Thermal Comfort and Environmental Impact in the Heating System Refurbishment of a Victorian Hall With Infrared Ceiling Panels

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Abstract

This study presents a holistic approach to evaluating the heating refurbishment of a historic Victorian hall in Brighton, UK, using infrared ceiling panels. While field studies have explored radiant heating ceiling panels in new constructions, limited research has investigated their application in renovating historic buildings with highly dissipative envelopes. The methodology addresses this gap and integrates perceived thermal comfort, financial feasibility, and environmental impact. The study involved a two-phase method: a thermal comfort analysis and Building Energy Simulations (BES). Results revealed that while infrared panels are easy to install, their environmental impact outweighs alternatives requiring more complex installations but offering economic returns and user satisfaction. The study provides valuable guidelines for designing and installing ceiling radiant systems in large community spaces, emphasizing comprehensive planning to achieve user comfort, energy savings, and environmental sustainability.

1. Introduction

The extent of building energy consumption is widely recognized. The task of decreasing building carbon footprints is becoming increasingly urgent, while people are raising their expectations for the perceived comfort and well-being of their living spaces (Nicol & Humphreys, 2002).

Field studies have tested the efficacy of radiant heating ceiling panels in new construction (R. Li et al., 2015), but few studies tested their applicability in the renovation of historic buildings with highly dissipative envelopes, despite being identified as suitable candidates for their refurbishment (Safizadeh et al., 2018). Conventional energy efficiency technologies in new buildings can decrease energy consumption by 20-30% on average, and reduce the carbon footprint by about 16%, just by installing a smaller or cheaper HVAC system (Kneifel, 2010). Moreover, in office buildings, the radiant ceiling panel system can create a more comfortable environment than conventional systems (Imanari et al., 1999; Bojić et al., 2013).

The study advocates for innovative methodologies in assessing both building-integrated and individual-oriented renovations. It introduces a holistic approach to evaluate the refurbishment of a spacious environment with infrared ceiling panels in terms of perceived thermal comfort, financial feasibility, and environmental impact. The distinctive case study of a historic Victorian hall (Brighton, UK) allows for addressing the integration challenge while preserving architectural integrity (Nair et al., 2022).

2. Method

This study aimed to evaluate the effectiveness of electric radiant panels in improving thermal comfort and reducing energy consumption in the Brighton Victorian Hall.

As part of the hall's renovation project, which involves upgrading the heating systems, two ceiling electric radiant heating systems were strategically installed in one room, the community hall, for testing before potential application throughout the entire building. The study employed a three-phase approach, including:

- Simulation phase utilizing Building Energy dynamic Simulation (BES) to consider the environmental impact

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- Objective thermal measurement phase with probes and a microclimatic monitoring station
- Subjective field study analysis assessing users' perceived thermal comfort through questionnaires

This paper discusses the study's first two phases.

2.1 Case Study

The "Exeter Street Hall" is a historical building located in Brighton, UK, built during the Victorian Age, in 1884. It was a Sunday School for St. Luke's Church, Prestonville, in Brighton.

Exeter Street Hall exhibits distinct architectural characteristics indicative of the Victorian era, allowing for its identification within the predominant construction style of that period. Victorian-era architecture is marked by its unapologetic devotion to ornament and flourish and its ornate maximalist interior design (X. Li & Densley Tingley, 2021).

The structure comprises a spacious central hall spanning approximately 135 square meters, flanked by two smaller rooms, each measuring around 25 square meters, positioned on opposite sides of the main facade facing the street (Fig. 1). Fig. 2 shows the architectural drawing of the building.

The building's energy efficiency is low, featuring walls primarily made of double layers of bricks and plaster (U-values 1.86 W/m²K). Interior walls are plastered on both sides, while exterior walls have plaster only on the inside, exposing the brick facade. The structure sits on brick wall foundations directly on clay ground, with a wooden plank floor raised about half a meter above, creating space for cables and equipment. Insulation is limited, with only the Main Hall's flooring insulated. The kitchen and Community Room's exterior wall is the sole insulated wall, positioned between two brick layers. Roofs are insulated in select areas, using a double layer between and above/below rafters (U-values 0.30 W/m²K). The windows are historically significant, featuring single-pane glass and wooden frames (U-values 5.8 W/m²K, SHGC 0.82). Chimneys are internally insulated, and false ceilings consist of plasterboard.

