# Use of air-to-air heat pumps for air conditioning in existing buildings: impact of building thermal mass on consumptions and comfort levels

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**Abstract**

The decarbonisation of the building sector is a central priority in European energy policy, as buildings account for about 40% of total energy consumption. In this framework, the residential sector plays a key role in this transition, with multi-family buildings representing a significant portion of housing. In these buildings, constraints on space and technical integration often make the use of thermal storage impracticable.
To this aim, this study investigates the potential of exploiting building thermal mass to enhance the performance of air-to-air heat pumps in existing residential buildings, with specific focus on the winter heating operation mode.
A building–heating system model was developed and validated, and an advanced control strategy was implemented to use structural thermal mass as a storage in a multi-family case-study building. Three construction clusters and multiple wall heat-capacity enhancement levels were compared against a baseline to assess the effects on energy consumption and thermal comfort.
Results show energy-consumption reductions of up to 20% in the highest-capacity configuration, with favourable comfort outcomes during occupied hours. These findings indicate that the thermal mass of buildings can support more efficient heat-pump operation, offering a cost-effective solution for existing buildings.



*Keywords: Heat pumps; Thermal capacity; Energy consumption; Thermal comfort*

## 1. Introduction

The decarbonisation of the building sector is a central priority of European energy policy, with recent directives strongly promoting electrification and the adoption of low-carbon technologies. Approximately 40% of the energy consumed in the European Union is used in buildings, of which around 80% is devoted to residential heating, cooling, and domestic hot water [1]. To reduce reliance on imported fossil fuels and achieve the EU's carbon neutrality targets, heat pumps are a key technology for accelerating the energy transition, given that over 70% of current heating and cooling energy demand is still supplied by fossil fuels, predominantly natural gas [2].

Historic and existing buildings represent a significant portion of the European building stock, with roughly 35% over 50 years old and nearly 75% considered energy inefficient [3]. Renovation of these buildings could yield substantial energy savings, potentially reducing total EU energy consumption by 5–6% and cutting $CO_2$ emissions by about 5% [3]. The residential sector plays a key role in the energy transition [4] and multi-family

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buildings constitute a large share of housing [5]. These buildings are often energy inefficient and, due to constraints on space, technical integration, and collective decision-making, designing optimised building–HVAC systems is frequently unfeasible.

In such contexts, particularly in existing buildings, the integration of systems like hydronic networks faces significant technical and economic challenges [6]. Outdoor air is the most common heat source in building refurbishments, and air-to-air heat pumps are frequently employed because they do not require hydronic distribution networks or dedicated thermal storage [7]. However, the lack of storage constrains operational flexibility, forcing the heat pump to respond directly to instantaneous heating demand. In poorly insulated buildings or under unfavourable outdoor conditions, this can lead to operation at low coefficients of performance (COP), higher electricity consumption, and potentially reduced indoor comfort, thereby exacerbating the risk of energy poverty [8].

Research has highlighted the potential of demand-side flexibility and thermal-energy storage to improve heating-system efficiency and reduce peak loads [9], [10]. Yet, the use of building structures as a form of passive thermal storage, particularly in existing buildings, remains insufficiently explored and a deeper understanding of how the thermal mass of opaque building elements can support more efficient heat-pump operation is therefore needed.

This study aims to address this gap by developing a dynamic model of multi-family residential building unit coupled with an advanced control strategy for air-to-air heat pumps designed to enhance the exploitation of the building thermal mass, with specific focus on the winter heating operation mode. The objective is to evaluate whether building elements can effectively serve as short-term thermal storage, thereby improving heat-pump performance while maintaining indoor comfort in existing dwellings.

## 2. Methodology

### *2.1. Selection of representative characteristics of residential buildings*

For the analysis, typical characteristics of Italian residential buildings were identified, reflecting patterns representative of the broader European building stock. The selection was performed through a preliminary investigation based on statistical data from the TABULA/EPISCOPE project [11]. For this study, a single-family unit in a multi-family building was selected, with their main characteristics summarized in Table 1.

