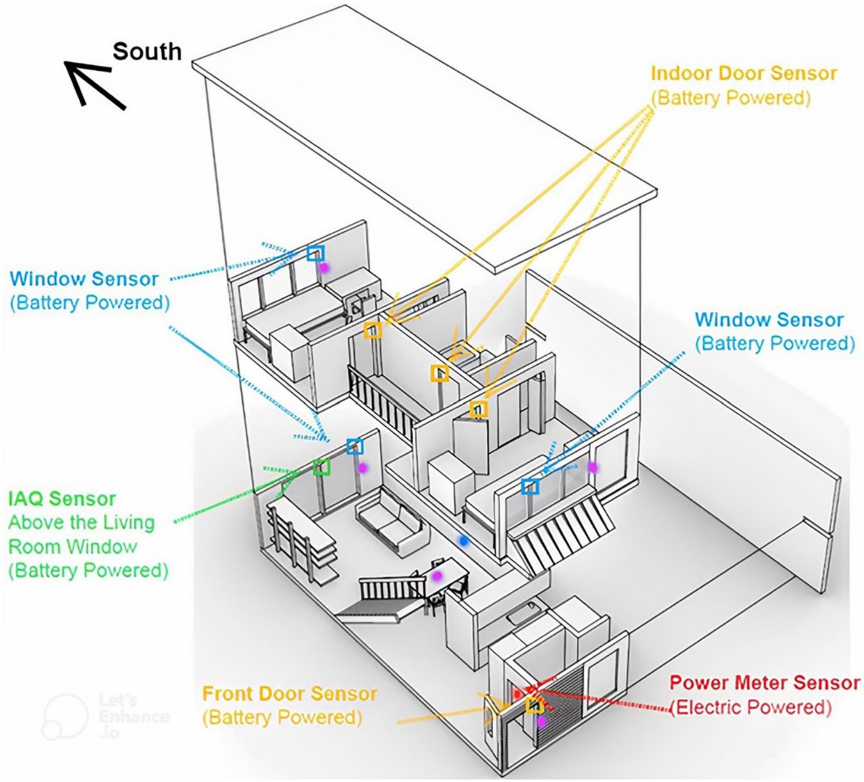

Fig. 5 This figure illustrates the locations of the sensors installed in each dorm, along with the floor plans of the individual dormitories.

Additionally, data from outdoor air sensors, collected from a rooftop location on one of the university's buildings, were incorporated into the master dataset, which contained the indoor parameters. These outdoor parameters included dry bulb temperature, dew point temperature, relative humidity, solar radiation, and rainfall.

Data Records

The datasets have been uploaded to a public domain of the FigShare website[40]. The data can be accessed using this link (https://doi.org/10.6084/m9.figshare.27155988). All pre and post retrofit datasets for each individual dorms are uploaded in separate folders. These are cleaned and unified using timestamps. Each dorm has its own individual file.

In this section, we present the list of variables measured in the field, along with their standardized names. We have also elaborated the procedures implemented to ensure data anonymization. The column names for energy usage from various electrical components are suffixed with "kWh". In addition to energy usage, we have included minute-level power demand columns, which are suffixed with "kW".

Variables related to outdoor weather. All outdoor weather variables were measured by sensors placed on top of Link Hall at Syracuse University, located 1.72 miles from the dorms. These sensors are deployed by a company called "WeatherStem," and the data is publicly available online at https://onondaga.weatherstem.com/data. The data is available in the dataset as well.

Outdoor temperature. Measured by WeatherStem. Named *Outdoor_Temp_C* in the dataset.

Outdoor relative humidity. Measured by WeatherStem. Named *Outdoor_RH_Percent* in the dataset.

Outdoor dewpoint temperature. Measured by WeatherStem. Named *Dewpoint_Temp_C* in the dataset.

Outdoor rainfall. Measured by WeatherStem. Named *X1_hr_Precipitation_m* in the dataset.

Wind speed. Measured by WeatherStem. Named *Wind_Speed* in the dataset.

Wind direction. Measured by WeatherStem. Named *Wind_Direction* in the dataset.

Solar radiation. Measured by WeatherStem. Named *Solar_Radiation_DNI_W_m2* in the dataset.

Variables related to IEQ. *Indoor temperature.* Measured by the Milesight (AM107) sensor. The living room temperature was measured both before and after the retrofit and is named *Indoor_Temperature_C* in the dataset. Additional temperature sensors were added to the two bedrooms in Spring 2023 (after retrofitting). These sensors are named *TEMP_C_ROOM_2_1* and *TEMP_C_ROOM_2_2* in the dataset.

Indoor relative humidity. Measured by the Milesight (AM107) sensor. The living room relative humidity (RH) was recorded both before and after the retrofit and is named Indoor_RH_Percent in the dataset. Additional RH sensors were added to the bedrooms in Spring 2023, with the sensors named *RH_PERCENT_ROOM_2_1* and *RH_PERCENT_ROOM_2_2*.

Indoor illuminance. Measured by the Milesight (AM107) sensor and named *Illumination_LUX* in the dataset.

