Cost and Energy Efficiency Analysis of HVAC Control Strategies for Thermal Comfort and Indoor Air Quality Management in Buildings in the Framework of EN 16798 Standard: A Case Study

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Abstract: - The decarbonization of the building stock, driven by European energy efficiency policies, has resulted in increasingly energy-efficient and tightly sealed buildings with minimal exchange of energy and matter with the external environment. This trend raises new challenges for designers, particularly regarding indoor air quality and thermal comfort. To address these concerns, EN 16798 provides guidelines on maintaining thermal comfort and adequate air exchange rates to ensure healthy and comfortable indoor conditions. This study analyzes the energy and economic impacts of applying EN 16798 prescriptions. Results indicate that thermal energy demands, particularly for cooling and dehumidification, can exceed those of the baseline scenario. However, total electricity consumption and associated costs remain comparable to the reference case, while simultaneously improving indoor conditions for occupants.

Key-Words: - dynamic analysis, thermal comfort, control strategies, CO_2, IAQ, mechanical ventilation.

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1 Introduction

In recent years, following the latest European directives on building energy efficiency (EPBD), there has been a pervasive focus on improving the energy efficiency of new buildings, [1], [2].

Newly constructed buildings, also influenced by European directives, are increasingly designed to be highly sealed to minimize thermal exchange and the exchange of matter—namely air and water vapor—between indoor and outdoor environments. However, this design approach can lead to health-related issues, particularly concerning indoor air quality and the potential formation of mold. These problems are especially evident during the winter season when excessive indoor humidity and insufficient air exchange become critical concerns, [3], [4]. A viable solution, applicable to both residential and public buildings, is the adoption of controlled mechanical ventilation (CMV) systems. These systems ensure adequate air exchange, thereby improving indoor air quality (IAQ) and limiting the concentration of CO_2 and volatile organic compounds (VOCs). VOCs, in particular, are considered pollutants that can pose risks to human health, [5], [6], [7], [8].

Heat pumps, particularly vapor compression systems, both aerothermal and geothermal, play a pivotal role in the energy transition and decarbonization processes, [9], [10], [11], [12]. By utilizing electricity from renewable sources, these systems can transfer significant amounts of thermal energy between thermal reservoirs at different temperatures, contributing to enhanced building energy efficiency, [13], [14].

In addition to addressing IAQ and energy efficiency in the management of public buildings, [15], [16], [17], [18], advanced technologies such as heat pumps must also account for indoor thermal comfort. Thermal comfort has been defined through two key indices: the Predicted Mean Vote (PMV) and the Percentage of People Dissatisfied (PPD), the latter one, a function of the PMV, [19]. The PMV specifically quantifies the perceived comfort level of occupants based on six parameters: air temperature, mean radiant temperature, air velocity, relative humidity, clothing insulation, and metabolic activity (with an additional parameter accounting for individual workload), [19], [20].

To establish optimal indoor conditions for thermal comfort, air quality, and lighting, the EN 16798:2019 standard on ventilation for buildings provides specific guidelines. These prescriptions aim to ensure occupant well-being and prevent the occurrence of Sick Building Syndrome (SBS), [3], [21], [22].

The aim of this study is to analyze the energy and economic performance of an HVAC system serving a residential building located in Milan, Northern Italy. The analysis involves varying the control settings for indoor thermal comfort and ventilation rates to manage indoor air quality. This allows for a comparison between a baseline scenario, representing typical HVAC system usage in Italy, and the requirements outlined in the EN 16798:2019 standard.