Table 1. Characteristics of the multi-family building unit analyzed.

| | **Multi-family building unit** |
|---|---|
| Construction period | 1976-1990 |
| Volume (net, $m^3$) | 197.37 |
| Internal floor area (net, $m^2$) | 73.10 |
| Envelope area (heat-transmitting, $m^2$) | 51.41 |
| Surface-to-volume ratio (S/V) | 0.20 |
| Ceiling height (net, m) | 2.70 |
| Windows ($m^2$) | 8.13 |

Then, construction clusters were identified based on data from the TABULA/EPISCOPE project [11], reflecting variations in materials, construction types, and building periods. Each cluster represents a combination of construction elements, each with specific functions and thermal properties.

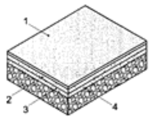
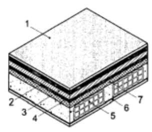
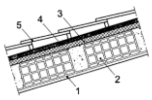
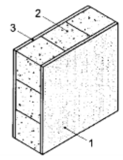
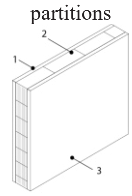
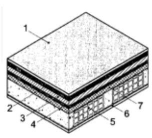
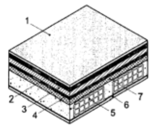
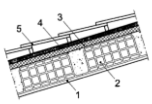
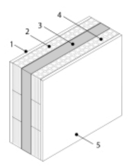
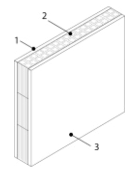
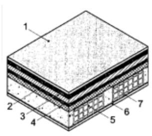
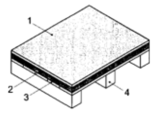
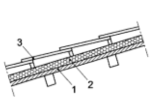
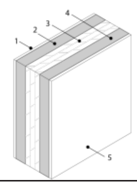
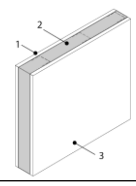
By combining the most common solutions in the existing residential stock with the key construction elements to be modelled (roof slab, ground slab, intermediate floor slab, external walls, internal partitions), three representative clusters were defined, as described in Table 2.

The determination of occupancy profiles was based on a detailed analysis of statistical data on residential building occupancy in Italy, using information collected from approximately 20,000 households, in accordance with the methodology described in [12]. For this study, a single-person household profile was adopted. For each pattern, the total metabolic heat gain was calculated to define the internal gains associated with occupant presence.

On weekdays, metabolic heat gains were set to 78 W from 21:00 to 09:00, and 180 W from 09:00 to 10:00 and 13:00 to 16:00. On weekends and holidays, gains were 78 W from 00:00 to 09:00, and 180 W from 10:00 to 11:00, 13:00 to 18:00, and 21:00 to 00:00.

In addition to occupancy profiles, internal gains from electronic devices were also considered. The technical literature does not provide specific guidelines for the determination of internal gains values for residential buildings. The national (Italian) standard UNI TS 11300-1 [13] only supplies data on total internal heat gains, without distinguishing between contributions from electronic equipment and those from occupants. Therefore, in this study, average values were selected, deemed reasonable based on the data available in the scientific literature and through comparison with the values reported in the aforementioned technical standard. The values adopted per unit of useful floor area of the dwelling are: 5 W/m² during daytime when occupants are present and active, and 1 W/m² during night time when occupants are present but inactive, as well as during daytime periods with no occupants.