Indoor CO_2. Measured by the Milesight (AM107) sensor and named *Indoor_CO2_PPM* in the dataset.

Indoor TVOC. Measured by the Milesight (AM107) sensor and named *Indoor_TVOC_PPB* in the dataset.

Variables related to energy consumption. *Heat pumps.* Measured by the ONSET (EG1430 Pro) sensor. Since heat pumps were installed only after the retrofit, this data is available only in the post-retrofit dataset. Named *First_Floor_Heat_Pump_KWh*.

Electric baseboard heater. Measured by the ONSET (EG1430 Pro) sensor. Available for bedrooms before and after the retrofit. Named *Bedroom_1_and_2_Heat_KWh* in the post-retrofit dataset. The first and second bedrooms are named *Entrance_amp_Bedroom_1_Heat_KWh* and *Stairs_amp_Bedroom_2_Heat_KWh* in the pre-retrofit dataset. In the living room, the baseboard electric heater, which was replaced after the retrofit, is named *Liv_Rm_amp_Kitchen_Heat_KWh*.

Stove. Measured by the ONSET (EG1430 Pro) sensor. Named *Stove_Receptacle_KWh* in the dataset.

Exhaust hood. Measured by the ONSET (EG1430 Pro) sensor. Named *Exhaust_Hood_Liv_Rm_Plug_KWh* in the dataset.

Heat recovery ventilation. Measured by the ONSET (EG1430 Pro) sensor. Available only in the post-retrofit dataset. Named *HRV_KWh* in the dataset.

Lights. Measured by the ONSET (EG1430 Pro) sensor. Named *Lighting_Circuit_KWh* in the dataset. This includes lights from all zones excluding bathrooms.

Refrigerator. Measured by ONSET (EG1430 Pro) sensor. Named *Refrigerator_KWh* in the dataset.

Water heater. Measured by the ONSET (EG1430 Pro) sensor. Named *Water_Heater_KWh* in the dataset.

Plug load. Measured by the ONSET (EG1430 Pro) sensor. The plug load in the first bedroom is named *Bedroom_1_D_Duplex_Recpt_KWh*, and in the second bedroom, it is named *Bedroom_2_D_Duplex_Recpt_KWh*.

Ground fault circuit interrupter (GFCI). Measured by the ONSET (EG1430 Pro) sensor. This is installed in the outlets for kitchen or bathroom counter to protect against electrical shock by quickly shutting off power if any ground fault or leakage current is detected. It is named as *Counter_GFCI_Receptacles_KWh* for kitchen and *Bathroom_Heat_GFCI_KWh* for bathroom.

Bathroom Circuit (separated from others): Measured by the ONSET (EG1430 Pro) sensor. Apart from GFCI, all other energy usage in the bathroom are measured by this circuit. Named *Bathroom_Circuit_KWh*.

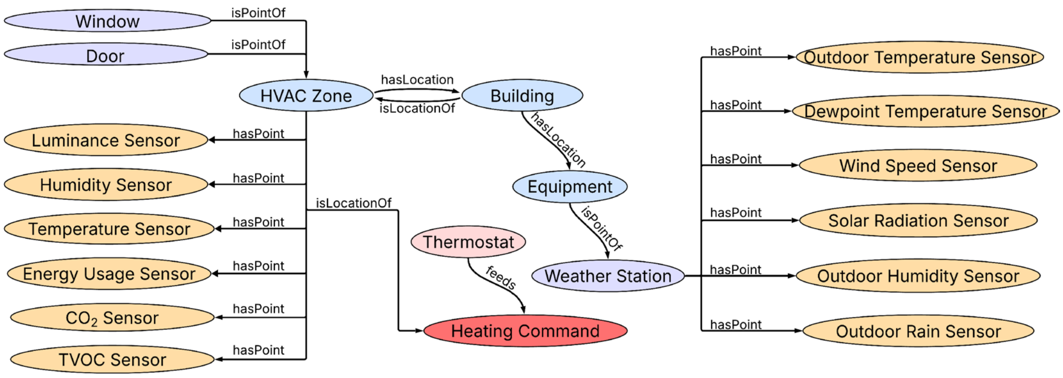

Fig. 6 This figure shows the Brick model for one HVAC Zone of the residential dorms.

Total HVAC energy usages. The overall HVAC energy usages from all HVAC devices are added. For pre-retrofit, it would be the HVAC energy usages from all baseboards in all five zones. For post-retrofit, it would be the HVAC energy usages from heat pumps and the baseboards combined. It is named as *HVAC_Energy_usage_KWh* in the dataset.

Combined Energy usage. The overall energy consumption from all devices in the building (including HVAC) are combined together. It is named as *Overall_Energy_usage_KWh* in the dataset.

CSV files are obtained from each sensor and then interpolated to minute-level data. It should be noted that the IEQ sensors have a time resolution of 5 minutes, which is linearly interpolated to 1-minute intervals. The power meter data is originally recorded at 1-minute intervals, so no interpolation is required. The window/door state data is registered by the device whenever a state change occurs, capturing the exact second of the event. The data is first chronologically sorted based on the second-level resolution. It is then converted to minute-level data using the following rule: if the window is open at any point during a given minute, the window state for that minute is recorded as open.