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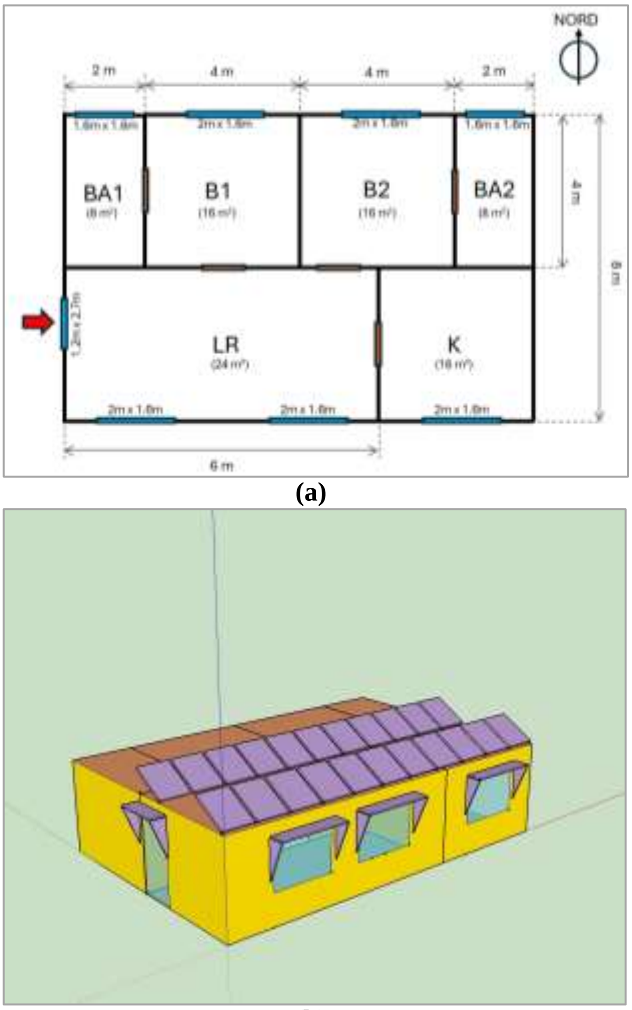
2 Materials and Methods

The analysis conducted is a dynamic simulation performed using TRNSYS software [23], coupled with a subsequent economic assessment. The case study involves evaluating the electricity consumption and thermal energy demand for heating, cooling, and domestic hot water (DHW) production in a highly energy-efficient building. The system features a multifunctional heat pump integrated with a renewable energy setup, including photovoltaic panels and a battery storage system. A total of nine annual simulations were conducted, varying the control strategies for indoor comfort management and CO_2 regulation. The following sections detail the characteristics of the building and the system, the standard's requirements, and the foundational assumptions for the economic analysis.

2.1 Building and HVAC System

The residential building analyzed is located in Milan and has a usable floor area of 96 m², divided into six thermal zones, each with a height of 3 meters: two bathrooms (BA1 and BA2), two bedrooms (B1 and B2), a kitchen (K), and a living room (LR). The floor plan, thermal zone areas, and 3D view of the building, modeled using Google SketchUp [24], are shown in Figure 1(a) and Figure (b), respectively. As previously mentioned, the building is highly energy-efficient, with an infiltration rate of 0.1 h^{-1}, and its opaque and transparent envelope components feature very low thermal transmittances (Table 1).



(a)

(b)

Fig. 1: Layout of the residential building (a) and 3D view as modelized in SketchUp [25] (b)

Table 1. Transmittance of the building's envelope components

Envelope component	***U-value*** W/(K·m²)
Windows (triple-glazed)	0.68
External walls	0.20
Internal walls	0.6
Roof	0.32
Floor	0.18

The building is assumed to be occupied by a family of four. Internal gains are attributed to the occupants and the use of appliances. Specifically, the sensible internal gains from occupants are 60 W per person, following IEA Task 44 [9], [25], while those from appliances are estimated using an hourly profile, as suggested by the same source, [25]. Latent heat gains are considered to be 0.0045 kg/(h·m²) in all rooms. Additionally, in the bathrooms and kitchen, latent loads from cooking and shower use are accounted for, with hourly production rates of 0.4 kg/h and 0.5 kg/h of vapor, respectively. Occupancy and shower usage profiles are shown in Figure 2, while profiles for sensible appliance loads can be referenced from [26].

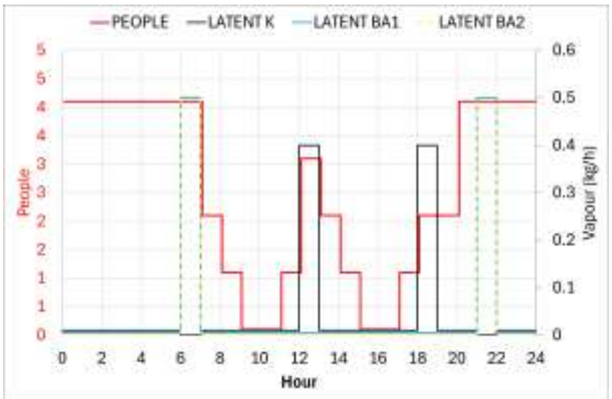


Fig. 2: Hourly people presence and latent gains in the bathrooms and in the kitchen

The HVAC system implemented in TRNSYS includes an air handling unit (AHU) equipped with an enthalpy recovery unit with 0.6 efficiency, a humidification section active during the heating season, and a cooling coil used for dehumidification during the cooling season. The AHU maintains relative humidity within the 40-70% range year-round and ensures minimum ventilation rates to manage indoor air pollutants and CO_2 concentrations. The AHU dynamically adjusts airflow rates to thermal zones for both CO_2 and humidity control. Maximum airflow rates are 180 kg/h for the living room, 150 kg/h for the kitchen, 100 kg/h for the bedrooms and 75 kg/h for the bathrooms. Minimum airflow rates are set at 20% of these maximum values.