Table 2. Characteristics of the construction clusters.

| | Ground slab | Intermediate floor slab | Roof slab | External walls | Internal partitions |
|---|---|---|---|---|---|
| **CLUSTER 1 (C01)** | Concrete ground floor slab  | Hollow brick and beam slab  | Hollow brick and beam slab  | Stone walls  | Solid brick partitions  |
| **CLUSTER 2 (C02)** | Reinforced concrete slab with hollow blocks  | Hollow brick and beam slab  | Hollow brick and beam slab  | Perforated brick walls with internal insulation  | Perforated brick partitions  |
| **CLUSTER 3 (C03)** | Reinforced concrete slab with hollow blocks  | Wooden slab with joists and planks  | Wooden slab with joists and planks  | Lightweight timber walls with internal and external insulation  | Lightweight partitions with insulation  |

## *2.2. Selection of the climatic location adopted for the analysis*

For the analysis, Milan was selected as the case study due to its representation of a typical cold-winter climate in Italy. The selection was based on the mean Heating Degree Days (HDD), an index of a location's heating demand calculated as the annual sum of the positive daily differences between the conventional indoor temperature (20 °C) and the mean outdoor temperature. In particular, Milan presents 2404°C·days HDD.

Climate data were obtained from the *Joint Research Center* (JRC) database [14]. From this source, Typical Meteorological Years (TMY) for the period 2006–2017 were extracted. The environmental parameters considered were: outdoor air temperature (°C), solar irradiance on horizontal surfaces (W/m²), and solar irradiance on vertical surfaces (W/m²).

## *2.3. Development of the predictive model of energy behavior*

To simulate the interactions between the building and air-to-air heat pump heating systems, a grey-box model was developed using MATLAB Simulink software. This approach was chosen as a compromise between white-box models, which offer high predictive accuracy but require detailed input data, and blackbox models, which rely on historical system behaviour. Indeed, grey-box modelling balances predictive accuracy, input data requirements, and computational effort, making it particularly suitable for the present study [15].

For the simplified modelling of the sample buildings, the procedure defined in UNI EN ISO 52016-1 [16], which proposes a Resistance-Capacitance (RC) approach, was followed. Each opaque envelope layer was represented by a single thermal resistance and capacitance based on their thermophysical properties, neglecting thermal bridges. Windows were modelled as resistive elements with thermal resistance derived from the glazing and frame, with two additional resistances for convective and radiative heat transfer. Internal elements, including furniture and partitions, were represented to capture their contribution to the building's thermal capacity, with the indoor zone treated as a single thermal zone. Internal partitions were modelled as RC networks reflecting their material properties.

Ventilation was represented via a thermal resistance based on an air exchange rate of 0.3 $h^{-1}$. Direct and indirect solar gains, internal loads, and ground heat exchange were modelled using simplified RC approaches, including a fictitious sun–air temperature for opaque surfaces and constant soil temperature.

A simplified air-to-air heat pump model was implemented, with operation controlled by indoor temperature and occupancy. Under the baseline condition, the heat pump activates when indoor temperature falls below the 20 °C setpoint and when at least one occupant is present, operating according to the modulation strategy reported in Table 3.

The model uses manufacturer data for power consumption, COP at two operating points, and the temperature of the two sources (indoors and outdoors) to derive the effective COP and partial-load performance on an hourly basis. COP adjustments account for variations in external and internal temperatures and, as a proportional control strategy is used, are corrected based on the load factor (CR), according to the calculation method described in [17]. Logical limits were applied to COP values (minimum 1.5, maximum 5.5).

This approach enables hourly estimation of electricity consumption while capturing the heat pump's dynamic interaction with the building. The model provides the following hourly variables: indoor air temperature (°C), heat pump modulation, load factor, Coefficient of Performance (COP), and electricity consumption (kWh).

Table 3. Modulation strategy of the heat pump (ΔT is the difference between the indoor and outdoor air temperature).

| **ΔT** | **Modulation** |
|---|---|
| ΔT > 3°C | 100% |
| 2.5 °C < ΔT ≤ 3.0°C | 80% |
| 2.0 °C < ΔT ≤ 2.5°C | 60% |
| 1.0 °C < ΔT ≤ 2.0°C | 40% |
| 0.0 °C < ΔT ≤ 1.0°C | 20% |
| ΔT = 0°C | 0% |

### *2.4. Model validation*

For the validation of the model, a building located in Devens, Massachusetts (USA, near Worcester, Climate Zone 6a, Cold–Humid), with a heating degree day range of approximately 4000–5000 °C·days was chosen. The building is a single-family residential unit, featuring exclusive use of an air-to-air heat pump for heating and continuous monitoring of its energy consumption over a full heating season [18].

