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How crucial are Personalised Environmental Control Systems (PECS) in newly constructed offices? A comfort-energy case study perspective

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Abstract

This study investigates the potential benefits of integrating Personalised Environmental Control Systems (PECS) in newly constructed office spaces, focusing on energy efficiency and thermal comfort. Two modern offices in Lucca and Massa, Italy, were analyzed through a combination of on-site data sampling and dynamic Building Energy Simulations (BES). Despite being equipped with contemporary HVAC systems, these offices often fall short of achieving optimal comfort and energy consumption levels, particularly under varying occupancy conditions. The findings demonstrate that PECS could significantly enhance energy efficiency by allowing for localized environmental control, especially in under-occupied offices. Implementing PECS in the studied offices could lead to energy savings of up to 85% in both winter and summer for Lucca, and up to 85% in winter and 42% in summer for Massa. The effectiveness of PECS is particularly evident in environments with extensive glass surfaces, such as the Massa office, where traditional HVAC systems struggle to maintain comfort without incurring high energy costs. Additionally, the study reveals that even when all occupants use PECS simultaneously, the impact on overall energy consumption remains minimal, preserving the efficiency gains. These findings highlight the importance of integrating PECS in modern office design as a forward-thinking approach to achieving personalized comfort and substantial energy savings.

Keywords

Personalised Environmental Control System, PECS energy efficiency, Thermal comfort, Building energy saving, Thermal comfort energy assessment

Introduction

The microclimatic conditions of living and working spaces play a crucial role in shaping the activities and well-being of their occupants (Frontczak et al., 2012). In particular, the relationship between environmental characteristics and individual perception is vital for psychophysical well-being. Thermal comfort, as the most influential Indoor Environmental Quality (IEQ) factor, not only shapes how a space is perceived but also significantly impacts energy consumption (Bluyssen, 2020).

In workplaces, designing thermally comfortable environments is essential, as it not only enhances long-term well-being (Sharpe and Mobasher Fard, 2022) and boosts productivity

(Antoniadou and Papadopoulos, 2017; Greenberger et al., 1989; Kaushik et al., 2020; Kawakubo et al., 2023; Kim et al., 2019; Sanaz et al., 2015) but also plays a key role in overall satisfaction or dissatisfaction within a space (Frontczak et al., 2012; Huizenga et al., 2006). This proactive approach helps prevent potential discomfort-related issues, with corresponding impacts on the health of occupants, as well as phenomena such as absenteeism, low productivity, and Sick Building Syndrome (SBS) (Mendes and Teixeira, 2014).

In the modern office landscape, a significant shift has occurred, influenced by the rise of remote work, often referred to as "smart working," and changing preferences in workplace environments. The traditional model of densely populated offices has been replaced by a more flexible and dynamic approach, with remote work becoming increasingly common. This transition was accelerated by the SARS-CoV-2 pandemic, which underscored the need for this new approach. As a result, the reduction in on-site personnel has exposed the inefficiencies of conditioning entire buildings for a limited number of occupants, leading to unnecessary energy waste and high energy consumption (Jiang et al., 2021).

In this context, numerous researchers have developed models and systems designed to meet individual needs, such as Personalised Environmental Control Systems (PECS). They are defined as systems that heat and cool individuals without affecting the environments of surrounding occupants (Arens et al., 2006). PECS could provide control of local worker desks while the primary HVAC system works with a wider setpoint range, drastically reducing energy consumption (Rugani et al., 2021). With the current energy crisis and consequent increase in energy prices (Hannon and Brown, 2022), PECS can indeed represent a valuable alternative for many businesses and households. Despite these advantages, the technological solutions for the implementation of PECS are still being researched, also to identify the most effective.