Fig. 1 – Picture of the Exeter Street Hall from the frontal street

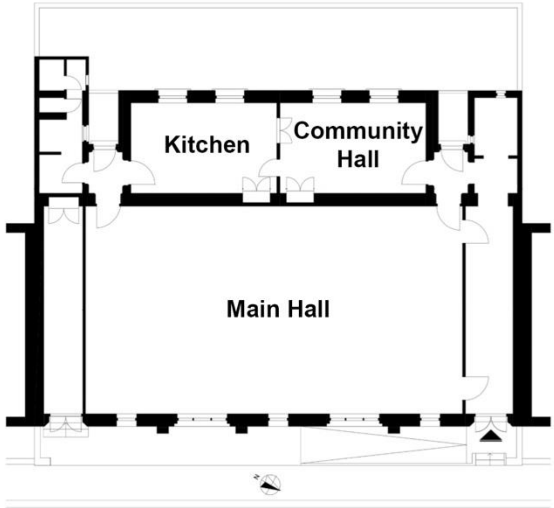

Fig. 2 – Architectural plan of the Exeter Street Hall

The building employs an air conditioning heating system, featuring gas heaters located in both the Main Hall and the Community Room. Given the considerable height of the rooms, the warm air generated by the air conditioning systems tends to rise to the ceiling, leaving the lower spaces uncomfortable for occupants.

The current heating system's performance has prompted an evaluation of electric infrared radiant ceiling panels to eliminate convective heat loss and air stratification. Among radiant systems, suspended panels offer advantages as they integrate into drop ceilings of existing and new buildings, allowing for design flexibility, reconfiguration, and easy maintenance access.

Two panels, each with a power of 1 kW, were installed in the Community Room, resulting in a total power of 2 kW (superficial T of 100 °C). Each panel is 1.6 m wide and 0.63 m high (Fig. 3, Fig. 4).

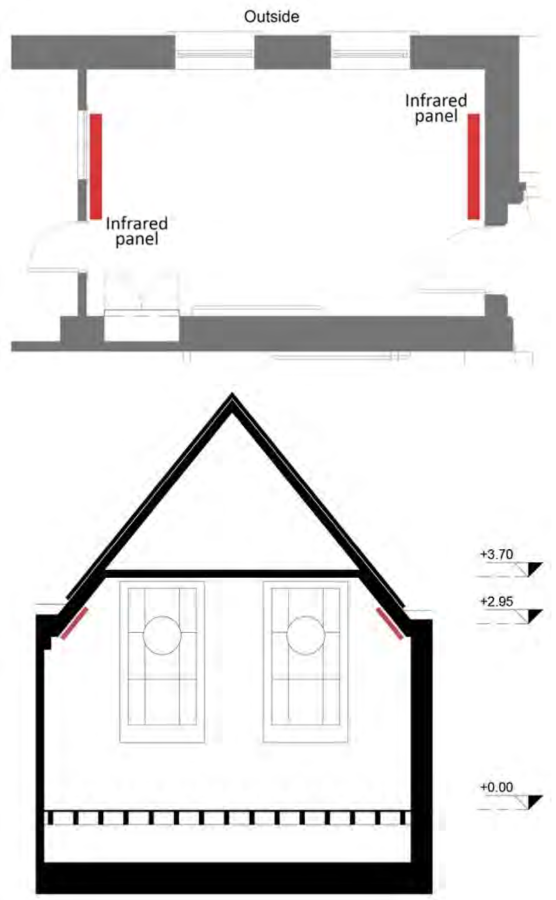

Fig. 3 – Architectural plan of the community hall with panel position

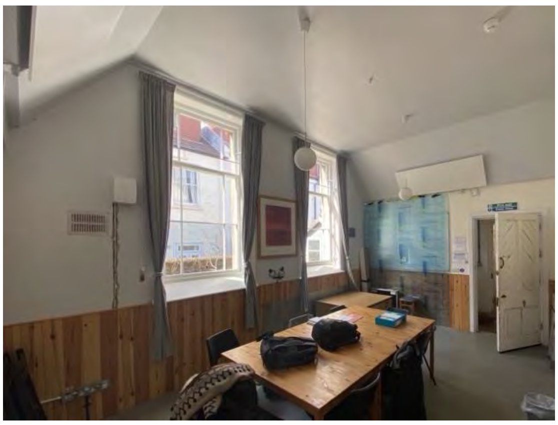

Fig. 4 – Picture of the community room with the two infrared panels installed on the sloped ceilings.