Energy monitoring occurred from December 2011 to February 2014, and a complete heating season (1 November 2012 – 30 April 2013) was used for model validation. Hourly external air temperature data for simulations were obtained from Worcester, about 30 km from the site. Model validation was conducted by comparing monitored and simulated monthly energy consumption.

### *2.5. Exploitation of building thermal mass via advanced heat pump control*

To investigate the potential of leveraging the thermal mass of building structures (e.g., opaque walls) as a means of energy storage for air-to-air heat pumps that lack hydronic storage, two complementary approaches were implemented. First, an advanced heat pump control strategy was applied, differing from the simple temperature-occupancy management previously shown; second, the thermal capacity of the walls was increased.

The advanced control strategy, shown in Figure 1, is designed to operate the heat pump under favorable conditions. Favorable conditions were considered when the temperature difference between the internal and external sources is ≤5 °C, regardless of occupancy, and with an increased setpoint. This allows the building structures to be thermally charged under conditions where the heat pump's performance (particularly COP) is higher.

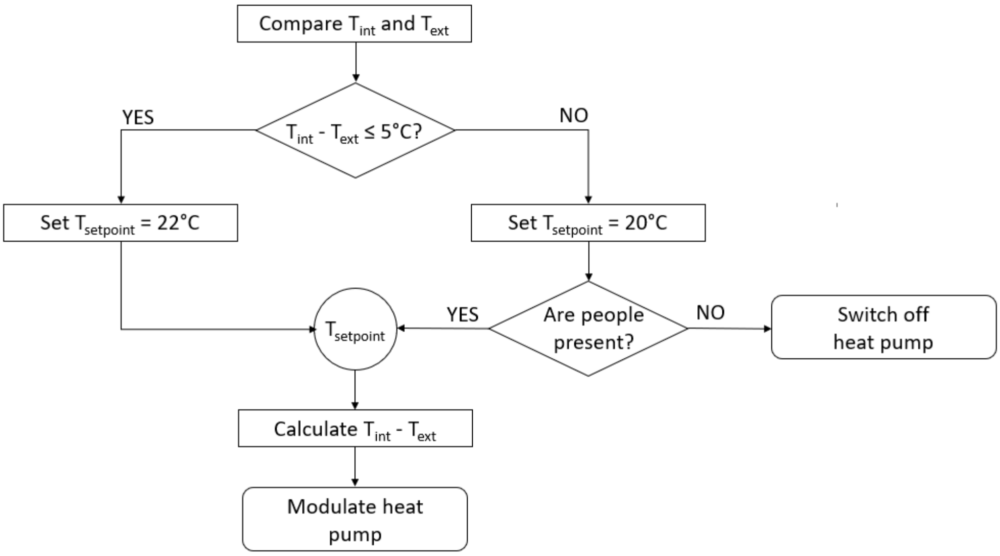



Figure 1. Flowchart of the advanced heat pump control used to assess the potential utilization of the walls' heat storage capacity.

Then, an additional capacitive layer was added to the interior side of the wall. In the RC model, this layer was represented with negligible thermal resistance and a thermal capacity designed to increase the wall's original capacity.

Three levels of thermal capacity enhancement were considered: a twofold increase (CAP2), a tenfold increase (CAP10), and a hundredfold increase (PCM). The hundredfold increase is substantial and representative of innovative materials, such as phase change materials (PCMs), which exhibit very high heat capacities within their phase-change temperature range until the transition is complete [19].

For the analysis, the following configurations were considered:

- Baseline: no advanced control or heat capacity enhancement;
- CAP: advanced control without additional heat capacity;
- CAP2: advanced control with a twofold heat capacity increase;
- CAP10: advanced control with a tenfold heat capacity increase;
- PCM: advanced control with a hundredfold heat capacity increase, representative of phase change materials.