Thermal zones' sensible loads for heating and cooling are managed by fan-coil units equipped with a fan and dual coils for heating and cooling. The fan-coil coils, as well as the cooling coil in the AHU, are connected to two 0.4 m³ water storage tanks located in the kitchen: a hot tank maintained at 45°C and a cold tank at 7°C, both supplied by a multifunctional vapor compression heat pump with inverter control. A domestic hot water (DHW) demand of approximately 1490 kWh [26] of thermal energy is drawn yearly from the hot tank, with an hourly profile as detailed in [27].

The heat pump's performance maps are shown in Figure 3, with rated performance values of 7 kW (source-side temperature of 7°C and water outlet temperature of 40°C). As shown in Figure 1(b), a 30 m² photovoltaic (PV) system is installed on the roof. This PV system is paired with a battery storage unit to minimize grid electricity exchanges and store surplus daytime energy. The estimated annual electricity demand for household appliances is approximately 2,700 kWh, [28].

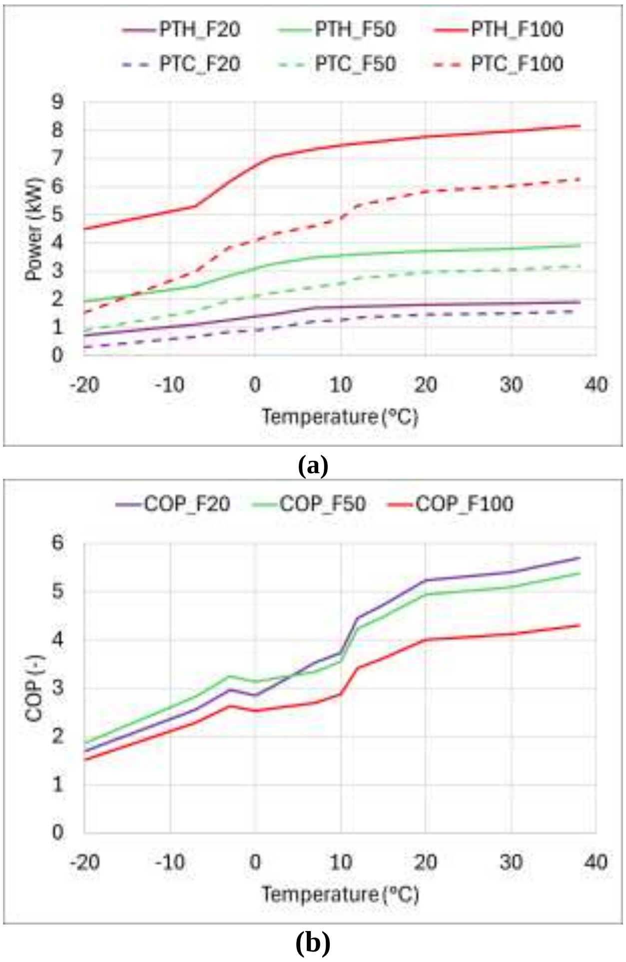


Fig. 3: Heat pump performance maps (thermal power for heating "PTH" and for cooling "PTC") vs source-side temperature for a water outlet temperature of 40°C. Data are given for three different inverter frequencies: 20, 50, and 100 Hz

The building was modeled using Google SketchUp with the TRNSYS 3D plugin [29] and subsequently imported into TRNSYS as Type 56. Parts of the HVAC system were modeled using types from the TESS Libraries, [30].

Hourly weather data for the simulations correspond to 2023 conditions in Milan, obtained from the Open Meteo database, [31]. This database provides climate data, such as temperature, humidity, precipitation, and solar radiation, using observations from weather stations, aircraft, and buoys, supplemented with meteorological models for areas lacking direct measurements, [32].

