Reducing Energy Consumption in Urban Office Buildings with Localised Heating and Heating Set-Point Temperature Reductions

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ABSTRACT

Traditional heating, ventilation, and air-conditioning (HVAC) systems are ubiquitous in our urban environment, and rely heavily on indoor air temperature modulation to maintain thermal comfort in buildings such as offices, hotels and retail spaces. However, achieving human comfort involves multiple factors, and alternative approaches are being explored. This paper looks at one such approach: integrating localized radiant heating through a heated desk surface while lowering HVAC air temperature set points to achieve comfort with reduced energy use.

The study adopts a multi-stage modelling approach. Initially, a detailed model of a typical office was created within the ESP-r building simulation tool, incorporating an advanced human thermo-physiology model. This model was used to determine the extent to which air temperature setpoints could be lowered while maintaining occupant comfort with desk heating, under various realistic operating conditions.

Further, a set of archetype models representing diverse office types commonly found in urban settings was developed. These archetype models were then utilized to evaluate the potential for energy savings at a larger scale, extrapolating from the temperature setpoint findings of the initial model.

The findings indicate that incorporating a heated desk allows the background setpoint temperature to be lowered to 18°C without compromising thermal comfort. Minor adjustments, such as a 1°C decrease in the heating set-point temperature, can lead to significant reductions in HVAC heating demand, ranging from 10% to 20%. These reductions translate directly to proportional savings in carbon emissions. The analysis reveals that older buildings present greater potential for energy savings compared to newer constructions, highlighting the importance of factoring in building age and thermal characteristics when implementing energy-saving strategies.

Keywords: occupant themophysiology model; building simulation; desktop radiant heating; energy savings; office buildings.

INTRODUCTION

The vast majority of buildings in the United Kingdom still rely on fossil fuels for heating, hot water, and cooking. In the UK, buildings were responsible for around 30% of greenhouse gas emissions in 2019. Of these emissions, approximately 23% of the total UK emissions are the result of heating [Bias, 2021]. To meet the UK's net-zero goal by 2050, the way that buildings are heated and powered must be decarbonized. Currently, 86% of homes in Great Britain are connected to the gas grid, and around 63% of non-domestic buildings are heated by gas [Bias, *ibid*].

Energy Savings Through Setpoint Adjustments

The setpoint temperature, the target temperature that the HVAC system tries to maintain, is a critical factor influencing both occupant comfort and energy consumption in buildings. Several studies have quantified the energy-saving potential of modifying HVAC setpoint temperatures. A study by Hoyt et al. (2015) found that reducing the heating setpoint from 21.1 °C to 20 °C saved an average of 34% of required heating energy in office buildings. Similarly, they found that raising the cooling setpoint from 22.2 °C to 25 °C led to an average of 29% in cooling energy savings and 27% total HVAC energy savings in office buildings across various climates. Research by Ghahramani et al. (2016) explored the impact of daily optimal setpoint temperatures on energy consumption in office buildings across different U.S. climates. They found that selecting daily optimal setpoints could lead to energy savings ranging from 6.78% to 37.03%, depending on the building size and climate. Sánchez et al. (2017) investigated the use of monthly adaptive setpoint temperatures in residential buildings in Spain and found that it could lead to a reduction of up to 80% in heating energy demand. Monge Palma et al. (2023) conducted a large-scale simulation study in Spain, analysing the impact of extending setpoint temperatures on energy demand in residential buildings. Their findings indicated that lowering the heating set-point by 1 °C could result in an average reduction of 20% in heating demand. They also highlighted the potential for significant natural gas savings at the national level if this strategy were implemented. Date et al. (2015) focused on the dynamic response of residential buildings with different levels of thermal mass to temperature setpoint profiles. They found that replacing a conventional night-time setback temperature profile with a ramp could achieve peak demand reductions of up to 10% and 25% for one-hour and two-hour ramps, respectively. This highlights the substantial impact even small changes in setpoint temperatures can have on energy consumption.

