Enhanced building energy flexibility using passive PCM envelope and HVAC control automation

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Abstract. One solution for improving the thermal performance of existing building envelopes is the use of pre-formed internal insulative panels that incorporate impregnated phase change materials (PCM). Such measures have the potential to enhance the energy flexibility of buildings when combined with HVAC control automation and digitalisation techniques, thereby offering the possibility of participation in demand side management measures such as demand response programmes. The current literature on building envelope physics lacks research on the integration of such PCMs in building envelopes and advanced HVAC control automation, especially in the context of research into the energy flexibility and demand response nature under heating and cooling scenarios. The aim of the current study is to evaluate how the addition of PCM impregnated internal wall panels and HVAC thermostat control automation affect both the thermal performance of the building envelope, as well as the wider building energy characteristics, when subject to different demand response events. The reference building is a detached residential house which has a floor area of 160 m^2 and a south-easterly facing aspect. This study presents a building energy management methodology to develop new energy flexibility indicators for HVAC thermostat control automation taking into consideration a pre-cooling period prior to the demand response event as well as evaluating the thermal energy storage capacity and peak power curtailment. Four different demand response scenarios are examined. Simulation results show that shorter envelope pre-cooling periods in association with longer demand response periods are preferable for all envelopes to achieve the maximum power curtailment for cooling. Gypsum boards enhanced with PCM were retrofitted as part of lightweight thermal mass and medium weight thermal mass envelopes and are shown to give best cooling demand shifting and performance. It is concluded that for energy flexibility scenarios, the pre-cooling length should be always less than the length of the demand response event to ensure higher cooling efficiencies.

Keywords. PCM thermal storage, demand response, energy flexibility, HVAC control automation, energy-efficient envelopes
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1. Introduction

Thermal energy storage (TES) is a practical solution to give flexibility to the energy demands and hence allows for a building to perform efficiently in times of high peak energy demands while also remaining comfortable for the occupants. TES is a storage arrangement that can store thermal energy by heating, cooling, melting, solidifying, or vaporizing a material [1].

The TES of a building is influenced by the building thermal mass and can be controlled by the building envelope material characteristics. The thermal mass will absorb heat and release it when the ambient temperature around it drops resulting with a relatively stable indoor temperature being maintained. When considering thermal energy storage, it can be called sensible heat storage when the material temperature rises or falls to store heat energy or latent heat storage when a material phase change occurs with little to no change in temperature.

Sensible heat storage materials are heavy, dense and a good heat conductor which heat up or cool down in order to store energy. Phase change materials (PCM) is a latent heat storage technology which can store large amounts of heat energy at mostly isothermal conditions or in a very narrow temperature range.

There is an increasing number of studies emerging which are working on smart thermal energy storage such as PCM to facilitate demand response and improving the energy performance of buildings. For example, a numerical study carried out by Rahimpour et al. [2] on buildings in five Australian cities showed that the retrofitting of PCM on ceilings, walls and floors had an influence on the HVAC demand. HVAC demands were reduced Hobart and Melbourne by 7.3% and 11.4%, respectively, but in the other cities were not affected due to climatic conditions.

Arıcı et al. [3] numerically investigated the effect on heating and cooling loads due to the integration of 100% concentrated PCM (with a range of temperatures) on an external wall of a building. It was concluded that the optimum melting temperature for maximum latent heat storage depends on the climatic conditions and on the location of the PCM in the external wall. Another significant finding from this research is that the optimum thickness for PCM for all climatic conditions and PCM locations was 20 mm and that the maximum delays in the peak heat fluxes ranged from 10.3 hours in August to 13.3 hours in July. This change in time lag by means of activating latent heat storage compared to a reference solution is significant when studying the retrofitting of PCM to enhance the TES of a building for demand response events. However, the effect of different building typologies was not studied.

A study done by Chen et al. [4] which had similar conclusions for sensible heat storage, showed that thinner thermal masses can contribute more to electricity flexibility at peak demand times in a demand response event due to its higher heat release ratio of the stored sensible energy. However, thicker thermal masses have a low heat-release ratio and are therefore not as effective during a demand response event. The heat release ratio is defined by thickness and thermal characteristics of the thermal mass.