Variables related to OB. *Window state.* The dataset includes window state sensors for three zones in each dorm, available for both pre- and post-retrofit periods. The living room window on the first floor is named *Window_1_1*, while the bedroom windows are named *Window_2_1* and *Window_2_2*. These are categorical variables, where 0 represents CLOSED and 1 represents OPEN states.

Door state. In the pre-retrofit dataset, door state data is available for all four doors in each dorm. The main entry door is named *Door_1_1*, while the bedroom doors are named *Door_2_1* and *Door_2_2*. The bathroom door is named *Door_2_3*. However, in the post-retrofit dataset, only the main door state is available due to the theft of sensors and budget constraints, and it is named *Door*. Like the window state, these are categorical variables, where 0 represents CLOSED and 1 represents OPEN states.

Sensor and room metadata. We have developed a Brick model for one HVAC zone, and all other Brick models for the remaining zones can be exact replicas of this model. The Brick model encapsulates all the entities and their inter-relationships. For example, 'hasPoint' indicates that an entity, such as an HVAC system or a zone, has associated data points like sensors or setpoints. Similarly, 'isPointOf' is the inverse of 'hasPoint,' linking a point to an entity. Other defined inter-relationships include 'isLocationOf,' 'feeds,' and 'hasLocation.' The schematic of the Brick model is shown in Fig. 6. Detailed definitions of the Brick ontology can be found at https://brickschema.org/ontology.

Data privacy and security. The university enforces strict policies regarding data privacy and security to ensure the confidentiality of participants. In accordance with these guidelines, all collected data and metadata are completely anonymized and cannot be used to identify any specific individual. Each dorm is assigned a unique identifier that cannot be linked to personal information. To ensure secure data transmission, wireless sensors use LoRa network devices, as WiFi is considered highly insecure for such purposes. The only wired sensor, the power meter, utilizes the university's Ethernet service, with data securely pushed directly to the cloud. Additionally, access to the dataset is restricted to computers within the campus network to specific individuals involved in the project, further enhancing data security.

Technical Validation

In this section, we outline the methods used for data validation and sensor calibration. We also detail the ventilation rates of various building components, including the HRV system, the evaporator unit of the ASHP, and infiltration rates determined through blower door testing. Additionally, we provide examples illustrating changes in the building's IEQ, thermal parameters, and OB using this dataset. Comparisons between the pre- and post-retrofit datasets are presented in the subsections that follow.

Dorm ID	Volume (ft^3)	Exterior Enclosure Area (ft^2)	Pre-Retrofit				Post-Retrofit (HRV Blocked)			
			CFM50	ACH50	ACH (CC Conv)	CFM50/ft^2	CFM50	ACH50	ACH (CC Conv)	CFM50/ft^2
1	6200	1671	439	4.25	0.43	0.26	191	1.85	0.19	0.11
2	6200	1175	205	1.98	0.20	0.17	144	1.39	0.14	0.12
3	6200	1175	223	2.16	0.22	0.19	139	1.35	0.14	0.12
4	6200	1175	307	2.97	0.30	0.26	139	1.35	0.14	0.12
5	6200	1175	338	3.27	0.33	0.29	162	1.57	0.16	0.14
6	6200	1175	276	2.67	0.27	0.23	123	1.19	0.12	0.1
7	6200	1175	402	3.89	0.39	0.34	121	1.17	0.12	0.1
8	6200	1671	503	4.87	0.49	0.3	119	1.15	0.12	0.07
Avg.					**0.33**				**0.14**	
Total	**49600**	**10392**								

Table 4. Pre and Post Retrofit Blower door test results.

	Cooling		Heating	
Airflow Rate (cfm)	**H**	**M**	**H**	**M**
	417	297	403	328
	L	**SL**	**L**	**SL**
	244	141	251	215
Sound (dBA) (H/M/L/SL)	43/36/30/19		43/36/29/25	
Dimensions (in)(H × W × D)	11-1/4 × 30-5/16 × 8-3/4			
Weight (Lbs)	18			

Table 5. Air flow rates and other specifications of indoor unit of ASHP.

Sensor calibration. We used 'Factory Calibration' method of the IEQ sensor (Milesight AM107) for its calibration. This method uses the Milesight Toolbox App, which communicates with the sensor via Near-Field Communication (NFC). The app is accessed by physically placing an NFC-enabled smartphone near the sensor. Factory calibration using the Toolbox App is typically performed twice a year, coinciding with the semester-end when dorms are vacated, and batteries are replaced. Sensor validity is verified by observing baseline CO_2 concentrations during periods when the dorms are unoccupied, such as Thanksgiving and Christmas breaks. Details about the sensor's resolution, accuracy, and model are provided in Table 3. For OB sensors, on-site verification is conducted to ensure that open/close parameters are accurately registered using the Apps-Anywhere mobile app. Similarly, power meter sensors are checked on-site through the ONSET portal provided by the manufacturer. The wattage of all appliances is initially determined from their device specifications and then cross-referenced with the data recorded in the portal for accuracy.