## 3. Results and discussion

### *3.1. Validation of the model*

Model validation was performed by comparing simulated and monitored monthly energy consumption, as shown in Figure 2. The simplified model demonstrates a good predictive capability, with seasonal deviations below 2%. Excluding the shoulder months of November and April, the mean absolute deviation is less than 5%, with a maximum deviation of 8.4%. Larger discrepancies occur in November and April, reaching up to 25% in April, likely due to reduced heating demand and variations in user operation of the heat pump.

While obtaining more detailed occupancy and operational data would improve accuracy, this is beyond the scope of the present study. Moreover, these months represent less than 20% of the total seasonal energy consumption, limiting their overall impact on validation.

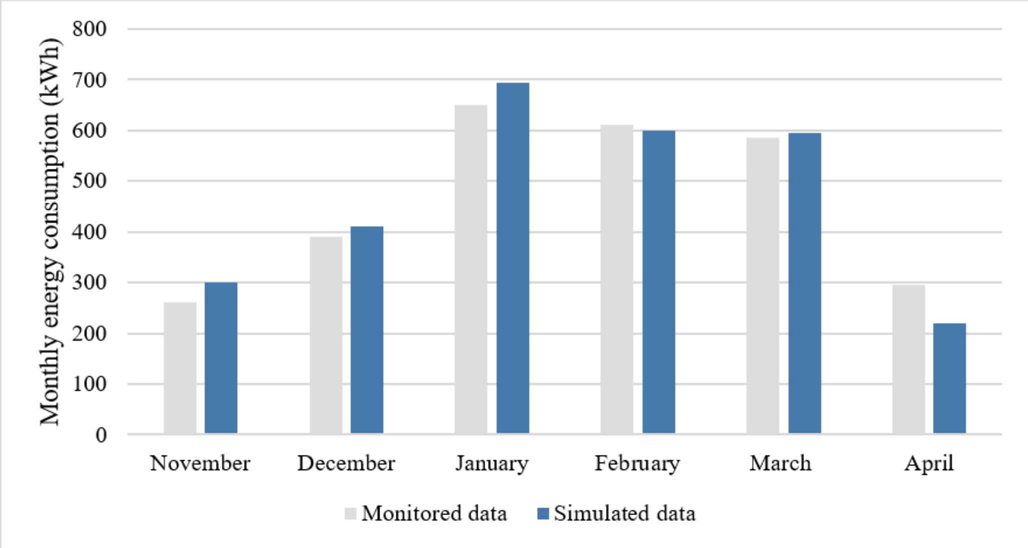



Figure 2. Comparison of monitored and simulated monthly energy consumption during the winter period 2012-2013.

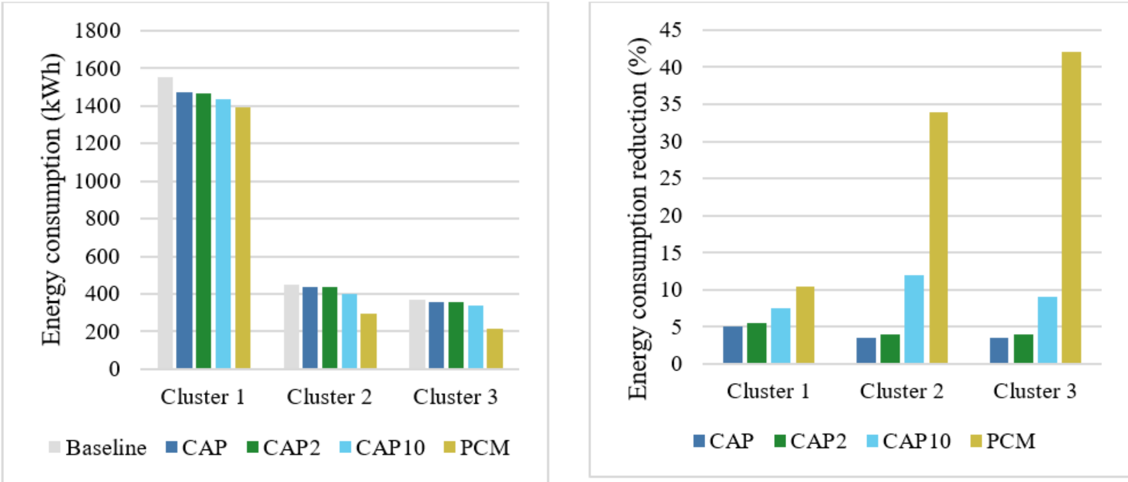
### *3.2. Analysis of the energy consumption*