2.2 BES Model

While the panels have been physically installed only in the community room, the EnergyPlus simulation encompassed the entire building (Fig. 5), considering the interrelationship between rooms to ensure accurate results and evaluating the feasibility of implementing the heating system throughout the Hall.

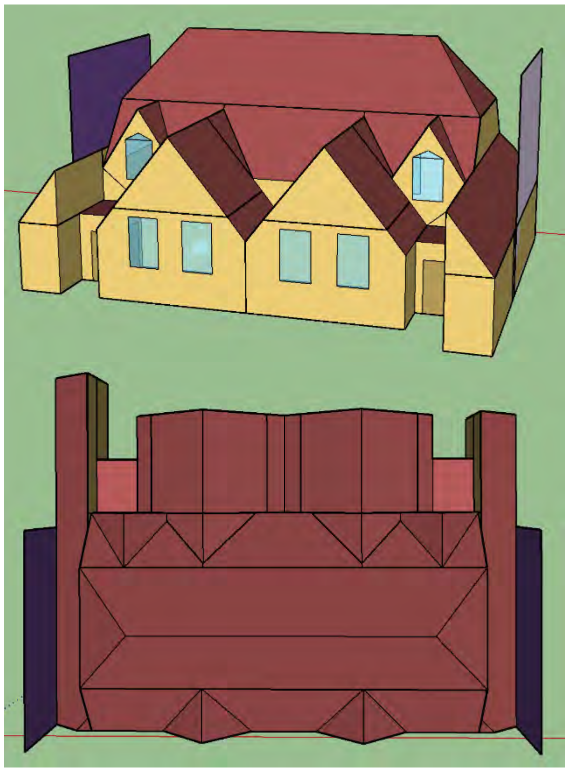

Fig. 5 – 3D pictures of the EnergyPlus thermal model

Two Typical Meteorological Year (TMY) weather files were selected and downloaded from two databases:

- Meteonorm, based on 19-year observations (2000-2019)
- JRC (Huld, Müller, and Gambardella 2012), based on 16-year observations (2005-2020)

The typical year is composed of 12 typical months of the full-time period available. Fig. 6 shows the output temperature trends of the climatic files used for the simulations.

Despite both being TMY files, the trends depicted by the variables show some differences. For instance, the temperature trends are very similar, as evidenced by an R^2 value of 0.57. However, the JRC weather file is much more flattened, lacking the peaks found in the Meteonorm weather file. Specifically, using Meteonorm as the statistical baseline, the JRC has a Mean Absolute Error (MAE) of 3.1°C and a Root Mean Square Error (RMSE) of 3.9°C.

Construction stratigraphies were modeled using a survey and documentation of the building.

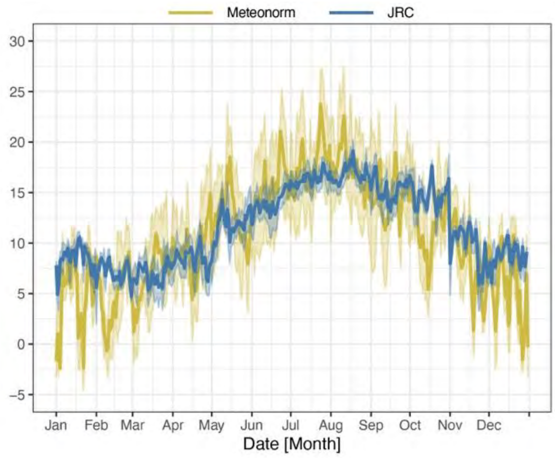

Fig. 6 – Annual evolution of daily temperatures in the TMY of Meteonorm and JRC. The solid lines represent the daily averages, while the opaque colored areas indicate the hourly minimum and maximum values observed throughout the day

It was not possible to create a personalized weather file with measured climate data and subsequently validate the model simulating the building with the Actual Meteorological Year (AMY). However, internal temperature and humidity monitoring was conducted throughout the winter season of 2021/2022. The internal temperature data obtained was compared with the simulated ones to evaluate the accuracy of the EnergyPlus model.