Ventilation rates of different building components. *Building infiltration rates measurement.* The pre-retrofit buildings, constructed in 1972, predate the energy crisis in America that triggered energy efficiency policies for buildings. Structures built after the mid-1980s were significantly more airtight compared to those constructed earlier. Table 4 illustrates the differences in infiltration ACH as measured by the blower door test for all dorms in the townhouse block. This air leakage testing was performed using 'The Energy Conservator Blower Door' equipment and DG-700 digital manometers. To prepare the apartments for the air leakage testing, four steps were taken: (1) All the windows and doors were shut and latched; (2) all interior doors were opened, except for the entry closet, mechanical room access door and bedroom closets; (3) The bathroom exhaust fan and ducted range hood were shut-off; and (4) the HRV units were shut off and taped over. Guarded blower door tests were conducted to measure air leakage specifically to the outdoors. In these tests, both the apartment under evaluation and the adjacent apartments were subjected to an induced pressure of −50 Pascals. This approach aimed to equalize pressure across the party walls to eliminate air leakage through these boundaries, ensuring the focus remained solely on air leakage to the outdoors. However, maintaining identical pressure levels across party walls is challenging, which can impact the accuracy of the outdoor air leakage measurements obtained through guarded blower door tests.

Ventilation rates from ASHP. The residential dorms were retrofitted with Daikin's Air Source Heat Pump (ASHP), model #RXL09QMVJUA. The airflow rates vary for both heating and cooling, depending on the fan configuration. There are four fan speed settings for both modes: high (H), medium (M), low (L), and super low (SL). These airflow values for heating and cooling are detailed in Table 5. In summary, airflow rates for cooling range from 141 to 417 cfm, while heating airflow rates range from 215 to 403 cfm. The outdoor compressor unit has only two configurations—high (H) and low (L)—for both heating and cooling. The compressor's airflow rates range from 865 to 1105 cfm for cooling and 777 to 922 cfm for heating. Further information on the ASHP's configuration can be found on Daikin's official website[41].

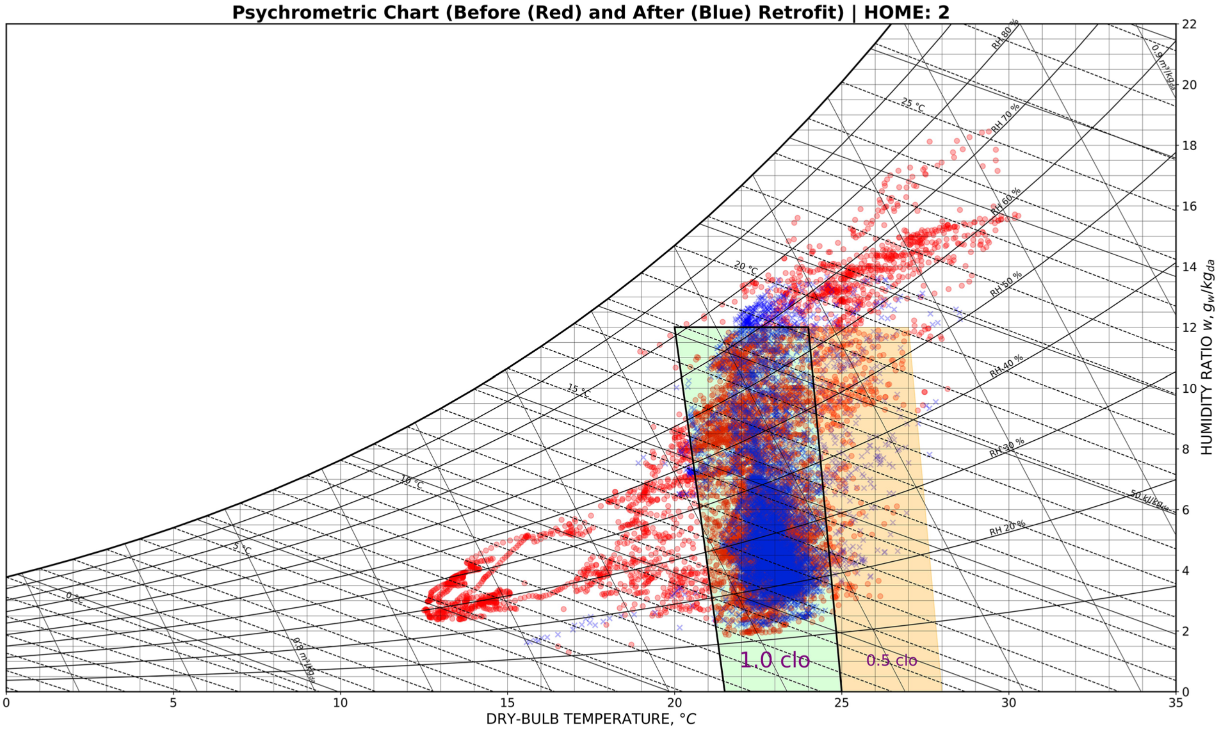

Fig. 7 This figure presents indoor temperature and relative humidity (RH) plotted on a psychrometric chart, both before and after the retrofit. The chart includes regions for 1.0 Clo and 0.5 Clo clothing insulation levels. The chart's coordinates are defined by ASHRAE Standard XX.