As offices adapt to the demands of modern work practices, integrating PECS into thermal management strategies presents a prudent and forward-thinking approach, aligning with broader goals of energy efficiency and personalized well-being. This study investigates the thermal and energy performance of two modern offices featuring large open spaces, focusing on usage patterns, thermal comfort, HVAC system management, and energy consumption. By examining the specific needs of these offices, the research aims to assess the feasibility and potential benefits of implementing PECS in contemporary office environments.

Method

This study aims to assess the comfort and energy consumption of two recently constructed offices with large open spaces. A novel methodology is proposed that combines on-site data sampling to determine actual thermal comfort with dynamic Building Energy Simulations (BES) to analyze energy consumption patterns. The research focuses on two office buildings in Lucca and Massa, Tuscany, Italy. The initial phase involved analyzing and surveying the buildings, including floor plans, internal loads, and usage profiles. Environmental parameters were monitored over six days in 2022 – two winter days and one summer day for each office. The collected data was then used to develop and calibrate BES models, reflecting the actual internal thermal conditions of the buildings.

The office in Lucca is located on the ground floor, within a two-story complex entirely designated for commercial use. The construction of the building dates back approximately to the early 2000s and is characterized by a reinforced concrete frame structure with external brick cladding. Figure 1 shows a frontal view and a picture inside the office.

Figure 1: Pictures of the office in Lucca from the frontal street (Google, n.d.) and inside the office

The building in Massa is part of an L-shaped structure facing two main roads. The studied office is situated on the second floor of the commercial complex, which spans four above-ground levels. The recently constructed directional center, built between 2000 and 2004, features a reinforced concrete frame structure with beams and columns allowing for a height of four above-ground floors. The entire external envelope is fully glazed with reflective surfaces providing moderate solar protection and an aesthetically pleasing appearance. Figure 2 shows a frontal view and a picture inside the office.

Figure 2: Pictures of the office in Massa from the frontal street and inside the office

The EnergyPlus simulation encompassed only the studied offices (Figure 3). The influence of boundary conditions on the model, including those from neighboring inhabited spaces, was considered by setting appropriate boundary coefficients in the simulation.

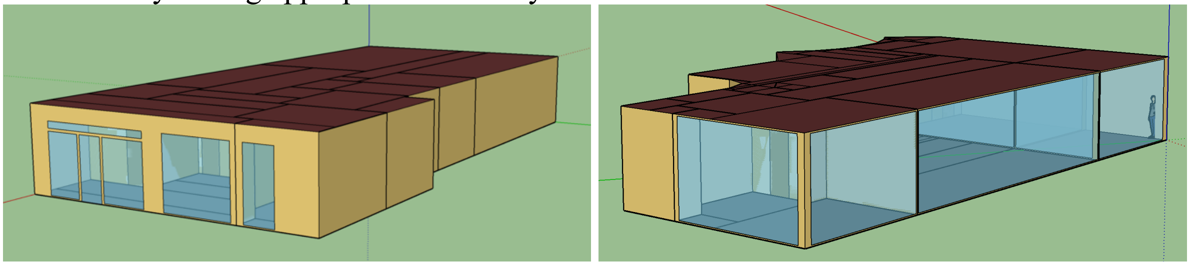

Figure 3: 3D pictures of the EnergyPlus thermal model, office in Lucca (left) and in Massa (right)

Construction stratigraphies were modeled using survey and documentation of the building, and subsequent measurements of internal thermal parameters validated the model. Internal loads and occupancy profiles were then modeled based on the actual usage of the building. Four scenarios of HVAC setpoints were simulated, as outlined in Table 1.

The actual scenario is the way the building is run by the operators, as documented during the measurement campaign. Scenario 3 demonstrates the energy savings achieved by operating the building with less comfortable setpoints, while Scenario 4 shows the potential energy savings when using local PECS, taking into account their energy consumption. Both buildings are serviced by a heat pump system with fan coil units. Two PECS were selected – one for winter and one for summer – representative of a broad market range and already tested for their contribution to thermal comfort (Rawal et al., 2020). For heating, a 40W PECS consisting of a radiant surface on the desk was used, while for cooling, a 10W fan was selected.