Markarian and Fazelpour [5] showed how PCM integration into building envelopes can reduce the need for the air conditioning system to be running in high demand times. However, the authors did not take into consideration, the pre-charging of the buildings sensible and latent TES elements. With these results considered, a pre-charging (pre-cooling) event could be implemented before a demand response event which would offer greater flexibility as the air conditioning system load requirement would be further reduced.

Devaux and Farid [6] performed a numerical and experimental study in Tamaki New Zealand where they compared two huts and validated an Energy Plus model. Hut 1 was a standard reference hut, while hut 2 had PCM fitted on the walls and ceilings along with PCM underfloor heating all with a melting temperature between 27 – 29 ^{o}C. During high power demand periods (4 hours long) the setpoint temperature was set to 18^{o}C, whereas during low demand periods the setpoint temperature was at 20.2^{o}C. Turning the underfloor heating off at 5:00 hrs and at 19:00 hrs was shown to be the best time to give optimum peak load shifting along it reduced energy consumption. Devaux and Farid [6] also examined peak load shifting for demand response events, however, pre-charging of the PCM prior to a demand response event to a higher setpoint temperature was not considered.

A gap in knowledge has been identified in field of demand response and PCM technology, and few studies have been published on the effect of PCMs for both heating and cooling scenarios in buildings while taking into consideration various demand response events with different enhanced building envelope typologies.

The current study proposes a new demand response indicator and investigates the pre-charging (pre-cooling) temperature by modulating the thermostat and the duration of this pre-charging period prior to a demand response event for power curtailment and peak load shifting. In addition, a digital design tool for building envelope energy flexibility assessment is developed in EnergyPlus using the in-built Runtime Language and a Python post-processing script.

2. Methodology

2.1 Overview

To simulate a demand response event a pre-charging timeframe was considered, where the building envelopes thermal mass was charged by increasing the thermostat setpoint temperature. This is known as an upward flexibility event. Immediately after such an upward flexibility event, the proposed demand response event took place. The demand response event was simulated for each timeframe of the day to determine the most efficient time of day for the upward flexibility event to take place for the activation of the TES. The energy flexibility for each building envelope considered was evaluated and analysed. The building envelopes were numerically modelled for both an upward and a downward flexibility event for cooling. The retrofitting of 100% concentrated PCM (**PCM-1**) [7] and PCM-enhanced gypsum wallboard (**PCM-2**) [8] to the building envelope was also considered in the analysis to determine the influence of PCM concentration on the TES of the building and thus its contribution to a demand response scenario when envelope pre-charging (pre-cooling) occurs.

2.2 Case study building

The reference building is a residential detached house constructed in 1999. The construction geometry considered for analysis can be seen in Fig. 1. The building has a floor area of 160 m^2 and an easterly facing aspect. The ground floor consists of four communal living spaces and a bathroom, while the first floor contains four bedrooms and a bathroom. The building has ceiling to floor height of 2.5 metres and a total external wall surface area of 139 m^2. The windows are double-glazed units, with a window to wall ratio of 0.22 and a total glazed area of 30.5 m^2, with a majority of the glazing on the ground floor. A typical dwelling house construction and geometry was considered for the thermal analysis in EnergyPlus. The digital energy model of this building was validated by the authors of this study elsewhere [9].

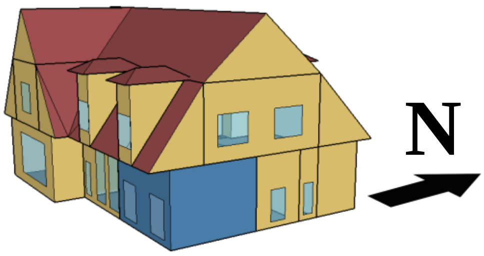

Fig. 1 - Digital CAD model of the building.

EnergyPlus [10] software was used to develop and analyse the building models. The software used for the data analysis and data post-processing was Python [11]. A Python code was developed to analyse the data efficiently and apply demand response indicators to evaluate the potential for an energy flexibility event. In the simulation setup, three-minute timestep intervals for a run period of three days were considered.