Thermal Comfort Considerations

While energy savings are a primary concern, maintaining occupant thermal comfort is equally important. Studies have shown that adjusting setpoint temperatures can impact occupant comfort levels. For example, Daniel et al. (2019) found that reducing the room temperature to 18 °C in residential buildings during the winter season decreased thermal acceptance by 70%. Aghniaey and Lawrence (2018) reviewed the impact of increased cooling setpoint temperatures during demand response events in commercial buildings. They highlighted the potential for adverse effects on occupants, such as thermal discomfort and decreased productivity, particularly at temperatures above 28 °C. This underscores the need for careful consideration of temperature modifications to ensure occupant well-being.

Thermal perception is subjective and varies greatly among individuals due to physiological differences, personal preferences, and psychological factors [Schweiker et al., 2018]. Measurement of comfort parameters like temperature and humidity are commonplace, however, people react differently to these conditions. Understanding thermal perception requires acknowledging subjective experiences and individual variations.

Personal Comfort Systems (PCS) are a promising technology for improving individual thermal comfort while reducing building energy consumption. These systems provide localized heating or cooling to individuals, allowing for a wider range of acceptable ambient temperatures and thus reducing the energy demand of central HVAC systems.

Some examples of PCS are, Heated chairs and cushions, employing conductive heat transfer, have been shown to effectively improve thermal comfort in cold environments, particularly below 16°C [Yang et al., 2018]. However, their impact on overall thermal sensation may be limited due to the body's inherent heat production in the torso [Yang et al., 2018, Hoffmann and Boudier, 2016]. Radiant heaters, utilizing radiative heat transfer, also enhance thermal comfort in colder temperatures [He et al., 2017], but their energy consumption can be higher compared to other heating PCS [Tang et al., 2022]. Warm air blowers, based on convective heat transfer, effectively improve thermal sensation but may cause discomfort due to perceived excessive airflow and potential overheating [Tang et al., 2022]. Similarly, localized cooling devices, employing convection, radiation, and conduction, have demonstrated efficacy in improving thermal comfort in warm environments, especially above 28°C [Tang et al., 2022].

Balancing Energy Savings and Thermal Comfort

The challenge lies in striking a balance between energy savings and occupant comfort. The literature suggests that while there is significant potential for energy savings by adjusting heating setpoints, it's crucial to consider the impact on occupant comfort and ensure that temperatures remain within acceptable ranges.

To address this challenge, Ghahramani et al. (2014) proposed a knowledge-based approach that integrates personalized thermal comfort preferences with energy consumption patterns. Their approach involves learning occupant comfort profiles and using them to select setpoints that minimize energy consumption while maintaining acceptable comfort levels. This method demonstrates the potential for optimizing HVAC operations by considering both energy efficiency and occupant comfort. Using PCS to improve thermal comfort can allow for greater flexibility in setpoint temperature shifting. PCSs generally consume less energy than traditional HVAC systems, offering potential energy savings [Gao et al., 2021]. However, energy efficiency varies depending on the cooling/heating mechanism, device design, and operating conditions [Tang et al., 2022]. The economic viability of PCSs hinges on factors like initial costs, operating costs, maintenance costs, and potential energy savings [Rawal et al., 2020]. While some studies report positive economic outcomes due to improved productivity and reduced energy use, a standardized cost-benefit analysis framework is needed for comprehensive assessment [Rawal et al., 2020].

This paper investigates a novel approach to reducing heating demand and associated energy consumption in office buildings: the utilization of electric heated desks as a personalized heating system. Office buildings are important components of our urban areas, for example in Glasgow city centre, office space accounts for around 80% of the total building floor space [SPEN, 2019]. Additionally, offices tend to use significantly more electricity than the other built environment sectors [BEIS, 2023] and the energy efficiency of the office sector is considerably poorer than other sectors of the built environment [BEIS, *ibid]*. Consequently, actions to reduce heating demand in offices could have a disproportionate impact on urban energy consumption overall.