Table 1: HVAC setpoint scenarios

	1. Standard	**2. Actual**	**3. Less conditioned**	**4. Less cond. + PECS**
Heating (H)	21 °C	*Various*	17 °C	17 °C
Cooling (C)	26 °C	*Various*	30 °C	30 °C

This study simulated four office occupancy levels: 25%, 50%, 75%, and 100%. In scenarios with PECS, occupants activate their PECS based on temperature conditions. The goal is to analyze PECS benefits, considering occupant loads and the additional electrical load from PECS. Maximum office capacities were 11 for Lucca and 8 for Massa. EnergyPlus simulations account for heat generated by occupants and the activation of personal systems, triggered by both temperature conditions and occupancy, with the "Energy Management System" (EMS) linking PECS activation to indoor temperature.

The offices were simulated using two different meteorological files, a Typical Meteorological year TMY and an Actual Meteorological Year (AMY) of 2022. The TMY weather file was chosen and downloaded from the Meteonorm database, statistically based on 19-year observations (2000-2019). The full-year 2022 weather data of the AMY type were acquired from the NASA Langley Research Center (LaRC) POWER Project.

The analytical framework unfolded through a comprehensive process encompassing various stages. Firstly, EnergyPlus was employed to assess the heating and cooling envelope needs. Subsequently, an exploration of systems efficiencies informed the determination of energy source needs. The subsequent steps involved the integration of energy cost conversion factors for detailed financial analysis in euros [€]. The calculation process unfolded as follows:

- EnergyPlus → Heating/Cooling envelope needs (Q_H , Q_C) [kWh];
- Systems Efficiencies (distribution, production, regulation, and emission) → energy source needs ($Q_{s,H}$, $Q_{s,C}$);
    - Energy cost conversion factor → Financial analysis [€]

In each scenario, the cumulative electricity consumption of the PECS was added, calculated based on their actual usage throughout the year, obtained by the EnergyPlus EMS.

The energy cost was set at 0.20 €/kWh (ARERA, 2023), but it is subject to rapid fluctuations. To assess the impact of potential changes, simulations applied cost variation factors of ±20%.

For the thermal comfort measures, four positions were selected in each office. In each one, probes were placed simulating seated office workers. Measures were conducted during the morning and the afternoon, for two winter days (February) and one summer day (July).

The time needed to reach the designed steady-state temperatures was measured, and the following data were recorded every 30 seconds: air temperature at face height (1.10 m), torso height (0.60 m), and ankle height (0.10 m); floor temperature; air velocity; air humidity; radiant asymmetry. The Deltaohm HD32.3 data logger was used, with a thermo-hygrometer, a globe thermometer, and an omnidirectional hot wire anemometer. The LSI M-Log was used with a thermometer, a surface thermometer, and a net radiometer.

The rational 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). Furthermore, we investigated whether desks caused discomfort due to vertical air temperature differences between head and ankles (ASHRAE, 2021; ISO, 2021). The comfortable vertical temperature gradient between head and feet limit is prescribed as 3°C/m by ASHRAE 55 (ASHRAE, 2023) and ISO 7730 (ISO 7730:2005, 2005), though Liu et al.

found that it changes with thermal sensation votes and could be increased to 5°C/m when the subject is thermally neutral (Liu et al., 2020).

Finally, radiant asymmetry was evaluated. Gao et al. found that exposure duration to radiant asymmetry affected the subject's thermal responses (Gao et al., 2023). The study examined the relationships between the percentage of dissatisfied subjects and Δt_{pr} under the tested conditions. The threshold of 5% discomfort corresponds to Δt_{pr} values of 4.4 °C (180 min) and 1.8 °C (60 min and 120 min) for the warm wall. In the case of the cool wall, it was 1.8 °C at 60 min, but the percentage exceeded 5% at 120 min and 180 min, even in a uniform environment.

Results

The results will be split between thermal comfort and energy consumption analysis.