Internal loads and occupancy profiles were then modeled based on the actual usage of the building.

2.3 Energy/Economic Impact Evaluation

The study conducted an energy and economic comparative analysis to evaluate the new system against other suitable options for the historic building.

An ideal heating system was modeled in EnergyPlus to obtain the energy needs of the building envelope. Various scenarios for heating were then identified, and the energy consumed by the systems was calculated based on the yields of each specific case.

Various scenarios were evaluated, from the least to the most efficient, all compatible with the historic building involved (Table 1).

Scenarios H_7 and H_8 pertain to the evaluation of infrared panels. Scenario H_8 differs from the others in temperature control. As the panels operate with radiant input, the EnergyPlus simulation was configured with the system setpoint based on the operative temperature rather than the air dry-bulb temperature. This led to varying energy consumption and, consequently, differences in the results of the proposed scenario. To be realistic, scenario H_8 would require a thermostat capable of measuring the mean radiant temperature and thus calculating the operative temperature.

Table 1 – Heating scenarios evaluating for the hall refurbishment

Scena.	Generator	Source	Terminal
H_1	Traditional boiler	Natural gas	Radiators
H_2	Condensing boiler	Natural gas	Fan coil
H_3	Gas heater	Natural gas	Internal unit
H_4	HP (air-air)	Electricity	Internal unit
H_5	HP (air-water)	Electricity	Radiant pan.
H_6	Electric radiators	Electricity	Radiators
H_7	Infrared panels	Electricity	Radiant pan.
H_8	Infrared panels	Electricity	Radiant pan.

The analytical framework unfolded through a comprehensive process encompassing various stages. Firstly, EnergyPlus was employed to assess the Heating envelope needs. Subsequently, an exploration of systems efficiencies informed the determination of energy source consumption. The subsequent steps involved the integration of energy cost conversion factors for detailed financial analysis in pounds (£). Therefore, the calculation process unfolded as follows:

- EnergyPlus -> Heating envelope needs (Q_H) [kWh]
- Systems Efficiencies (distribution, production, regulation, and emission) -> energy source consumption ($Q_{s,H}$) [kWh]
  - o Primary Energy conversion factor (gas, electricity) -> Primary energy analysis ($Q_{P,H}$) [kWh]
  - o Energy cost conversion factor -> Financial analysis [£]

The primary energy conversion factors were set at 1.50 for electricity and 1.13 for natural gas (UK Department for Energy Security and Net Zero 2023).

The Energy costs for England were set at 0.27 £/kWh for electricity and 0.07 £/kWh for natural gas (Nimble Fins, 2023). Since the costs are subject to rapid variations, simulations were conducted by applying variation factors of ± 20% to evaluate the impact of potential changes over the years.

2.4 Thermal Comfort Evaluation

A thermal comfort analysis with objective measures, including real-time thermal data from strategically placed probes, was conducted to compare the new radiant panels with the previous heating systems.
A Deltaohm HD32.3 data logger was used to measure air temperature, globe temperature, air velocity, and air relative humidity at face height (1.10 m). The probes were placed in 3 locations (next to the windows, at the center of the room, and next to the internal wall) and measured 2 conditions: the heating panel switched off and on. These are single-day measurements that complement the temperature and humidity monitoring conducted throughout the winter season of 2021/2022. It was then verified that the measurement day fell within the typical winter range and did not deviate from the average conditions.
The model developed by Fanger (Fanger, 1970) was used to assess thermal comfort based on the ambient measured data, which calculates as output the Predicted Mean Vote (PMV). The inputs of the models are four environmental parameters (air temperature, mean radiant temperature, relative humidity, and air velocity), obtained with the Deltaohm probes, and two individual parameters (clothing insulation and metabolic rate). Clothing insulation data ($I_{clu,i}$) and activity (MET) were collected through a survey held in the community hall between February and March 2022, with a total of 59 participants.
All participants were asked to dress as they would normally for a workday. The clothing insulation (I_{clo}) was calculated using equation [1] (ASHRAE, 2021):