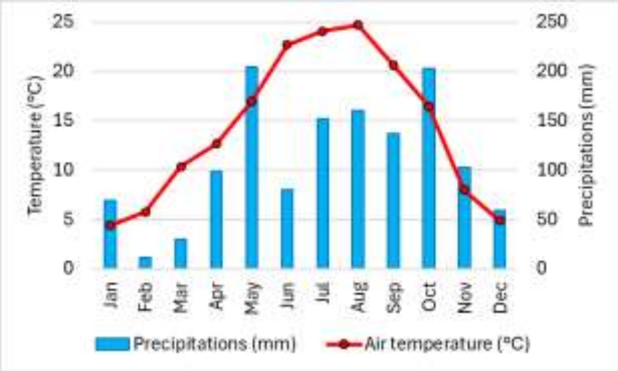


Fig. 4: Monthly climatic data for Milan

For Milan in 2023 (Figure 4), monthly temperatures ranged from a minimum of 4.4°C in January, the coldest month, to a maximum of 24.7°C in August. Precipitation was variable throughout the year, peaking in May and October (205 and 203 mm respectively).

2.2 Ventilation in Buildings according to EN 16798

EN 16798 standard provides guidelines for ventilation rates and thermal comfort conditions within buildings. This standard categorizes buildings into four classes, where Category I is the highest performing and Category IV the least, in terms of perceived comfort by the occupants. This study, has analyzed the energy consumption and the associated costs related to adopting specific ventilation rates and internal temperature set points to achieve these four categories. The parameters for these categorizations are listed in Table 2.

Table 2. Building categories considering thermal comfort according to 16798 standards

Building category	Temperature heating/cooling	PMV heating/cooling
I	21/25.5°C	-0.2/0.2
II	20/26°C	-0.5/0.5
III	18/27°C	-0.7/0.7
IV	16/28°C	-1.0/1.0

Regarding thermal comfort, the standard sets indoor temperature set-points at 21°C in winter and 25.5°C in summer for Category I, and 16°C in winter to 28°C in summer for Category IV. These set-points aim to maintain a Predicted Mean Vote (PMV) between -0.2 and 0.2 for Category I and between -1 and 1 for Category IV. PMV calculations follow standard guidelines, accounting for a clothing factor of 1 clo in winter and 0.5 clo in summer, a metabolic rate of 1.2 Met, and relative humidity levels of 50% in winter and 60% in summer. Besides thermal comfort, the standard focuses on determining necessary airflow rates to dilute pollutants, such as VOCs and CO_2. Table 3 shows that maximum CO_2 concentrations vary for different zones—like kitchens, living rooms, and bedrooms—depending on the building category. The values expressed by the standard actually refer to the maximum CO_2 levels to be added to the concentration of CO_2 relative to the external environment. Table 3 lists these values, assuming a constant external concentration of 420 ppm, [33].

Ideally, operating the HVAC system to achieve a Category I building maximizes occupant well-being.

Table 3. Building categories considering carbon dioxide concentrations, according to the 16798 standard

Building category	Living zones	Bedrooms
I	970 ppm	800 ppm
II	1220 ppm	970 ppm
III	2150 ppm	1370 ppm
IV	2150 ppm	1370 ppm

2.3 Economic Analysis Assumptions

The economic analysis is conducted using an average annual unit value for electricity in Italy, as indicated by ARERA, The Italian Regulatory Authority for Energy, Networks and Environment. [28] particularly in 2023, there was significant variability in quarterly prices, primarily due to geopolitical instabilities. The unit price for electricity (excluding taxes and additional costs) in the four quarters for consumers in the standard-free market was 0.42, 0.12, 0.12, and 0.16 €/kWh, respectively. In the following analysis, an average price of 0.35 €/kWh for electricity drawn from the grid is adopted, taking into account additional costs such as excise taxes and charges for transport and meter management, [34]. This average value reflects a simplified approach to account for price fluctuations, excluding the geopolitical instability observed in the first quarter. It also acknowledges that, in the Italian market, the final price to the consumer is influenced more significantly by fixed costs, such as transportation charges, metering expenses, and taxes, than by variations in the commodity price itself.

Furthermore, it should be emphasized that the total cost of electricity being analyzed refers only to the actual amount drawn from the grid, not the total demand, part of which is met by the photovoltaic system. For the electricity fed back into the grid due to overproduction, no remuneration from the network operator is considered.