PMV was calculated using physical parameters from summer and winter measurement campaigns. Figure 4 displays these results as box plots for each office and season.

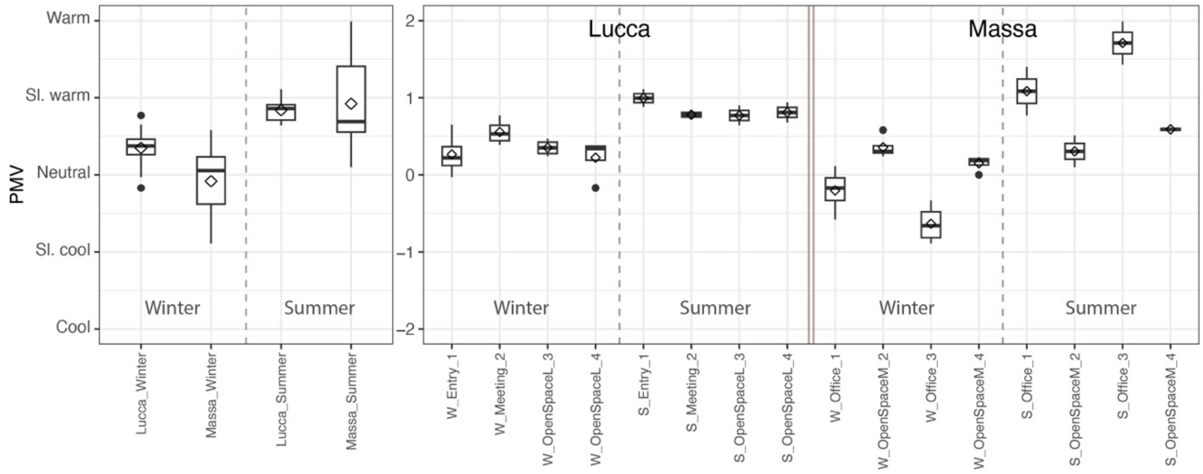

Figure 4: PMV values for the two offices: the left side shows the data by season, while the right side presents the measurements by the four probe positions for winter (W) and summer (S).

The Massa office shows wider box plots compared to Lucca. In Lucca, the PMV values have standard deviations of 0.25 in winter and 0.15 in summer, while in Massa, they are 0.45 and 0.60, respectively. This variation is due to the HVAC system's operation in Massa, where two rooms had their systems turned off (1 and 3), unlike Lucca, where all fan coils ran simultaneously. In winter, Lucca's office meets ISO 7730 category B, slightly below Massa, which falls into category A. However, in summer, both offices exceed category C, indicating uncomfortably warm conditions. These results, especially during the summer, demonstrate that the Massa building relies heavily on the system to ensure comfortable conditions, resulting in very high energy consumption.

Localized discomfort was assessed by examining vertical temperature differences and radiant asymmetry, measured in both parallel and orthogonal directions at each position.

No significant discomfort from radiant asymmetries was detected, with most results showing less than 2°C of asymmetry. The average Percentage Dissatisfied (PD) was 0.2 in winter (cold wall) and zero in summer (warm wall), meeting ISO 7730 (ISO 7730:2005, 2005) category A standards. Summer results, particularly for the glass-windowed office in Massa, indicate that the reflective films effectively reduce infrared radiation that could cause discomfort. In contrast, the office in Lucca showed slightly higher asymmetry near non-reflective windows (positions 1 and 5), though not enough to cause discomfort.

Average vertical temperature differences (Figure 5) were 2°C (PD 1.8) in winter and 0.8°C (PD 0.6) in summer. Lucca shows a more stable environment, consistently below 2.5°C, meeting

ISO 7730 category A and ASHRAE Standard 55's 3°C/m limit (ASHRAE, 2023). Massa, however, showed more variation. Positions 1 and 3, with the HVAC system off, had no vertical stratification, while positions 2 and 4, especially in winter, exhibited discomfort. Ceiling-mounted fan coils in Massa, running at full capacity, led to vertical asymmetry up to 4°C, with a PD of 8.1 (category C (ISO 7730:2005, 2005)). In summer, this effect was less pronounced as cool air from ceiling systems stayed lower, avoiding stratification at user height.