By providing localized radiant heat directly to occupants, this strategy has the potential to maintain comfort while allowing for lower ambient temperatures, thus reducing the energy required to heat the entire building. This investigation enriches the literature on the transition towards a sustainable and decarbonized urban environment.

METHOD

A group of detailed computer models has been developed on the ESP-r platform [ESRU, 2024] to simulate the performance of heated desks in an office environment. The simulation approach follows two branches: *Thermal Comfort Assessment*, this branch focuses on evaluating the human thermal comfort of the desk users using a multi-segment human thermal model and a detailed desk geometry within the office. The aim is to capture the influence of the heated desk on the human body and optimize the lowest acceptable setpoint temperature. *Energy Reduction*: this branch focuses on the energy reduction benefits resulting from the use of localized heating, which can allow for a lower heating setpoint temperature in the office environment.

Characterization of the Desk

The desk's thermal properties were evaluated using thermographic imaging to measure surface temperature on both its upper and lower surfaces. Figure 1 shows a thermographic image of the desk, while spot temperature measurements confirmed surface temperatures reaching up to 45°C at an environment of 20°C. A separate array of temperature sensors [Brüel & Kjær Indoor thermal comfort kit] was used to assess the surrounding environment and validate the thermographic readings. The desk's construction materials were provided by the manufacturer.

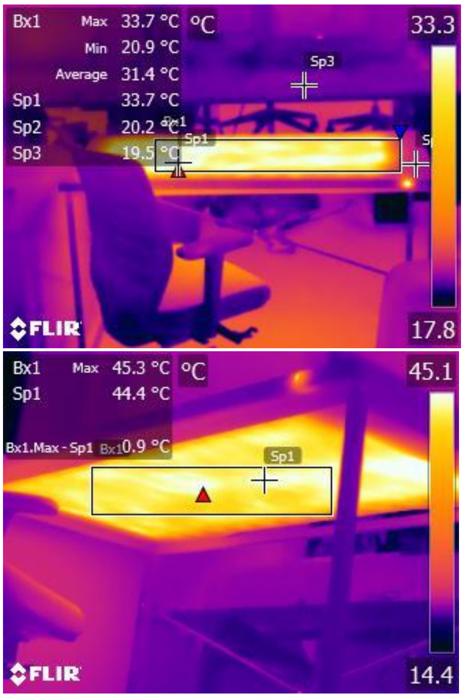

Figure 1: Thermographic image of the heated desk (a) upper surface, (b) lower surface.

The heated desk was modelled within the building simulation as a surface with four construction layers, as detailed in Table 1. The desk produces 170W of heat from its heating element when turned on. To mimic its operation, 170W of heat was injected into the inner surface of the desk model. A controller was implemented to modulate the heat injection, ensuring the element's inner temperature did not exceed a 50°C limit, which was considered the maximum safe surface temperature.

Table 1: construction layers of the heated desk.

Material	Thickness (cm)
Plywood	0.75
Insulation fibre glass	0.8
Heating element	0.2
Plywood	0.75
Total	2.5

Thermal Comfort Assessment

In this analysis, an advanced human thermo-physiology model (HTM) was used to understand thermal interactions with the environment. This model divides the human body into 25 segments, representing specific body parts, and incorporates factors like blood circulation, sweating, and shivering to predict local skin temperatures [Rida, 2020]. Thermal sensation was determined using the widely-used Berkeley model [Zhang et al., 2010].

A representative modular office model (4m wide x 5m long x 2.7m high) was created in ESP-r, featuring the heated desk positioned near a south-facing window. Several virtual mean radiant temperature (MRT) sensors were strategically placed near the desk to capture local radiant conditions. The HTM model received input parameters including air temperature, relative humidity, and the four MRT values.