3 Analyses Performed

A total of nine annual dynamic analyses were conducted using the TRNSYS simulation software, focusing on the building and system described in the previous paragraph and considering weather data for Milan, as outlined in section 2.2. These dynamic analyses aim to determine the electrical and thermal energy demands of the building, varying the set-point conditions of the system in accordance with standard 16798. Specifically, the nine dynamic analyses, presented in Table 4, refer to a reference case, i.e. the typical set-point conditions used in residential buildings in Italy (a winter set-point temperature of 20°C, a summer set-point of 26°C, and a CO_2 concentration limit of 1500 ppm). Additionally, the analyses examined energy consumption under the conditions specified by the standard and also detailed in Table 2 and Table 3. The dynamic simulations from F-I (Table 4) were conducted not by controlling the set-point temperature of the internal environments, but by considering direct control of the PMV calculated directly by type56 in TRNSYS; the individual room PID environmental thermostat maintained comfort conditions as established by the standard.

Table 4. Dynamic analyses performed

Scenario	Controlled variable	Set-point
A (reference)	Air temperature; CO_2	20/26°C; 1500/1500 ppm
B (cat. I)	Air temperature; CO_2	21/25.5°C; 970/800 ppm
C (cat. II)	Air temperature; CO_2	20/26°C; 1220/970 ppm
D (cat. III)	Air temperature; CO_2	18/27°C; 2150/1370 ppm
E (cat. IV)	Air temperature; CO_2	16/28°C; 2150/1370 ppm
F (cat. I)	PMV; CO_2	-0.2/0.2; 970/800 ppm
G (cat. II)	PMV; CO_2	-0.5/0.5; 1220/970 ppm
H (cat. III)	PMV; CO_2	-0.7/0.7; 2150/1370 ppm
I (cat. IV)	PMV; CO_2	-1.0/1.0; 2150/1370 ppm

4 Results and Discussion

Table 5 presents the results obtained from the dynamic analysis. Focusing on case A, it is observed that the energy required for cooling and dehumidification during the summer season annually is similar to the energy provided by the heat pump to the hot storage for heating and DHW production (2848 kWh and 2880 kWh).

Table 5. Results from the dynamic analysis: ET refers to thermal energy given by the heat pump to the hot tank, EC is the cooling energy to the cold tank, EE_{HP} is the electricity demand of the heat pump and EE_{tot} is the total electricity demand

Scenario	ET (kWh)	EC (kWh)	EE_{HP} (kWh)	EE_{tot} (kWh)
A (ref.)	2880	2848	2950	6389
B (cat. I)	3165	2939	2987	6505
C (cat. II)	2919	2805	2931	6392
D (cat. III)	2338	2513	2813	6233
E (cat. IV)	2034	2225	2719	6128
F (cat. I)	3240	4456	3443	7020
G (cat. II)	2697	4006	3271	6770
H (cat. III)	2438	3710	3162	6623
I (cat. IV)	2175	3219	3001	6440

The total electrical energy required by the heat pump is 2950 kWh, while the annual electrical energy required by the system for the heat pump, the AHU, demands from building equipment, and losses related to the battery and PV system total 6389 kWh. Comparing these results with those obtained in scenarios B to E, where air temperature control is performed to maintain the specified set-points in order to classify the building from category I to IV, it is observed that the total electrical energy demand is only higher in scenario B (6505 kWh, +1.8% compared to the base case, while the heat pump demand is greater by 1.3%). In scenarios C, D, and E, however, the overall electricity consumption is lower, though with a significant reduction in thermal comfort within the building. It is also noted that case C best reflects the conditions of the reference scenario A, where the set-points are the same, but the maximum CO_2 conditions change from a value of 1500 ppm for living zones and bedrooms to a maximum of 1120 and 970 ppm, respectively. The results of the analysis conclude that the modification of the maximum allowable CO_2 value had a limited effect on the overall demand for electricity (6392 kWh vs 6389 kWh). Focusing on cases F to I, which involve controlling the environment not on air temperature but on PMV, it is observed that the electricity and heat pump consumption is always higher compared to the reference case (percentage increases ranging from 0.8% up to 9.9%. Significant increases in electricity in this case are attributable to the heat pump (percentage increases ranging from 1.7% in case H, up to 16.7% in case F). However, if attention is paid to the thermal energy values required for DHW and heating and for cooling, it is observed that the former are similar to those obtained in cases B to E, while significant variations in terms of consumption occur during the cooling season, where there are very high increases (up to 4456 kWh in case F, compared to 2848 kWh (56.5%) of the base case and compared to 2939 kWh (51.6%) of case B). These increases in the cooling case are attributable to the fact that to achieve the comfort conditions inside the environments during the summer period, using the values specified by the standard, i.e., air velocity of 0.1 m/s, 0.5 clo, and 1.2 Met, the comfort values indicated in Table 2 for summer are obtained for internal air temperatures generally lower than 24.5°C. For the case under examination, therefore, the control on the PMV proved to be ineffective during the summer season, while the deviations for the same building categorization were in line with the demand for thermal energy for heating and DHW. However, the control on the PMV appears to be the most capable of maintaining stable comfort conditions within the considered environments, as shown in Figure 5, where the detected values of internal PMV stability in the living room are compared for the same day of the heating season in cases C and G.