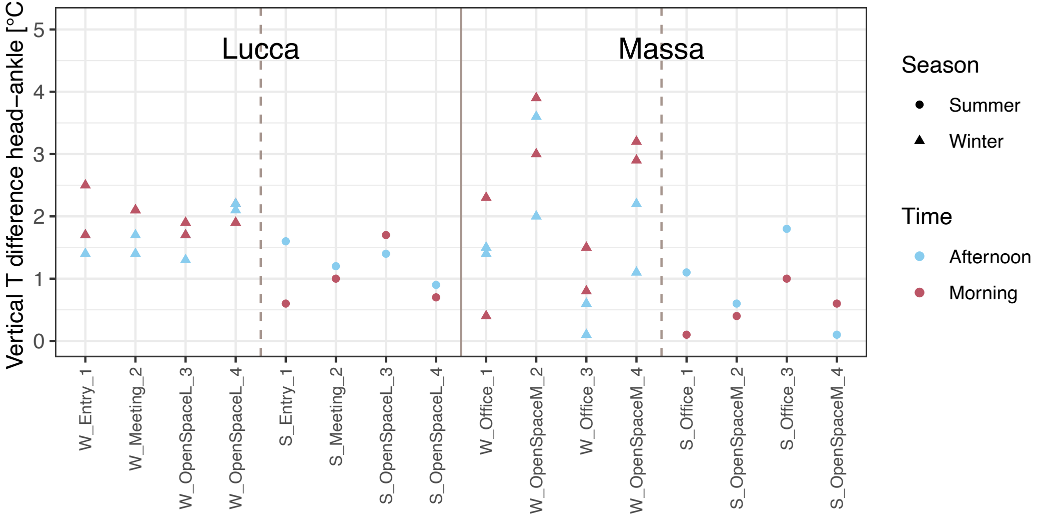

Figure 5: Vertical temperature differences for both offices of Lucca and Massa, divided for the four probes positions and for the winter (W) and summer (S) measurements.

Energy and cost results for both offices are presented for heating and cooling, based on the 2022 AMY and typical TMY weather files. Figure 6 shows the building's energy needs, Figure 7 shows the energy cost, and Figure 8 shows the percentage reduction in scenario 4 (less conditioned with PECS) compared to the corresponding scenario 1 (standard setpoint).