A packaged terminal heat pump with constant volume fan control, direction expansion cooling coil and electric heat pump according to baseline building HVAC system types of recommendations of ANSI/ASHRAE/IES Standard 90.1-2013 [12] was selected. HVAC system schedules were matched to the occupancy schedules, and according to the recommended indoor temperatures for energy calculations of (BS EN 16798:2019 2019 [13]. The simulation model uses climatic data made available by EnergyPlus [14]. In this study, the climatic region of Madrid, Spain was used as the geographical region which has a Mediterranean climate (Köppen Climate Classification subtype “Csa”) [15]. For the analysis of the cooling period, the design day was 21st of July. For the analysis of influence of different building envelopes on the potential of energy flexibility and demand response events, two different construction envelopes were chosen; a lightweight (LW) building typology and a mediumweight (MW) building typology, which differ in thermal mass and are shown in Table 1. The window U-value was constant for both building constructions with a value of 2.46 $W.m^{-2}.K^{-1}$.

Tab. 1 - LW and MW construction components.

Construction Envelope	LW Building U-value ($W.m^{-2}.K^{-1}$)	MW Building U-value ($W.m^{-2}.K^{-1}$)
External Walls	0.473	0.449
Ceiling	0.66	0.79
Floor	0.38	0.45

2.3 Phase change materials

To investigate different concentrations of PCM on the TES potential of a building envelope, the original gypsum board construction material of the external walls was replaced with PCM. The PCM types chosen were 100% concentrated PCM (with thickness of 10mm, PCM concentration of 100%, specific heat capacity of 2000 $J.kg^{-1}.K^{-1}$, and melting point of 25°C) (**PCM-1**) [16]; and PCM-enhanced gypsum wallboard (with thickness of 12.5 mm, PCM concentration of 30%, specific heat capacity of 2000 $J.kg^{-1}.K^{-1}$, and melting point of 25°C) (**PCM-2**) [8].

2.4 Building Energy Flexibility Scenarios

The numerical model was developed with the capability of simulating an energy flexibility event for each hour of the day by varying the room setpoint temperature. To simulate a demand response event, a pre-charging timeframe was considered, where the building envelope thermal mass was pre-cooled by decreasing the thermostat setpoint temperature. This is considered to be an upward flexibility event. Immediately after the upward flexibility event, the proposed demand response event takes place. Fig. 2 shows an example energy flexibility event programmed for the HVAC thermostat for a cooling event. The demand response event was simulated for each timeframe of the day to determine the most efficient time of day for the upward flexibility event. The energy flexibility for each building envelope considered was evaluated and analysed. The building envelopes were numerically modelled for both an upward and a downward flexibility event for cooling.

In Fig. 2, for pre-cooling of the building envelope, the thermostat setpoint temperature is decreased from 25 °C to 23 °C for either 0.5 hours, 1 hour or 2 hours for the pre-cooling stage followed immediately by a demand response event which sees the setpoint temperature increased to 27 °C for either 1 hour, 2 hours or 4 hours before returning to the normal operating temperature of 25 °C.

Simulation results of this study show that all temperature changes of the indoor environment due to demand response events are within the recommended ranges and comply with ASHRAE Standard 55-2013 [17].

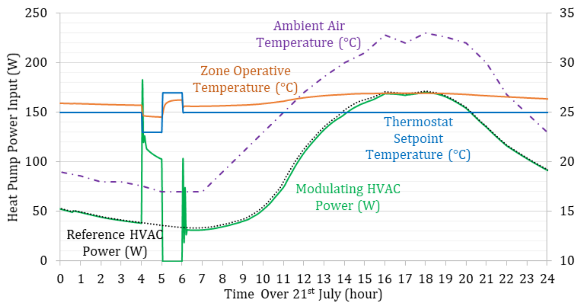

Fig. 2 – Energy flexibility event example, pre-cooling at 23°C for 1 hr, demand response at 27°C for 1 hr.

In this study, six different building envelopes were considered for cooling energy flexibility assessment:

1- LW Building with gypsum board (LW gypsum board),

2- LW Building with concentrated PCM panel (LW PCM-1),

3- LW Building with PCM-enhanced gypsum board (LW PCM-2),

4- MW Building with gypsum board (LW gypsum board),

5- MW Building with concentrated PCM panel (LW PCM-1), and

6- MW Building with PCM-enhanced gypsum board (LW PCM-2). Fig. 2 summarises the simulation scenarios.