$$I_{cl} = 0.835 \cdot \sum_i I_{clu,i} + 0.161 \quad [1]$$

where $I_{clu,i}$ is the effective insulation of garment i, and I_{cl} is the insulation for the entire ensemble. The median clo value was 0.87 ± 0.23. Most participants were seated, with a MET set at 1.1. However, some were standing or moving, with a MET set at 1.9.
PMV results will be variable depending on the specific participants' I_{clo}, MET, and positions inside the room.

3. Results

Fig. 7 displays the primary energy consumption results for the building across the 8 heating scenarios, utilizing simulations performed with two different weather files in EnergyPlus. While Fig. 6 suggests that the two weather files exhibit similar trends but with varying magnitudes and significantly different daily peaks, the building envelope heating requirements were found to be 19% lower for the JRC weather file compared to those of Meteonorm. Consequently, for the additional scenario, H_8 (opera-

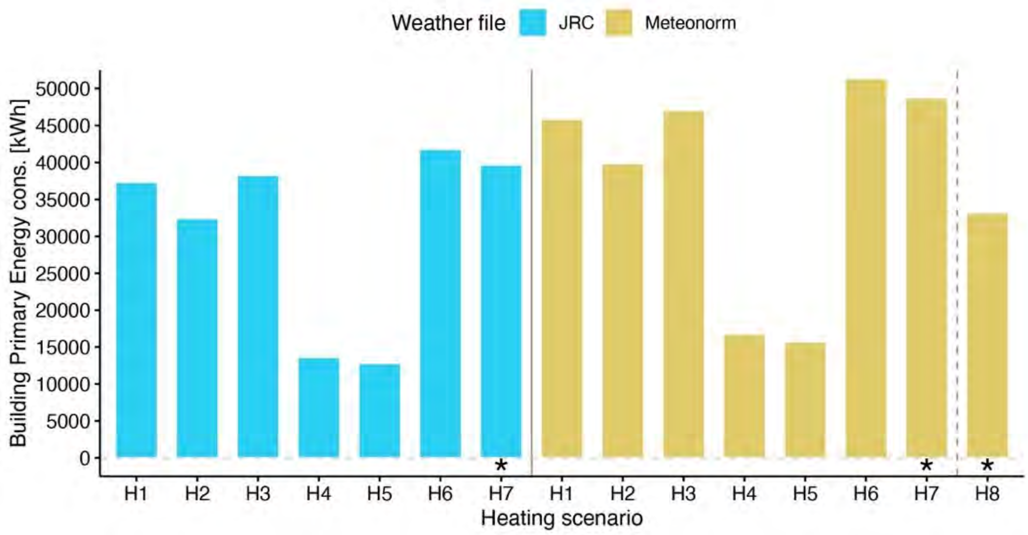

Fig. 7 – Building Primary Energy consumption according to the weather file and the Heating system scenarios. The scenarios marked with an asterisk (*) pertain to the solution installed in the Community Room, which involves the installation of infrared radiant pan els.