Energy consumption was analysed for the three construction clusters by comparing the baseline configuration with the cases featuring increased thermal capacity, the results are summarized in Figure 3. In Table 4 seasonal mean COP values of the heat pump for the different combinations of operating configurations and construction clusters are indicated.

The overall effects observed in Figure 3 depend primarily on four factors (some of which act in opposition) whose combined outcome was difficult to predict a priori. The first factor has a positive impact on heat pump performance and consequently on the reduction of energy consumption: the increase in COP associated with a greater proportion of operation under favourable thermal conditions (i.e., limited temperature differences between the heat exchange sources) and reduced operation under unfavourable conditions. The second factor exerts a negative influence on heat pump performance, arising from the reduction of the load factor (which entails a downward correction of the COP) during periods in which the unit operates while the set-point returns from the elevated value (thermal charging phase) to the standard one. The third factor is the increase in thermal losses during periods when the dwelling is unoccupied and the thermal charging action is activated. It is evident that the first (positive) effect contrasts with the other two (negative) effects. The fourth factor concerns the differing thermal storage and release behaviour of the building components across the various configurations, which affects the indoor air temperature and, together with the occupancy profile, influences the distribution of heat pump on/off cycles.

The data reported in Table 4 show that the thermal charging strategy produces, relative to the Base configuration, a modest increase in the seasonal average COP, an effect that disappears in the C-PCM configuration. In this latter case, the temperature fluctuations around the set-point are more limited than in the other scenarios, and the heat pump operates predominantly at low load factors, resulting in a downward correction of the COP. Conversely, the values presented in Figure 3 highlight the reductions in energy consumption obtained when moving from the Base configuration to the alternative configurations. As shown in the Figure 3b, reductions over the seasonal period range from slightly below 5% to very substantial values in the case of the C-PCM configuration. These reductions tend to increase with the thermal capacity of the walls; this phenomenon is particularly evident in the construction clusters characterized by medium-to-high levels of thermal insulation (Clusters 2 and 3), for which the largest reductions occur in the C-CAP10 and C-PCM configurations.

However, it should be noted that the pronounced reductions observed for the C-CAP10 and C-PCM configurations are partly attributable to a secondary effect of the elevated thermal capacity of the walls, namely the slower decline in the average indoor air temperature values at the beginning of the heating season. Specifically, analysis of the outdoor air temperature trends and the indoor air temperature profiles obtained from the simulations reveals that, for the C-CAP10 and C-PCM configurations, there is a period of several days (which lengthens with increasing thermal capacity) at the start of the heating season during which the indoor air temperature remains above 20 °C, still influenced by the residual effects of the preceding warmer days; consequently, the heat pump does not engage. This behaviour, which is particularly pronounced in the more highly insulated construction clusters, is clearly visible in Figure 4. Such behaviour is not observed in the other configurations, which exhibit lower thermal capacities.




(a) (b)

Figure 3. Seasonal energy consumption (a) and percentage reductions in energy consumption compared to the baseline (b) for the different configurations.