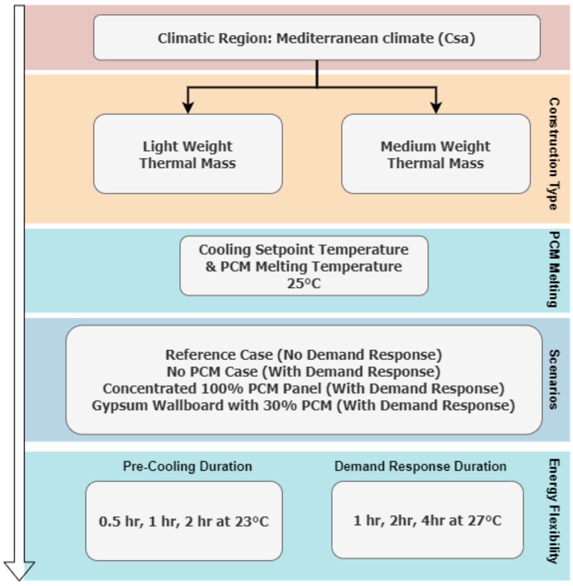

Fig. 3 - Simulation cases for a cooling energy flexibility scenario.

2.5 HVAC thermostat algorithm and data analysis

A sensitivity analysis algorithm has been programmed in EnergyPlus Energy Management System (EMS) using EnergyPlus Runtime Language [18]. This helps to automatically create various demand response events by thermostat modulating the thermostat temperature and schedule. The modulating process was repeated for each time interval of the day to numerically investigate what is the optimum pre-charging time of the day, as well as demand response duration for each building envelope. To post-process this wide array of data, Python scripts were developed which allowed for demand response indicators to be programmed and applied to the data. Currently, EnergyPlus software does not have any specific energy flexibility class, and the developed demand response and energy flexibility algorithm in this study can be integrated into EnergyPlus to further improve its capability to implement and analyse energy flexibility in buildings.

2.6 Demand Response Indicators

Reynders et al. [19] defined three indicators for quantifying energy flexibility in a DR event. These are: storage capacity (CADR), rebound effect (RE_{ADR}) and storage efficiency (η_{ADR}). To apply these performance indicators, the difference in HVAC power usage between the modulating building zone and reference building zone is calculated using equation 1:

$$P_{diff} = P_{mod} - P_{ref} \qquad (1)$$

Where P_{diff} = Difference in HVAC power consumption (W), P_{mod} = Modulating HVAC power consumption (W), and P_{ref} = Reference HVAC power consumption (W).

The capacity available for energy storage (SC) is defined as the amount of energy that can be stored during the pre-charging phase (pre-cooling) prior to the demand response event, without interfering with internal thermal comfort of the building zone as shown in Fig. 4 and can be calculated using equation 2.

$$SC = \int_0^{DR} |P_{diff}| \, dt \qquad (2)$$

Where SC = Storage Capacity (kWh).

The rebound effect indicator (RE) is defined as the amount of energy which is required by the HVAC system to restore the internal dwelling conditions to the ordinal setpoint temperature after the demand response event has passed and is given by equation 3.

$$RE = \int_{Post-DR}^{\infty} |P_{diff}| \, dt \qquad (3)$$

Where RE = Rebound Effect (kWh).

In this study, the rebound effect for six hours after the demand response event was considered. An indicator that is not considered by Reynders et al. [19] is the power curtailed during the demand response event. This is an indicator needed to define the amount of energy that can potentially be curtailed during the demand response event and is shown in Fig. 4. It is also needed to define the storage efficiency of the building and can be calculated using equation 4.

$$PC = \int_{DR}^{\mathrm{Post-DR}} |P_{diff}| \, dt \qquad (4)$$

Where PC = Power Curtailment (kWh)

According to Reynders, Diriken, and Saelens [19], the storage efficiency (η) is described as the fraction of stored heat prior to the demand response event compared to the heat released to maintain the internal comfort temperature during the demand response event and is given by equations 5 and 6.

$$\eta_{DF} = 1 - \frac{RE}{SC} \tag{5}$$

$$\eta_{UF} = \frac{RE}{SC} \tag{6}$$

Where η_{DF} = Efficiency of a downward flexibility event, and η_{UF} = Efficiency of an upward flexibility event.

However, indicators defined by Reynders et al. [19], do not take into account an event where both a pre-charging phase and a demand response event are considered. Therefore, in the current study, the storage efficiency indicator was further improved to consider the pre-cooling thermal energy storage event as shown in equation 7 and Fig. 4.

$$\eta = \frac{PC}{SC + RE} \tag{7}$$

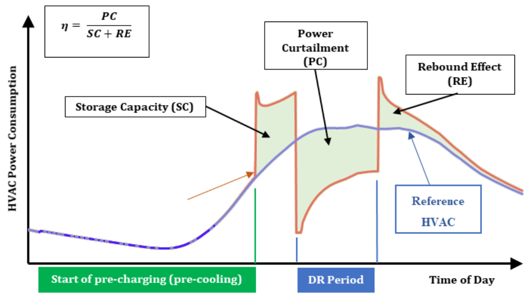

Fig. 4 – Energy flexibility indicators and schematic.