Ventilation rates from LUNOS E2 HRV. The HRV unit offers multiple ventilation rates, which can be adjusted using the controller. Ventilation rates range from 5 cfm to 35 cfm, with increments of 5 cfm, allowing for configurations of 5, 10, 15, 20, 25, 30, and 35 cfm. However, the controller settings cannot be adjusted remotely. Due to this limitation, a fixed airflow rate of 15 cfm has been set for all HRV units across all dorms.

Changes in the Indoor thermal comfort. ASHRAE Standard 55 defines thermal comfort as "the condition of mind that expresses satisfaction with the thermal environment"[42]. This definition suggests that thermal comfort is highly subjective, as it depends on personal preference. Nevertheless, ASHRAE Standard 55 defines a comfort zone on a psychrometric chart where there is a high probability of experiencing adequate thermal comfort indoors. In this study, we used actual data measured from the dorms to plot indoor dry bulb temperature and relative humidity on a psychrometric chart. Figure 7 shows the psychrometric charts of the residential dorms before (red dots) and after (blue dots) the retrofit, superimposed on the same plot. We observe that the blue dots (post-retrofit) are more constrained within the 1.0 Clo (normal clothing levels) range compared to the red dots (pre-retrofit).

This improvement is due to the building's-controlled air infiltration rates and the provision of adequate heating/cooling loads through heat pump systems. Additionally, the HRV systems installed in the dorms improve air quality while conserving energy.

Changes in the IAQ. As discussed earlier, the HRV systems compensate for the significant reduction in air infiltration rates while maintaining air quality and conserving energy. As a result, we observed a significant decline in TVOC exposure after the retrofit. Although TVOC generation can vary between different occupants, the decline in exposure was consistently observed across all dorms, with an average reduction of 57.78%[43]. Figure 8 shows the hourly average TVOC concentrations before and after the retrofit, where we see significant reductions across all dorms. The U.S. EPA warns that long-term exposure to high levels of TVOC can cause various health issues, including eye, nose, and throat irritation, headaches, nausea, and damage to the liver, kidneys, and central nervous system[44]. The results in Fig. 8 demonstrate that retrofitting buildings with adequate HRV systems can help reduce indoor TVOC concentrations. The hourly averaged data presented in Fig. 8 was collected over two semesters for both the pre- and post-retrofit periods.

Changes in window use behavior. We measured changes in window operation behavior before and after the retrofit, observing significant reductions in both the frequency and duration of window openings post-retrofit. Figure 9 shows instances of window operations at different outdoor and indoor temperatures. Each dot in the cluster diagram represents a window opening event, with the size of the dot indicating the duration of the opening (larger dots represent longer durations). The red clusters represent window operations before the retrofit, while the blue clusters represent operations after the retrofit.

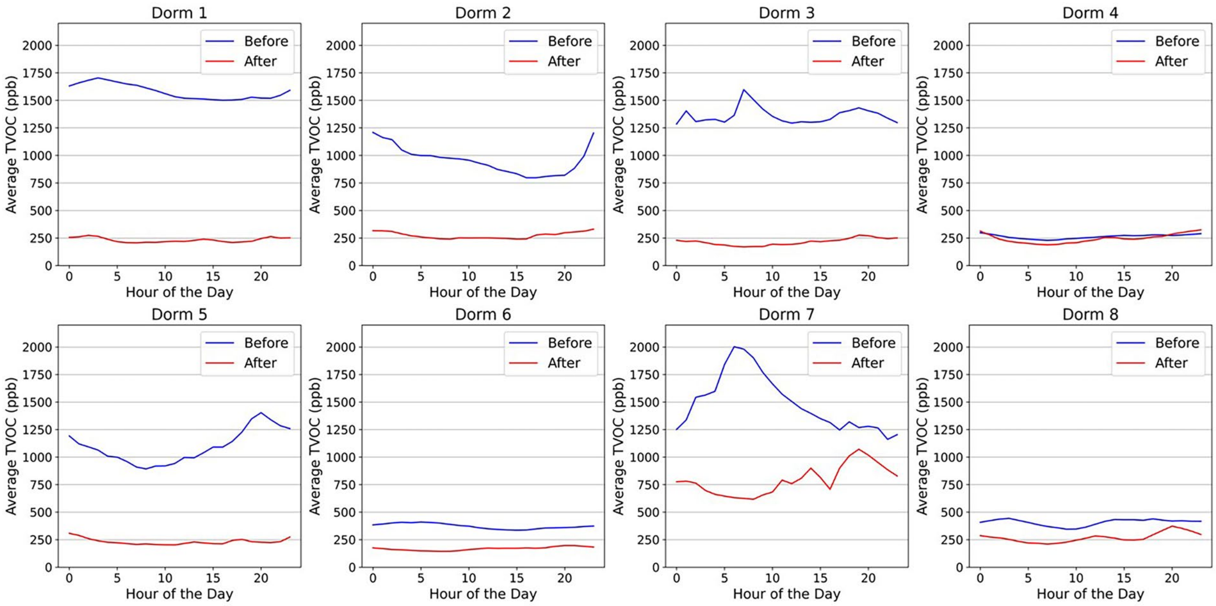

Fig. 8 This figure shows the hourly average TVOC concentrations in the dorms before and after the retrofit. Data was collected for two semesters both pre- and post-retrofit. The figure demonstrates that the inclusion of HRV systems significantly reduced indoor TVOC concentrations after the retrofit.