Table 4. Seasonal mean COP values of the heat pump for the different combinations of operating configurations and construction clusters.

| | Baseline | CAP | CAP2 | CAP10 | PCM |
|---|---|---|---|---|---|
| Cluster 1 | 3.91 | 3.94 | 3.93 | 3.93 | 3.92 |
| Cluster 2 | 3.78 | 3.81 | 3.81 | 3.79 | 3.75 |
| Cluster 3 | 3.75 | 3.80 | 3.80 | 3.79 | 3.73 |

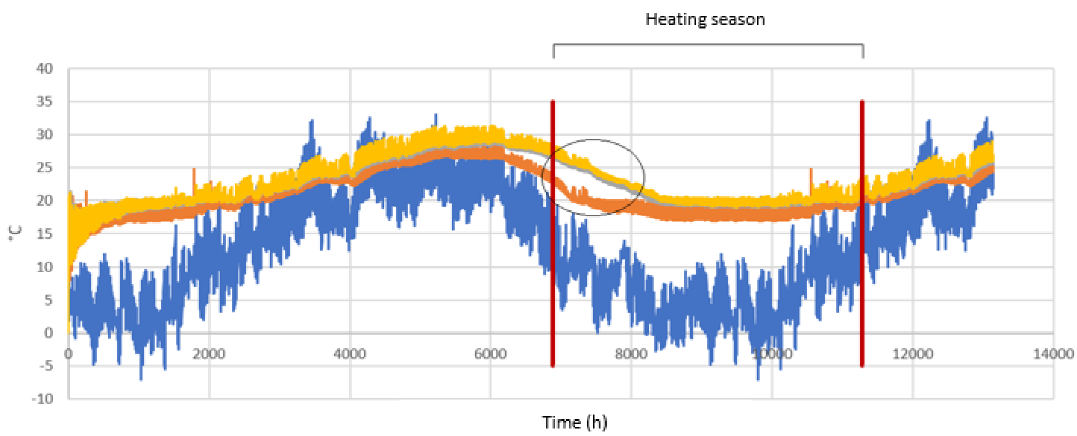



Figure 4. Comparison of outdoor ($T_{ext}$) and indoor ($T_{int}$) air temperature trends over an extended portion of the heating season for the PCM configuration. The circled region highlights the resistive–capacitive effects of the building structures across the three construction clusters. Legend: $T_{ext}$ (blue), $T_{int}$ for cluster 1 (orange), $T_{int}$ for cluster 2 (grey), $T_{int}$ for cluster 3 (yellow).

To assess solely the effect of the thermal charging of the building components (based on their dynamic performance in combination with the operation of the heat pump) the comparison with the Base configuration was repeated for sub-seasonal time intervals, obtained by simply excluding from the heating season the initial phase in which the previously described phenomenon occurred. The qualitative trends observed earlier are confirmed; however, from a quantitative perspective, as expected, the values of energy-consumption reductions decrease. In particular, a maximum reduction of approximately 20% is observed for the C-PCM configuration within construction Cluster 3.

### *3.3. Thermal comfort analysis*

For the thermal comfort analysis, the Mean Absolute Deviation (MAD) from the air temperature setpoint (20 °C) was evaluated. MAD quantifies the average absolute deviation of the simulated values from the reference, calculated as (Eq. (1)):

$$MAD = \sum_{t=1}^{n} \frac{|R_{v,t} - F_{v,t}|}{n} \qquad (1)$$

where:
$R_{v,t}$ is the reference value at time t (pre-set setpoint in this study)
$F_{v,t}$ is the simulated value of the parameter at time t
$n$ is the total number of data points.

The MAD was calculated for the entire heating season and for all analysed configurations (Figure 5). Overall, the advanced heat pump control strategy, aimed at exploiting the thermal storage capacity of walls, leads to higher indoor air temperatures during the periods of thermal charging. Figure 5 shows that MAD increases with the wall thermal capacity, particularly for the more highly insulated construction clusters (Clusters 2 and 3). This increase is due to the slower decline of indoor temperatures in high-capacity configurations (CAP10 and PCM), which prolongs heat pump inactivity but results in larger deviations from the setpoint (20 °C). Consequently, the observed energy savings for some thermal-charging configurations correspond to a greater challenge in maintaining comfort over the full heating season.