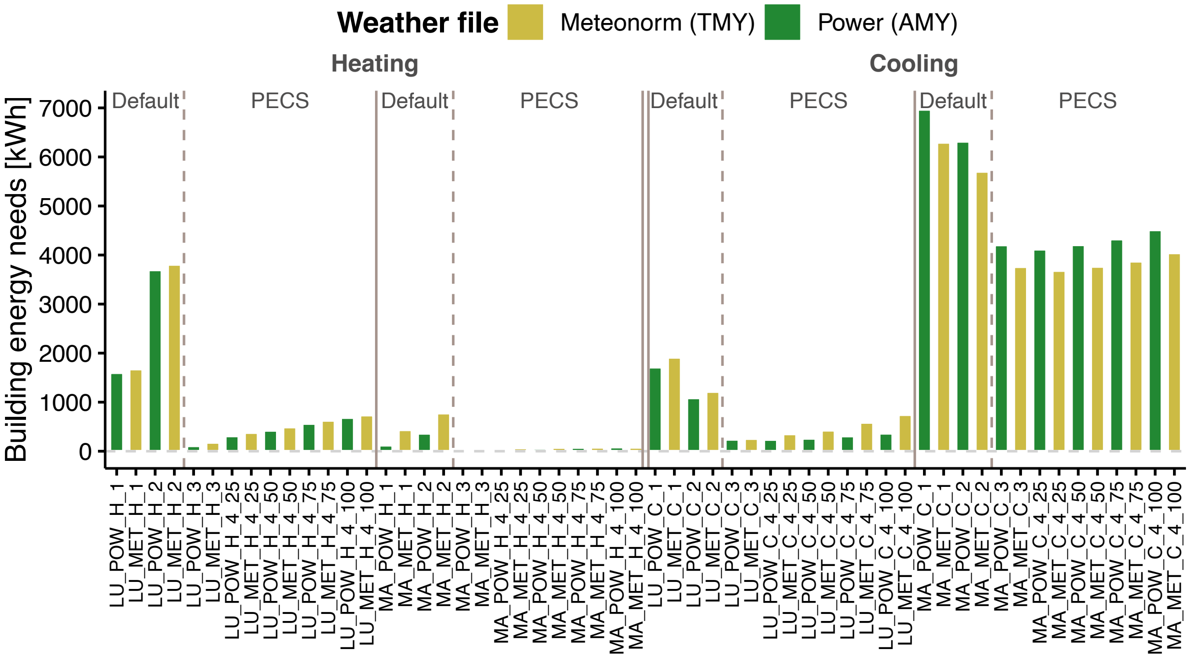

Figure 6: Building energy needs according to the weather file and the Heating (H) and cooling (C) system scenarios, divided for the office in Lucca-LU and Massa-MA. 1 is the standard setpoint scenario, 2 is the actual scenario, 3 is the less conditioned scenario, and 4 is the less conditioned scenario with PECS.

The results from the two weather files show minor deviations in winter consumption and more noticeable differences in summer, though within reasonable limits. The 2022 climate conditions closely matched those in the typical Meteonorm weather file.

The Lucca office shows higher heating consumption, with winter usage reaching up to 3,700 kWh compared to 1,600 kWh under the standard 21°C setpoint. In summer, less favorable conditions result in a consumption of 1,100 kWh versus the expected 1,700 kWh.

In Massa, large windows help reduce heating costs through solar gains. However, summer cooling requires significant energy, with current consumption at 5,700 kWh (with fan coils in offices 1 and 3 turned off), compared to the projected 6,300 kWh for cooling to 26°C.

Less conditioned scenarios (3), would nearly eliminate both winter (about 170 kWh in Lucca and 50 kWh in Massa) and summer (about 250 kWh in Lucca and 3,800 kWh in Massa) consumption. In scenario 4, where the presence of PECS is accounted for based on the number of users, energy consumption does not significantly increase compared to scenario 3 and remains well below that of scenarios 1 and 2.