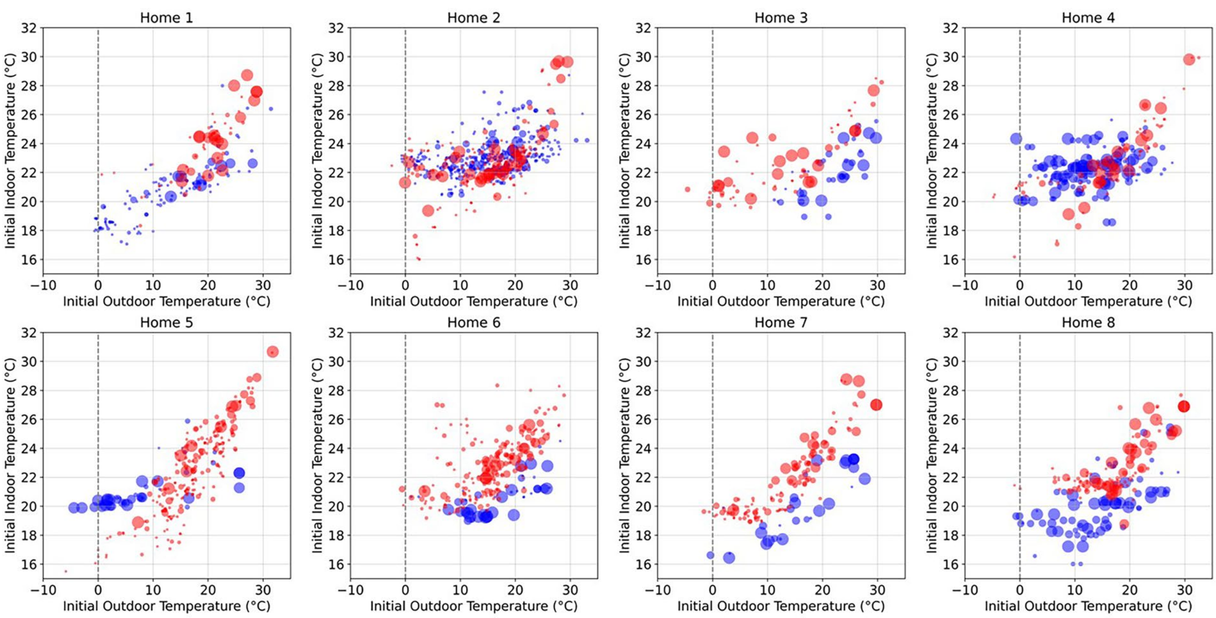

Fig. 9 This figure shows a cluster diagram of window operations before and after the retrofit. Red clusters represent window openings before the retrofit, while blue clusters represent window openings after the retrofit. The X and Y coordinates of the plot represent the initial outdoor and indoor temperatures at the time of the window opening. The diagram clearly illustrates changes in students' behavior, with reduced window openings after the retrofit due to improved indoor conditions, even during transitional seasons.

We observe distinct changes in window operation patterns. Before the retrofit (red clusters), the indoor temperature range was less restricted, particularly during the transition and summer seasons. The absence of a cooling system before the retrofit often led to prolonged window openings in August and early September, represented by the red dots in the upper right corners of the sub-plots. After the retrofit, the window opening duration decreased by 34.51%. Also, the frequency of window opening reduced by 12.33%[43].

Changes in indoor temperature and relative humidity distribution. Post-retrofit, the indoor temperature and relative humidity (RH) were more constrained within defined ranges. Figure 10 shows the Kernel Density Estimation (KDE) plots for indoor temperature and RH, where we observe that the dataset post-retrofit