Notably, if MAD were calculated only during periods of occupancy, values would decrease and approach those of the baseline; for instance, for the PCM configuration in Cluster 3, MAD would drop to 0.60 °C. Moreover, it should be noted that the 20 °C setpoint, assumed as the comfort condition, is commonly used in design but does not necessarily reflect actual comfort conditions. For instance, using the PMV (Predicted Mean Vote) index [20] for sedentary winter conditions (metabolic rate = 1.2 met, clothing insulation = 1 clo), with an air velocity of 0.1 m/s and relative humidity at 50%, the neutral thermal temperature would be around 22 °C. Analysis of indoor temperature trends over the heating season shows that temperatures rarely exceed 22 °C across all configurations, indicating a limited risk of warm discomfort.

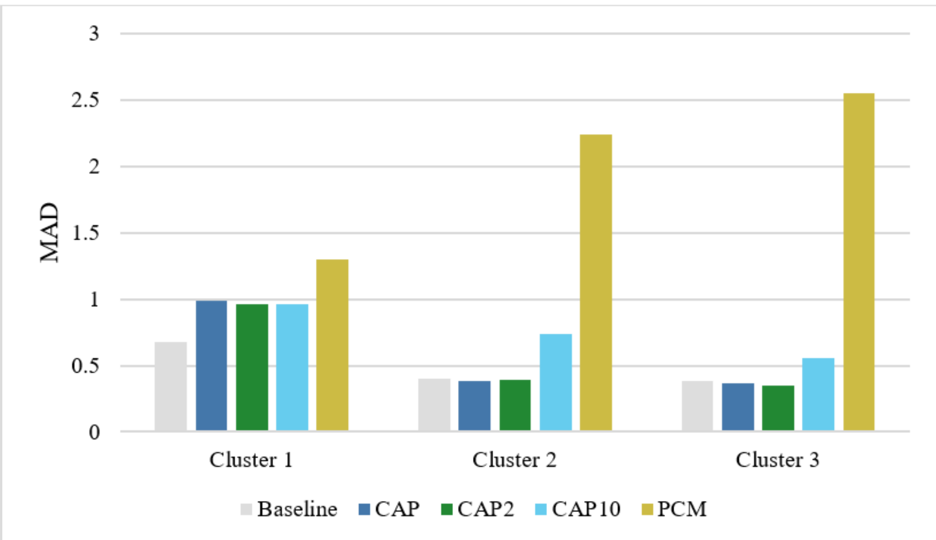



Figure 5. Mean Absolute Deviation (MAD) during the heating season for the analyzed configurations.

## 4. Conclusive remarks

This paper aimed at investigating the potential of leveraging the thermal mass of building structures to support air-to-air heat pumps, with the aim of reducing energy consumption while maintaining indoor thermal comfort. To this end, a coupled building–HVAC system model was developed and validated, and an advanced heat pump control strategy was tested on a case study building under different thermal capacity scenarios.

Three construction clusters, typical of the European residential building stock, were tested. Moreover, three levels of enhanced wall thermal capacity were considered: a twofold increase (CAP2), a tenfold increase (CAP10), and a hundredfold increase (PCM). These configurations were compared against a baseline condition, which featured neither the advanced control strategy nor additional thermal capacity.

The analysis shows that increasing the thermal capacity of building walls can reduce seasonal energy consumption for air-to-air heat pumps, with savings more pronounced in better-insulated buildings. Energy reductions ranged from below 5% up to around 20% in the PCM configuration.

Regarding comfort, the advanced control strategy led to higher indoor temperatures during the periods in which the setpoint was intentionally raised, resulting in larger deviations from the 20 °C setpoint, particularly in highly insulated clusters. However, considering only occupied periods, Mean Absolute Deviation (MAD) values approach baseline levels, and indoor temperatures rarely exceeded 22 °C, indicating minimal risk of warm discomfort.

Based on the results of the tested configurations, building structures can effectively serve as thermal storage when used in combination with air-to-air heat pumps. Significant energy savings require coupling the advanced control strategy with high thermal capacity structures. In this context, innovative materials, such as those exploiting phase-change effects, have shown promising potential.

Future research could focus on optimizing heat pump control strategies to maximize the benefits of using structures thermal mass for specific building capacities and on experimentally validating these findings in real buildings.

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