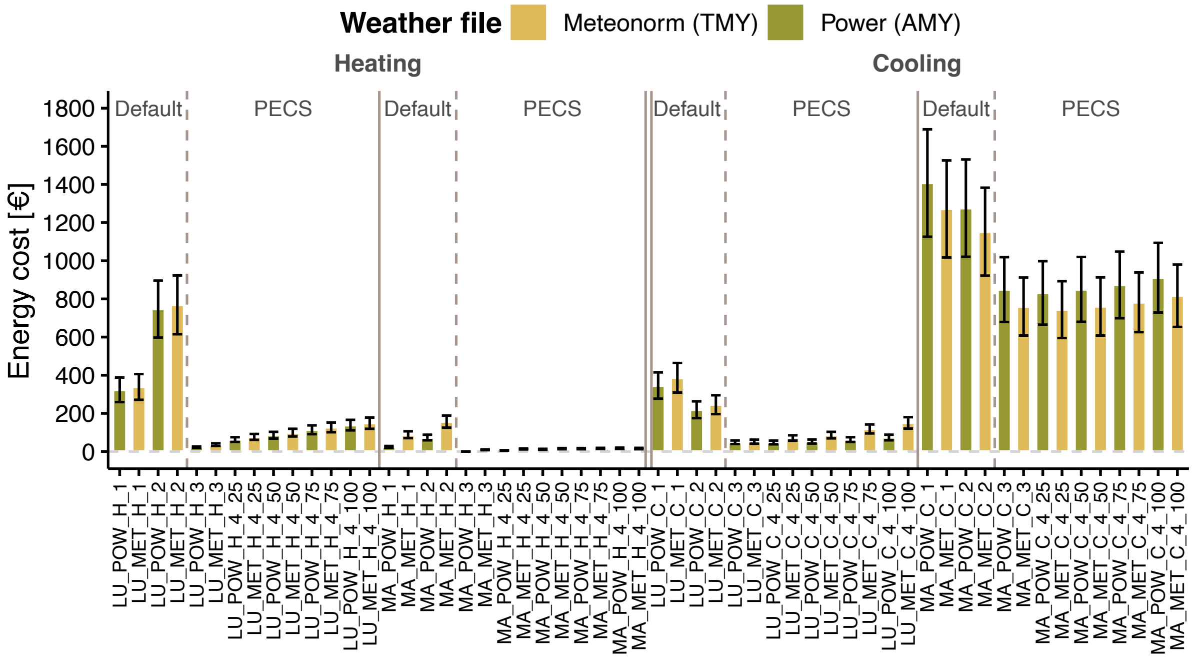

Figure 7: Absolut energy cost according to the weather file and the Heating (H) and cooling (C) system scenarios, divided for the office in Lucca-LU and Massa-MA. 1 is the standard setpoint scenario, 2 is the actual scenario, 3 is the less conditioned scenario, and 4 is the less conditioned scenario with PECS.

Since cost values are based on system energy consumption, the comparative analysis between scenarios remains consistent. In Lucca, current heating costs are around €800 and cooling costs about €250. In Massa, heating costs are approximately €200 and cooling costs €1,300. The less conditioned scenario would reduce Massa's cooling costs to €760 and Lucca's heating costs to €50. The addition of PECS consumption does not significantly alter the overall situation. In Lucca, if all PECS were used, winter and summer costs would peak at €150. In Massa, the costs would be €20 for winter and €900 for summer.

Discussions

The measurements from the case study offices provide insights into the current state of recently constructed offices in terms of occupancy, thermal comfort, and energy consumption. Both offices feature open spaces that are fully climatized but often underutilized. During the measurement phases, both offices were under-occupied, particularly the Massa office, which had only 1-2 people present, with others working remotely. While winter comfort conditions generally fall within ISO 7730 category B, summer conditions exceed category C, with a PMV reaching 1. These conditions are maintained using modern heat pump HVAC systems, with floor-mounted fan coils in Lucca and ceiling-mounted ones in Massa. However, when the fan coils, particularly in Massa, were operated at full capacity, the PMV improved but led to vertical temperature stratification and high energy consumption.

Despite being newer and better designed than older offices, which typically have poorer insulation and less efficient heating and cooling systems, these offices still do not achieve optimal comfort and energy efficiency. Introducing PECS could enhance local comfort for individuals while reducing overall space conditioning, leading to significant energy savings.

Figure 8 shows the percentage reductions in energy consumption for scenarios 4, where PECS are used, compared to scenario 1, which utilizes standard setpoints for the main HVAC system.