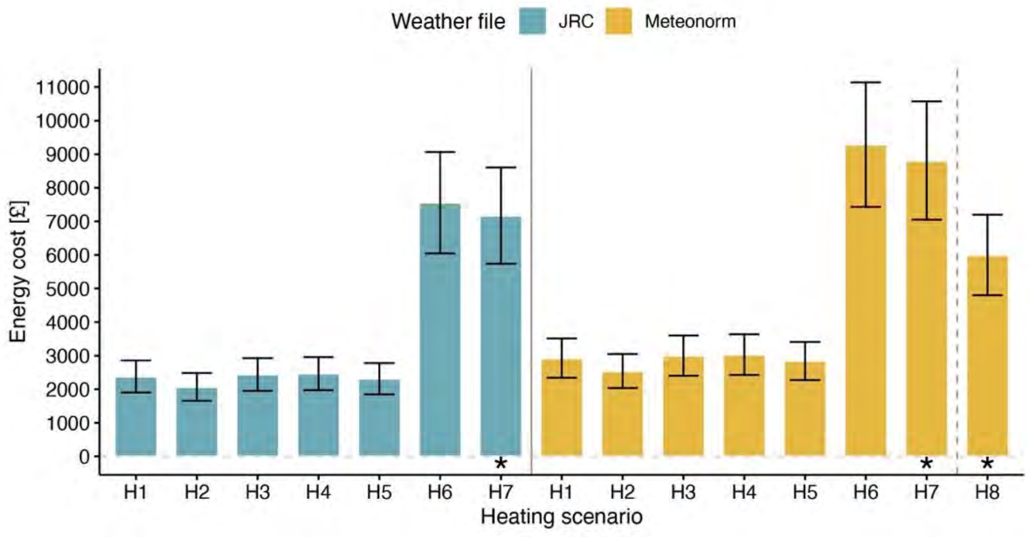

Fig. 8 – Absolute energy cost according to the weather file and the Heating system scenarios. The scenarios marked with an asterisk (*) pertain to the installation of infrared radiant panels. The interval bars show the result in the case of a ±20% change in input energy cost.

tive temperature setpoint), only the Meteonorm climatic file (more realistic and featuring more peaks) was used for simulation.

The values presented below refer to the entire building and not just the community room, thus highlighting a comprehensive solution for the entire Victorian hall.

Among the simulated heating, gas systems showed about a significant 28,000 kWh more primary energy requirement on average (with a total of 33,000/47,000 kWh) compared to electric systems with heat pumps (with a total of 12,000/16,000 kWh). Electric infrared panels, more in line with gas systems, exhibited a higher primary energy consumption of approximately 40,000/51,000 kWh per year. The simulation with an operative temperature setpoint reduced electric panels' primary consumption to 33,000 kWh annually, positioning it between heat pump and gas scenarios.

Fig. 8 shows the annual energy cost of the simulated heating scenarios. Electric radiators and infrared panels incurred higher energy costs, reaching up to 9 k£. The operative temperature setpoint lowered costs to 6 k£, still more than double compared to the first five scenarios: H_1 to H_3 (gas scenarios) all hover around 2,100 and 3,000 £, while H_4 and H_5 (heat pump) around 2,300 and 3,000 £. The higher cost was attributed to the significant price difference between electric and gas energy (0.27 vs. 0.07 £/kWh) and the efficiency of the systems.

Fig. 9 shows the PMV results divided for scenarios with heating panels switched on and off and for positions inside the room: next to the window, in the center of the room (with greater exposure to panels), and next to the internal wall. The PMV results pertain solely to the community room, unlike the previous ones presented for the entire building. This is because the panels were installed only in the community room, where measurements with the microclimatic monitoring station were feasible.

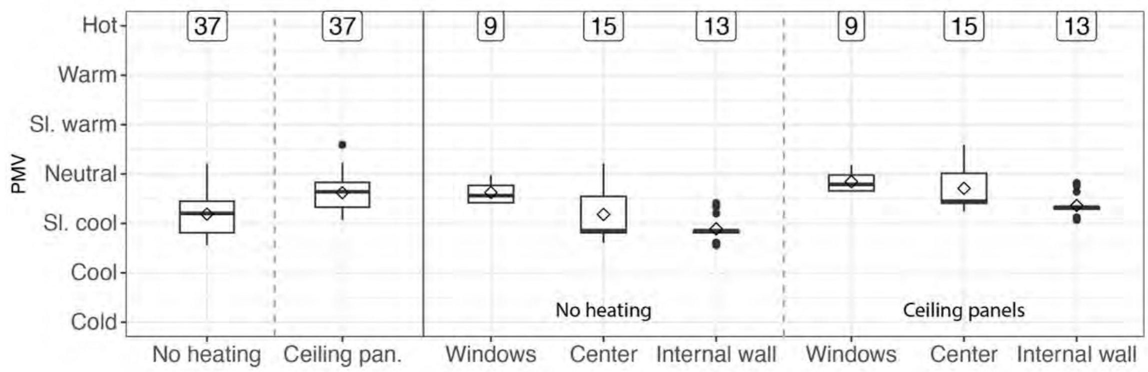

Fig. 9 – Predicted Mean Vote (PMV). Results divided by panels switched on/off and position in the room. The top box represents the number of surveys for the specific sub-category.