The room's air temperature was adjusted to observe the impact of the heated desk on local MRT under various scenarios. Skin temperature distribution and thermal sensation were then calculated based on these temperature adjustments. Figure 2 illustrates the office room used for thermal comfort assessment, and Figure 3 depicts the arrangement of MRT sensors.

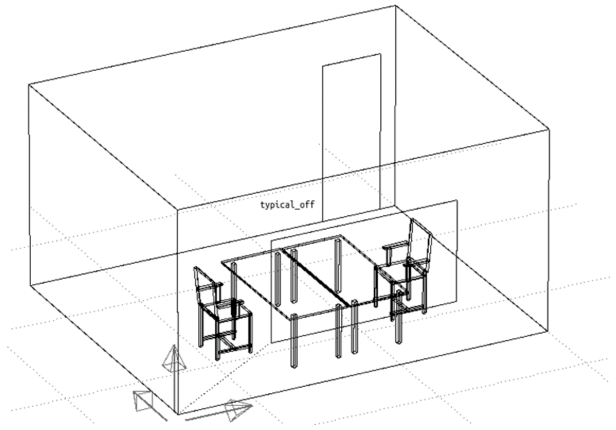

Figure 2: the modular office model with heated desk in ESP-r.

The HTM model utilized local environmental parameters as inputs, including air temperature, mean radiant temperature, relative humidity, and air velocity. These values were obtained from the building performance simulation (BPS), ensuring a uniform air temperature (in °C) depending on the model scenario, a relative humidity of 50%, and an air speed of 0.1 m/s. Additionally, constant personal factors such as clothing insulation (0.8 Clo) and metabolic rate (1.2 Met) were considered.

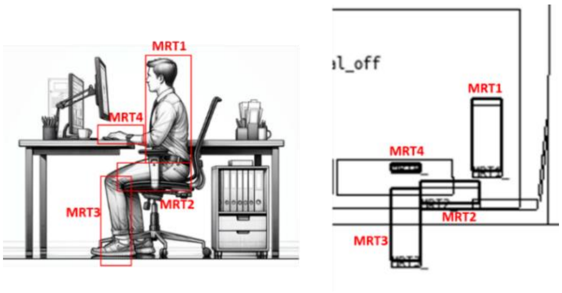

Figure 3: a schematic and in model representation of MRT sensors with regards to the heated desk.

Heating Demand Reduction

Heating demand in buildings is influenced by various factors. Building construction plays a crucial role, as well-insulated structures with energy-efficient windows and doors reduce heat loss and, consequently, the need for heating. Climate conditions like temperature, wind, and humidity also significantly impact heating requirements, with colder climates and windy conditions necessitating increased heating. Internal loads, including occupancy levels, appliance usage, and lighting, contribute to the overall heat load within a building. Furthermore, ventilation rates, though essential for maintaining indoor air quality, can raise heating demand by introducing cold outdoor air. Effectively minimizing heating demand and enhancing energy efficiency in buildings can be achieved by balancing these factors through strategies such as proper insulation, passive solar design, control of internal loads, and optimization of ventilation.

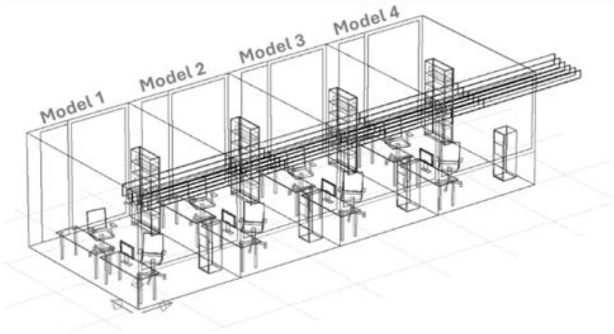

Figure 4: office model cells with different building facades.