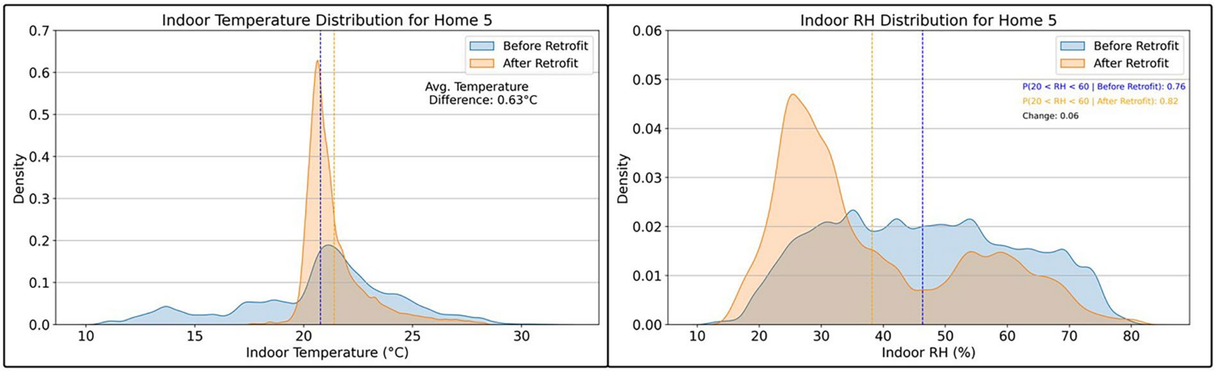

Fig. 10 This figure shows kernel density estimation plots of indoor temperature and RH before and after the retrofit. The results demonstrate that indoor temperature and RH were more tightly controlled after the retrofit, thanks to the heat pumps effectively conditioning the building year-round.

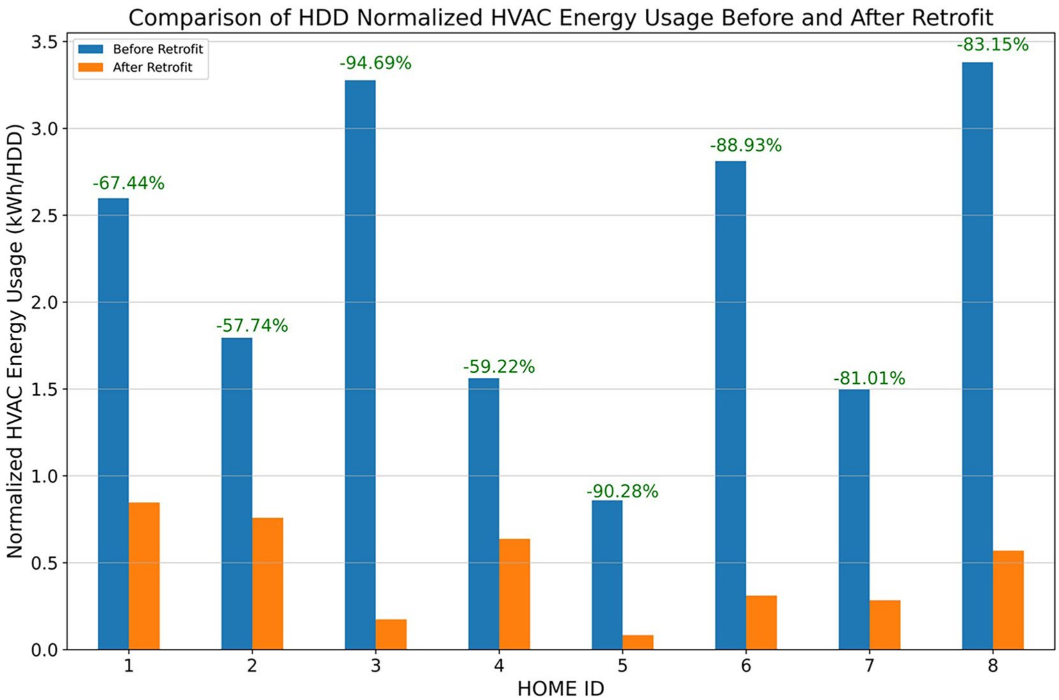

Fig. 11 This figure shows the Heating Degree Day (HDD)-normalized HVAC energy usage before and after the retrofit for each dorm. After the retrofit, the buildings used heat pumps with a COP close to 4, resulting in an 80% reduction in average energy use. Before the retrofit, buildings relied on electric baseboard heaters with an effective COP of 1.

has a lower standard deviation compared to pre-retrofit. The inclusion of a dedicated cooling system with a significantly higher efficiency (4.2x increase in rated COP) is responsible for the tighter control of thermal variables in the indoor space.

Changes in HVAC energy usage. We computed the changes in HDD (Heating Degree Days)-normalized HVAC energy usage before and after the retrofit. On average, we observed a 77.81% reduction in HVAC energy usage across all dorms post-retrofit. This reduction is expected, as the electric baseboard heaters (rated COP of 1) were replaced with heat pumps (rated COP of 4.2). The HRV systems further enhance energy efficiency by operating continuously. Figure 11 shows the HDD-normalized HVAC energy usage before and after the retrofit.