3. Results

3.1 Peak power and cooling energy analysis

When studying the building envelope to investigate power curtailment, it can be seen that the energy flexibility event which has a 2-hour pre-charging (pre-cooling) time and a 4-hour demand response time offers the highest power curtailment. For example, Fig. 5 shows the power curtailment for MW thermal mass envelope with 100% concentrated PCM for all flexibility events and it can be observed that 2-hour, and 0.5-hour pre-cooling, followed by a 4-hour demand response event, offer the highest power curtailment and energy flexibility for cooling.

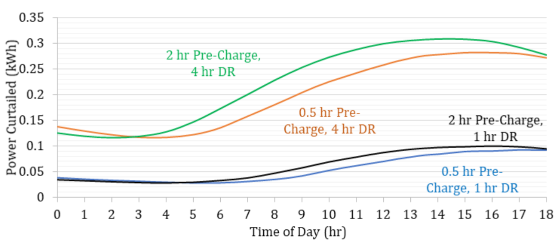

Fig. 5 - Power curtailment for MW PCM-1 envelope across each energy flexibility event.

From the results achieved in this study, it can be concluded that for energy flexibility scenarios, the pre-charge length should be always less than the length of the demand response event to ensure higher efficiencies. A pre-charging event which is the same length or longer than the demand response event is the least efficient type of energy flexibility event and should be avoided when participating in an energy flexibility scenario.

It can be observed that in the 0.5-hour pre-charging event and the 4-hour demand response, power curtailment is highest in the LW envelopes for each class of material, however, the MW buildings have a higher efficiency for each class.

By considering Fig. 5, it can be seen that the highest power curtailment for each energy flexibility event in a MW 100% concentrated is achieved around 14:00 hrs. The energy flexibility event start time of 14:00 hrs sees the highest power curtailment (0.31 kWh) due to the highest ambient air temperature occurring during the demand response period, with the 2-hour pre-charge and 4-hour demand response. The lowest power curtailment value is seen for 0.5-hour pre-charge and the 1-hour demand response with a value of 0.09 kWh.

However, to achieve the highest efficiency, the energy flexibility event should start later in the day at a time of 18:00 hrs. The maximum efficiency is seen later in the day due to the reduced rebound effect. Taking this into consideration when applying an energy flexibility scenario to a dwelling house, it is important to consider the purpose of the energy flexibility event and is it essential to curtail power or essential to have an efficient event. Similar trends are seen for LW building envelopes across all energy flexibility events.

Another observation is that the length of the demand response event is the most influential variable on power curtailment and efficiency, compared to the pre-charging length and therefore, the length of demand response event should be considered the most when implementing an energy flexibility event.

The data shown in Tab. 2, Tab. 3, and Tab. 4, is the mean value for each energy flexibility event across the whole design day for storage capacity, power curtailment and flexibility efficiency, respectively. Tab. 2 shows that the LW and MW PCM-1 envelopes have the highest average storage capacity across all events. The LW and MW are shown to have the lowest average storage capacity for each day which shows that the building envelopes storage capacity performance can be enhanced by PCMs. It can also be concluded that the percentage of PCM retrofitted to the wall has an influence on the storage capacity.

Tab. 2 - Average value for storage capacity across the cooling design day.

	Storage Capacity (kWh)								
Pre-charging length	0.5 hr			1 hr			2 hr		
DR length	1 hr	2 hr	4 hr	1 hr	2 hr	4 hr	1 hr	2 hr	4 hr
LW Gypsum	0.04	0.04	0.04	0.08	0.08	0.08	0.14	0.14	0.13
MW Gypsum	0.04	0.04	0.04	0.08	0.08	0.08	0.14	0.14	0.14
LW PCM-1	0.05	0.05	0.05	0.09	0.09	0.09	0.15	0.16	0.15
MW PCM-1	0.05	0.05	0.05	0.09	0.09	0.09	0.16	0.16	0.16
LW PCM-2	0.05	0.05	0.05	0.08	0.08	0.08	0.15	0.15	0.15
MW PCM-2	0.05	0.05	0.05	0.09	0.09	0.09	0.16	0.16	0.16

For the daily average values of power curtailment shown in Tab. 3, it can be observed that the LW PCM-2 and the LW PCM-1 offer the greatest amount of power curtailment across each energy flexibility event. It can be noticed that the LW gypsum envelope has only a marginal difference in the power curtailment values.