To assess the potential energy savings achievable by using heated desks and lowering the setpoint temperature, two office building cases were simulated:

Case A: This case consists of four small office rooms with identical dimensions (3m wide x 5m long x 2.7m high), each featuring a common external facade (Figure 4). Table 2 details the construction materials used for each room (Models 1 to 4). Two air change rates (0.5 and 1.5 ACH) were simulated to highlight the potential heating demand reduction in different infiltration scenarios.

Case B: This case is a larger office building with four stories, each with a 490 m² floor area (Figure 5). The external façade has a U-value of 0.3 W/m²K, and the building features double-glazed windows with a U-value of 2.8 W/m²K.

Both Case A and Case B were simulated under five different climate conditions, using weather data from Aberdeen, London, Montreal, Rome, and Sydney. This approach provides a more comprehensive understanding of the feasibility of implementing localized heating solutions across diverse climates.

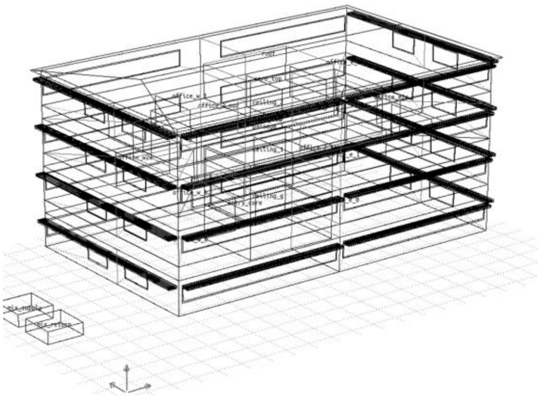

Figure 5: a graphical representation of a building with large office area.

Table 1: Thermal characteristics of the office building used for each room.

Model 1	Model 2	Model 3	Model 4
Single glazed U= **5.7W/m²K**	Double glazed U= **2.8W/m²K**	Double glazed U = **2.8W/m² K**	Triple glazed U= **0.9W/m²K**
External wall U= **0.618 W/m²K**	External wall U= **0.618 W/m²K**	External wall U= **0.2 W/m²K**	External wall U= **0.2 W/m²K**

RESULTS AND DISCUSSION

This section presents the results obtained from the various modelling cases described in the methodology, focusing on both thermal comfort and energy assessments.

Thermal Comfort Assessment

From the simulation results, the back surface of the desk reached approximately 43°C, while the top surface temperature was around 32°C. Table 2 shows the mean radiant temperature (MRT) distribution, with MRT 4 registering the highest value due to its proximity to the desk surface. MRT 2 represents the scenario where the thighs are partially covered under the desk, while MRT 3 corresponds to the mean radiant temperature at leg level.

Table 2: desk surface temperature, air temperature and local MRT temperatures.

	TDB (˚C)	MRT1 (˚C)	MRT2 (˚C)	MRT3 (˚C)	MRT4 (˚C)	T_DESK_ FRONT (˚C)	T_DESK_ BACK (˚C)
CASE 1	17.2	18.2	19.2	23.1	22.4	42.9	30.6
CASE 2	19	19.7	20.7	24.4	23.5	43.2	31.1
CASE 3	20.9	21.2	22.2	25.7	25	43.6	32.5
CASE 4	22.7	22.7	23.6	26.9	26.4	43.9	33.8

As the HTM model is dynamic, results after 30 and 60 minutes were plotted, following the transition from thermal neutrality to each thermal exposure case. Figure 6 illustrates both overall and local thermal sensation results. The results indicate that the overall thermal sensation shifts towards a colder feeling by approximately half a scale point for every 1°C reduction in the environment. Notably, in the "desk off" case, the feet, legs, and hands are among the body parts most affected by colder temperatures. Conversely, the desk significantly shifts the thermal sensations of those body parts toward neutrality, resulting in a slightly overall warmer sensation compared to the case without localized heating. The results clearly demonstrate the potential for thermal acceptability in an environment of 18°C. This finding will be used as the minimum setpoint temperature for the energy reduction analysis.