Overall, the situation slightly improves with the presence of the panels, but still falls within the range of a slightly cool sensation (from -0.8 ± 0.5 to -0.4 ± 0.4). Significant improvements are not noticeable even in terms of position within the room. The most neutral condition appears near the windows; indeed, the panels moved the PMV from -0.4 ± 0.2 to -0.2 ± 0.2. The contribution is greater in the center of the room, moving from -0.8 ± 0.5 to -0.3 ± 0.4.

4. Discussions

Proper planning is essential ahead of applying innovative technologies to ensure user comfort and energy savings in certain environments.

The room, primarily used for one-hour teaching activities, does not always have continuous use throughout the day, making the panels unsuitable. Radiant systems perform best when installed over large surfaces with a clear view factor to users and operating at low temperatures. However, their current position prevents optimal radiant contribution, leading to overall dissatisfaction with the thermal environment. PMV predictions indicate a slightly cool thermal sensation (-0.4 ± 0.4). The most comfortable area seems to be near the windows, likely due to the sunny winter day providing radiative benefits. While the panels offer some comfort in the room's center, where occupants are more exposed to radiation, the improvement does not significantly reach a neutral sensation.

Although PMV is not recommended for predicting thermal sensation in non-uniform environments, such as those created by Personal Comfort Systems (PCS) (Rugani et al., 2023; Cheung et al., 2019), it remains widely used in uniform settings. While the studied radiant panels are not strictly PCS, they also do not create a completely homogeneous environment. With caution regarding the obtained results and planning to analyze the detailed outputs provided by studies in real environments using questionnaires, it can be preliminarily concluded that the panels do not seem to provide the desired contribution.

The two panels installed in the community room adhere to some principles of PCS, offering localized warmth, quick activation, and easy installation. However, they deviate from fundamental PCS principles: high consumption (1 kW per panel), delayed response (panels needed to be switched on 2 hours before room use), and high operating temperatures (100 °C). Essentially, radiators were mounted on the sloped ceiling, causing heat stratification at the top of the room and insufficient radiant heat for users. Installing even larger panels in the main hall would have exacerbated these issues, increasing the distance between users and panels, and potentially amplifying consumption and energy expenditure.

Although they are the easiest solution to install, as they involve a simple connection to the power line, their environmental impact is higher than other possible scenarios that would require a more complex installation, but a winning economic return and a reduction in energy consumption.

5. Conclusions

While radiant heating ceiling panels have proven effective in building refurbishments, their application in the renovation of historic structures presents unique challenges. The research conducted within a Victorian hall in Brighton underscores the importance of a holistic approach, considering perceived thermal comfort, financial feasibility, and environmental impact.

In the specific community room, where two panels were installed, suboptimal functioning and slightly cool sensation were obtained due to installation issues and operational practices.

BES simulation revealed significant primary energy consumption gaps, with electric infrared panels showing low efficiency compared to electric heat pumps and reaching similar consumption as the gas systems. The high cost of electricity and the low efficiency of systems result in scenarios with electric radiant ceiling panels reaching energy costs up to three times higher compared to all other scenarios.

The PMV results obtained from measurements conducted with the probes show consistent findings in the slightly cool sensation scenario, without significantly improving comfort levels.

Despite the ease of installation, the cost and environmental impact of simple solutions prompt a reconsideration in favor of more complex scenarios.

LCC and LCA analyses are necessary to evaluate the entire lifecycle of these systems, particularly the installation costs, which will be assessed in future phases of this study.
The findings provide valuable guidelines for designing and installing radiant systems in large community spaces, stressing the importance of comprehensive planning for user comfort, energy savings, and environmental sustainability.

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