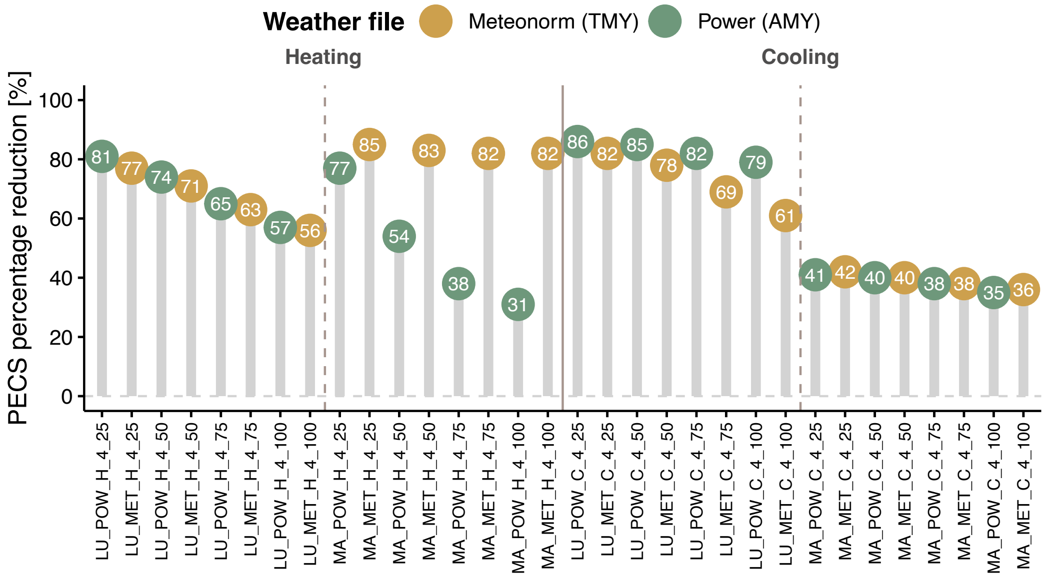

Figure 8: Percentage reduction in scenario 4 (less conditioned with PECS) compared to the corresponding scenario 1 (standard setpoint), according to the weather file and the Heating (H) and cooling (C) system scenarios, divided for the office in Lucca-LU and Massa-MA.

The results indicate savings of up to 80-85% in both summer and winter for the Lucca office, and up to 85% in winter and 42% in summer for the Massa office. The lower summer savings in Massa are due to the higher energy consumption shown in Figure 6, largely attributed to the office's extensive glass surfaces. These glass surfaces also contribute to significant differences between the two weather files in winter, linked to varying irradiation profiles. The differing percentages are also influenced by the very low absolute consumption, where small variations can lead to large percentage differences.

The two offices, which can accommodate up to 11 people in Lucca and 8 in Massa, do not show significant drops in performance even if all occupants simultaneously use the studied PECS (40W for heating and 10W for cooling). The maximum percentage drop, from 25% to 100% occupancy, is 24 percentage points in Lucca during winter. In Massa, the winter AMY scenario shows a 46-point reduction, though this is mainly due to the low absolute consumption values.

The observations from this study, focused on modern offices, suggest that even greater improvements could be achieved in older buildings with lower performance levels in terms of both comfort and energy savings. This conclusion aligns with a recent study by Kent et al. on a zero-energy office building (Kent et al., 2023).

Conclusions

This study highlights the potential benefits of integrating Personalised Environmental Control Systems (PECS) in newly constructed office spaces, particularly in terms of energy efficiency and thermal comfort. Our analysis of two modern offices in Lucca and Massa reveals that while these spaces are designed with contemporary HVAC systems, they still fall short of achieving optimal comfort and energy consumption levels, especially under varying occupancy conditions.

PECS offer a promising solution by allowing for localized environmental control, which can significantly reduce the energy demand for heating and cooling, especially in under-occupied offices. The data indicate that implementing PECS could result in energy savings of up to 85% in winter and summer for Lucca and up to 85% in winter and 42% in summer for Massa. These savings are particularly pronounced in environments with extensive glass surfaces, such as the Massa office, where traditional HVAC systems struggle to maintain comfort without incurring high energy costs. Moreover, the study shows that even when all occupants utilize PECS simultaneously, the impact on overall energy consumption remains minimal, ensuring that the efficiency gains are not compromised. The results suggest that PECS could be particularly beneficial also in older buildings with less efficient insulation and HVAC systems, potentially offering even greater improvements in energy savings and occupant comfort.

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