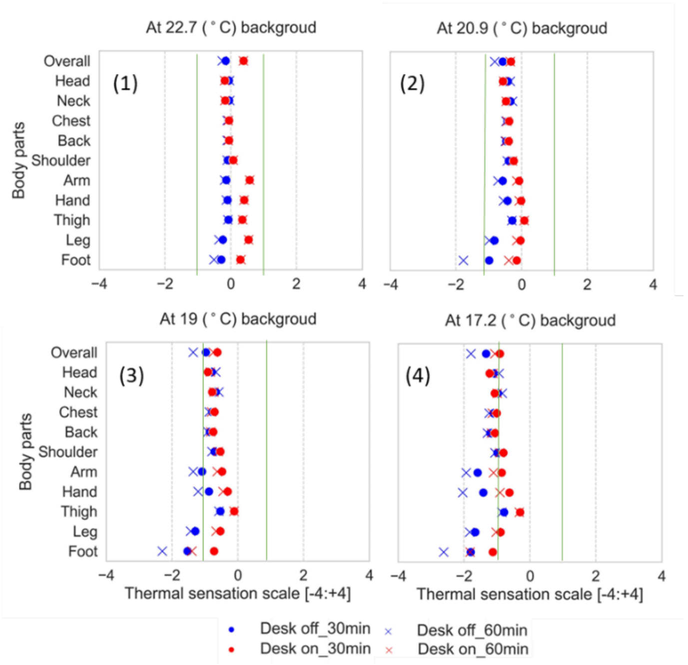

Figure 6: illustrates the local and overall thermal sensation after 30 and 60 minutes for two scenarios: with the heated desk ON and OFF, each sub plot refers to different air temperatures (1) 22.7°C, (2) 20.9°C, (3) 19°C, and (4) 17.2°C.

Reduction in Heating Demand

Case A simulations demonstrate the potential heating demand reduction for four different construction types in five different cities. Figure 7 illustrates the potential heating reduction per square meter, achieved by shifting the setpoint temperature from 21°C to 18°C, at two different infiltration rates. As expected, higher infiltration rates correlate with increased heating demand and, consequently, a greater potential reduction from the setpoint change. The results highlight the relationship between building envelope insulation and energy demand for heating. In colder climates like Montreal, the absolute annual heating demand was higher compared to Aberdeen or London. However, the energy reduction achieved by shifting the setpoint was lower in the least insulated model (Model 1) but similar or slightly higher in the better-insulated cases (Models 2-4). Warmer cities showed less energy reduction due to their lower absolute annual heating demand. Figure 8 presents the percentage reduction in heating demand when shifting the setpoint temperature by 1°C between 21°C and 18°C for both (a) Aberdeen and

(b) London. The results show that Model 4 has the highest percentage of energy reduction, despite having a lower absolute energy demand compared to the other models. This is due to the higher insulation of its building façade.

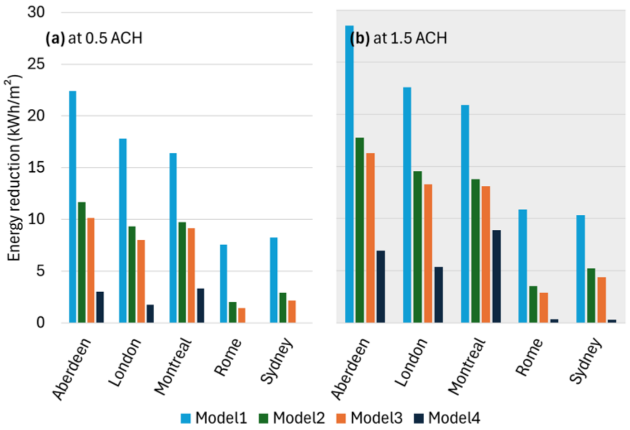

Figure 7: Energy reduction achieved by lowering the heating setpoint from 21°C to 18°C for the different scenarios.