Comparison of building performance in extreme weather events. During the last week of January 2022, outdoor temperatures dropped to below −21 °C, an extreme cold event. A similar event occurred after retrofitting the building, during the first week of February 2023, when the temperature fell below −22 °C. We calculated that the average percentage reduction in energy usage during this extreme cold event was 79.74%[43]. Figure 12 shows the indoor/outdoor temperature, relative humidity (RH), and overall HVAC energy usage during

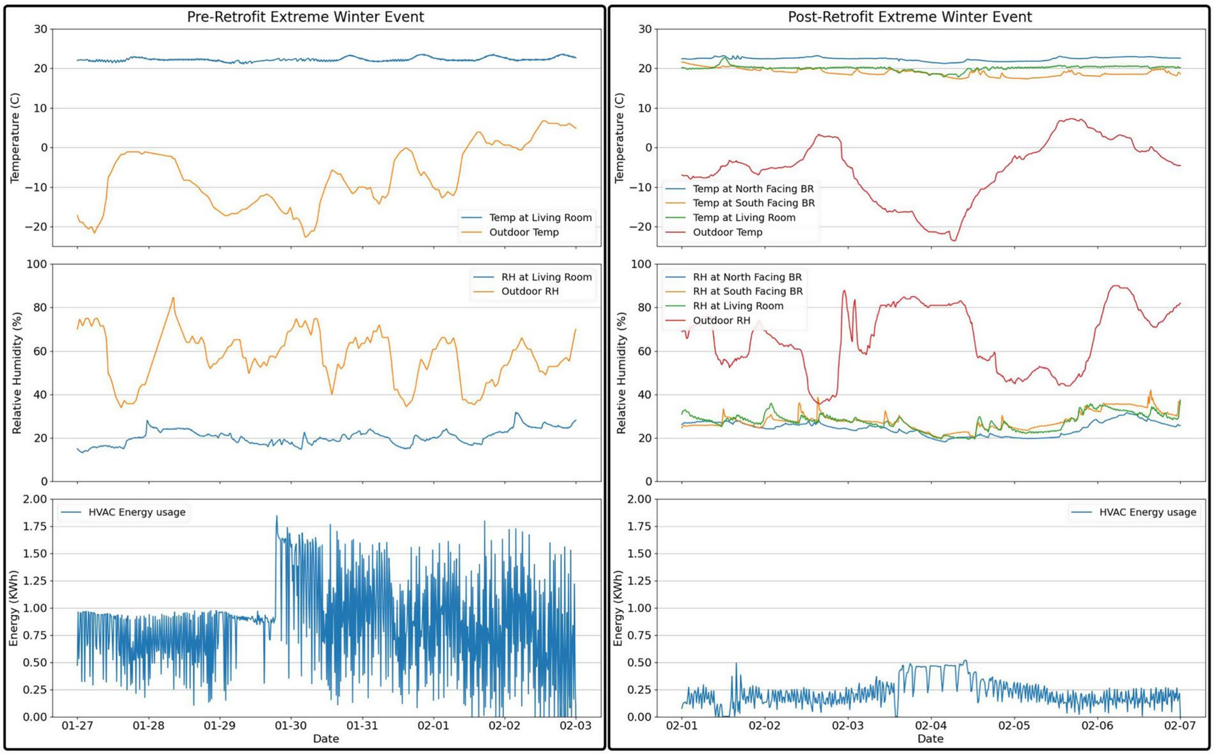

Fig. 12 This figure compares indoor thermal conditions and HVAC energy use during extreme winter events, both before and after the retrofit. The site experienced an extreme cold spell before the retrofit in the last week of January 2022, when temperatures dropped to about −20 °C. A similar event occurred after the retrofit in the first week of February 2023, with temperatures dropping to around −21 °C. The figure shows a significant reduction in HVAC energy consumption during the extreme cold event after the retrofit.

these timeframes. The figure illustrates that indoor temperature bounds were well maintained in both pre- and post-retrofit periods. However, post-retrofit HVAC energy usage was significantly lower, with more than three times less energy consumed. It is important to note that this efficiency was achieved even when outdoor temperatures dropped below −20 °C–28 °C lower than the temperature at which the rated COP of 4.2 is measured. This demonstrates the remarkable resilience and efficiency of heat pump systems compared to baseboard electric heaters.

These are just a few examples of the data analysis that can be conducted using this dataset. The results presented above, along with others not mentioned here, have already been published in various journals[43,45–50]. We believe this dataset can be utilized by researchers across the globe for several types of analyses:

i. Determine the impact and change in OB on the residential dorm's energy usage profiles.
ii. Assess the impact of building envelope and energy retrofits on overall energy use in residential dorms.
iii. Evaluate the effect of smart heat recovery systems on (IAQ) and overall building energy efficiency.
iv. Analyze the typical behavior of students in using building components such as stoves, refrigerators, exhaust hoods, water heaters, plug loads, thermostats, lights, and other appliances, as measured by the building's electrical circuits.
v. Develop machine learning models to predict the usage of HVAC and other electrical components, and integrate these models into energy simulation engines like EnergyPlus to replace constant schedules.
vi. Create advanced generative models to predict future electric load profiles for various building components. These models can account for factors such as projected outdoor temperatures and relative humidity, generating load profiles that consider elevated future temperatures.

The scope of this dataset extends beyond these points, and we believe that researchers can use it to perform numerous analyses not mentioned here.

Code availability

All the codes used to clean the raw datasets have been uploaded to GitHub for public use (https://github.com/prpandey92/Retrofit_with_OB_Energy_IEQ_Quantification_Database). The raw datasets are available upon request.

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Competing interests
The authors declare no competing interests.

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