Tab. 3 - Average value for power curtailment across the cooling design day.

	Power Curtailed (kWh)								
Pre-charging length	0.5 hr			1 hr			2 hr		
DR length	1 hr	2 hr	4 hr	1 hr	2 hr	4 hr	1 hr	2 hr	4 hr
LW Gypsum	0.07	0.12	0.20	0.07	0.12	0.21	0.07	0.13	0.22
MW Gypsum	0.06	0.11	0.19	0.06	0.11	0.20	0.06	0.12	0.21
LW PCM-1	0.07	0.13	0.22	0.07	0.13	0.23	0.08	0.14	0.25
MW PCM-1	0.06	0.11	0.21	0.06	0.11	0.21	0.06	0.12	0.22
LW PCM-2	0.07	0.12	0.21	0.07	0.13	0.22	0.08	0.14	0.24
MW PCM-2	0.06	0.11	0.21	0.06	0.12	0.21	0.07	0.12	0.23

The MW envelopes are shown to have the worst power curtailment potential, however, in general MW buildings require the least amount of reference HVAC energy consumption and are overall more favourable at reducing energy consumption during demand response events.

Looking at the average flexibility efficiency values in Tab. 4, the MW PCM envelopes have the highest efficiency when they are involved in short pre-charging events and long demand response events. However, when short pre-charge lengths are combined with short demand response events, the LW PCM buildings are better performers. The MW gypsum building has overall worst performance for the short pre-charging events.

Tab. 4 - Average value for flexibility efficiency across the cooling design day.

	Flexibility Efficiency (%)								
Pre-charging length	0.5 hr			1 hr			2 hr		
DR length	1 hr	2 hr	4 hr	1 hr	2 hr	4 hr	1 hr	2 hr	4 hr
LW Gypsum	96	130	169	66	100	138	47	75	112
MW Gypsum	91	134	188	62	98	147	41	69	112
LW PCM-1	104	141	181	69	106	147	45	75	117
MW PCM-1	99	145	203	62	103	156	35	68	115
LW PCM-2	102	139	180	67	104	145	46	74	115
MW PCM-2	99	144	202	65	105	156	39	70	116

When the pre-charging events increase towards 2 hours, the LW envelopes are seen to outperform the MW buildings. For a combination of long pre-charging phases and short demand response phase, the MW PCM-1 envelope is seen to be overall the worst performer. This is due to a large quantity of energy that can be stored in the thermal inertia, however, cannot be released in the short demand response period.

4. Conclusions

This study gives important data on how the building envelope can provide energy flexibility for the grid and how innovative design of building envelope using PCM can increase the overall energy performance of the building and more importantly offer energy-resilient buildings. Demand response strategies presented here for building envelope design could be used in energy retrofit policies and demand response strategies. A building sensitivity assessment to show the characterisation and performance of each TES building envelope in a cooling condition was carried out. A detailed assessment of the power curtailment performance of four different energy flexibility scenarios were looked at and discussed in detail.

- It was clear for the cooling scenario that, the short pre-charging period and long demand response period is the most preferable event across all envelopes for maximum power curtailment and efficiency.
- PCM-impregnated gypsum board retrofitted on the LW, and MW envelopes are shown to give an overall good performance in flexibility efficiency and in power curtailment.
- The MW envelopes showed to be resistant to the effects of the external environment due to the heavier sensible thermal inertia that is involved with it.
- For shorter demand response events, the LW sensible TES is shown to be most effective as the storage capacity can discharge faster over the short demand response period. The PCM enhanced envelopes are marginally better than the Gypsum envelope when the pre-charging period is shorter.
- Overall, the thermostat modulation from 25 °C to 23 °C in the pre-charging phase is less effective than changing the thermostat from 23 °C to 27 °C in the demand response phase.

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Data Statement

The authors confirm that the data supporting the findings of this study are available within the article. Currently, the CAD files used by the simulation models are not available to be shared publicly.