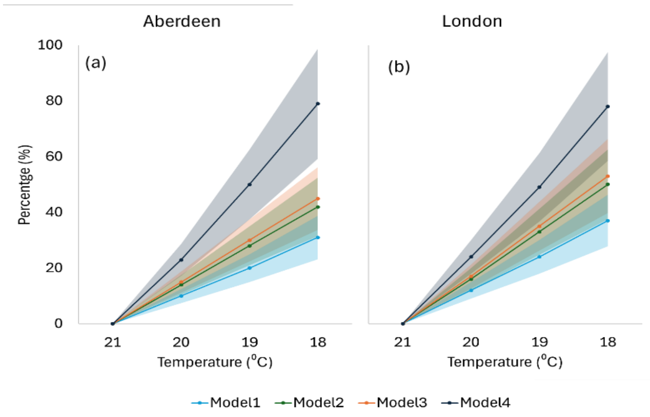

Figure 8: Percentage of energy reduction achieved when changing the set point, relative to a base case of 21°C (a) Aberdeen, (b) London.

Case B simulation demonstrates the potential reduction in heating demand achieved by shifting the heating setpoint temperature in a building with large office spaces. Figure 9 illustrates the changes in annual heating demand at different setpoint temperatures. Notably, shifting the setpoint temperature from 21°C to 18°C results in a reduction of approximately 27% in heating demand for both Aberdeen and London, and a reduction of 16% for Montreal.

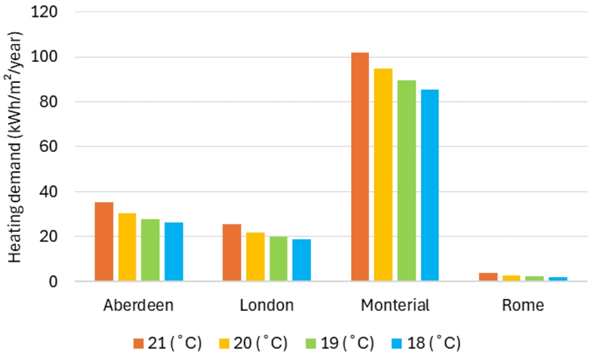

Figure 9: Total annual heating demand (kWh/m²) in different cities at varying setpoint temperatures.

CONCLUSIONS

This research targets a key energy consumer in our urban environment: office buildings. Specifically, the work evaluated the potential for a personalized radiant heating system (heated desk) to reduce air temperature set points and has demonstrated significant potential for enhancing thermal comfort while simultaneously reducing energy consumption in office environments. Through building simulations using ESP-r, the targeted heating approach was found to maintain acceptable thermal sensation for individuals engaged in office work even at a reduced background temperature of 18°C, aligning with personalized comfort preferences and reducing the need to heat the entire space uniformly.

Energy assessments conducted across diverse office buildings and under varying weather conditions further highlighted the substantial energy-saving potential of this personalized approach. Estimated savings of 5-15% per 1°C reduction in background temperature, and up to 30-50% when transitioning from a standard 21°C to 18°C, emphasize the significant contribution that personalized heating systems can make to energy efficiency efforts in the building sector. These findings are particularly relevant in regions like the UK, where heating demands are substantial, and transitioning to lower background temperatures can yield substantial energy and cost savings.

The findings of this study highlight the potential of personalized heating solutions to not only improve occupant comfort but also contribute significantly to energy efficiency efforts in the building sector.

FUTURE WORK

Investigating the long-term effects of localised heating systems on occupant health, comfort, and productivity in real-world settings, and scaling-up to investigate the potential for the technology at city and national scales.

Exploring the integration of such devices with building automation systems and smart controls to optimize energy efficiency and personalized comfort.

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