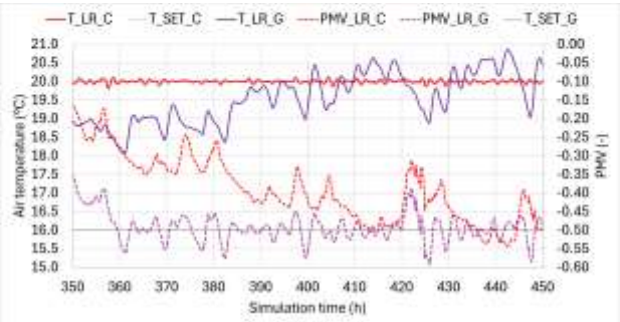


Fig. 5: Trends of air temperature and PMV for the same day (January 15-19, 2023) of the heating season in scenario C ("_C") and G ("_G") in the living room

Table 6. Results from dynamic analysis: EE_{grid} refers to electricity demand from the grid

Scenario	EE_{grid} (kWh)	€
A (ref.)	1812	634 €
B (cat. I)	1879	658 €
C (cat. II)	1784	624 €
D (cat. III)	1666	583 €
E (cat. IV)	1632	571 €
F (cat. I)	1859	651 €
G (cat. II)	1809	633 €
H (cat. III)	1715	600 €
I (cat. IV)	1790	627 €

Table 6, instead, lists the electricity withdrawals from the national grid for the 9 scenarios considered along with the electricity cost values from the grid, considering a unit price for electricity of 0.35 €/kWh. It is observed that it starts from the base case where the annual price for electricity from the grid is 634€; this value is comparable to that of case C (624€), which is the closest to the reference case as mentioned. It is also observed that the over-demand for thermal energy for cooling compared to the base case and the temperature control case (increases in some cases over 55%), figures on the total final electricity consumption and costs required from the grid on more limited percentages (+2.6% of case F (651€) compared to the base case). This aspect can be justified by the fact that the over-demand for thermal energy for cooling still occurs at a time (summer) when photovoltaic production is high.

5 Conclusion

The main findings of this dynamic analysis regarding the definition of electric and thermal energy demands and costs following the implementation of a control system that maintains thermal comfort and ventilation rates according to standard 16798, aimed at categorizing the building into classes I to IV, are:

- The stricter CO_2 concentration control (cat. II and scenario C) compared to typical usage conditions in Italian buildings (scenario A) shows similar values in terms of electricity demand and consequently final costs (6392kWh vs 6389 kWh of total energy demand of case C respect reference case (A), +0.04 %).
- Controlling PMV rather than air temperature generally requires more thermal energy, particularly for cooling and dehumidification, showing a significant increase (+56.5% compared to the base case and +51.6% compared to air temperature control). However, PMV control is more precise and results in less fluctuation of perceived internal comfort by occupants (Figure 5).
- The increase in thermal energy required for heating and cooling in categories I and II with both control options shows limited final increases in terms of electricity demand from the national grid and consequently costs (up to 2.6% compared to the reference case). However, this approach achieves an improvement in IAQ and internal thermal comfort compared to the reference scenario A. This is partly attributable to the fact that the over-demand for thermal

energy during the summer occurs when PV production is high.

These results highlight the need for further studies to deepen the understanding of consumption effects on other types of buildings and systems under the guidelines defined by the 16798 standard. Moreover, it could be interesting to evaluate the impact of a generation system that does not include a multifunctional heat pump for air conditioning and combined DHW production.

Declaration of Generative AI and AI-assisted Technologies in the Writing Process

The author wrote, reviewed and edited the content as needed and has not utilised artificial intelligence (AI) tools. The author takes full responsibility for the content of the publication.

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