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# Improving the building energy flexibility using PCM-enhanced envelopes

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ABSTRACT

Pre-formed internal insulative panels with impregnated phase change materials (PCM) can significantly increase both the thermal resistance and thermal capacitance of existing or new building envelopes, thereby improving the overall energy performance of buildings. A further advantage is that such measures have the potential to enhance the energy flexibility of the building, 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 energy flexibility and demand response, especially in the context of the building envelope integrated design with high latent heat materials such as PCM for demand response applications. The objective of the current study is to examine how the addition of PCM impregnated building envelopes affects both the thermal performance of the building envelope, as well as the wider building energy characteristics when subject to different demand response events. A reference building is utilised, which is a residential detached house with a floor area of 160 $m^2$ and a south-easterly facing aspect. Another contribution of this study is proposing new energy flexibility indicators taking into consideration envelope pre-cooling and pre-heating periods prior to the demand response event. Simulation results show that shorter envelope pre-cooling periods (0.5 hr) together with longer demand response periods (4 h) are preferable for all envelopes to achieve the maximum power curtailment for cooling. PCM-enhanced envelopes are shown to give best cooling demand shifting and energy flexibility efficiency. The MW PCM-1 and MW PCM-2 envelopes have the highest flexibility efficiency with a value of 244%. For heating, gypsum board enhanced with PCM retrofitted on the envelopes are shown to give an overall good performance in energy flexibility efficiency and in power curtailment compared to the other building envelopes in all durations of an energy flexibility event. For heating, the maximum energy flexibility efficiencies range from 250% for the LW Gypsum Board envelope to 356% for the LW PCM-2 envelope.

## 1. Introduction

With relation to the 2021 Glasgow Agreement policy (COP26), many countries are obliged to adopt low-carbon policies in order to hold the global average temperature to below 2 °C [1]. In this context, the European Union (EU) has the ambition to scale down carbon footprints by 80% to 95% below 1990 levels by 2050. Enhancing energy performance in the building sector has been highlighted as an important step forward in the context of the 2050 Roadmap to moving to a competitive low-carbon economy [2], as 36% of the total $CO_2$ emissions come from this sector, with HVAC systems contributing to 50% of the total final energy consumed in the EU [3].

Considering this from a global perspective, a 100% changeover to heat pumps would increase the current worldwide electrical energy demand by up to 11% and would increase the peak load demands by up to 65% [4]. This resultant energy demand shift in the form of electrical energy is likely to induce severe strain on the various national grid systems. This will lead to grids becoming less reliable during peak times with significant consequences such as voltage fluctuations and even power outages [5].

On the other hand, due to the increasing integration of renewable energies, such as wind and solar into the electricity grid, the grid itself will possibly become less resilient due to the variability of these renewables [6]. This insecurity in the energy supply is likely to only increase due to the growing dependence on electricity to the meet carbon neutral goals by 2050 [7].

One possible way of tackling electricity supply and demand mismatches is through the concept of energy flexibility [8]. The flexibility of the energy system is considered to be a promising potential solution

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that would ensure improved operation of the energy grid while still integrating a high share of renewable energy sources.

Demand-side management (DSM) strategies that can make buildings more energy resilient include demand response (DR), thermal energy storage (TES), and renewable energy integration. As outlined by Mariano-Hernández et al. [9], future smart buildings are likely to have integrated on-site renewable generation, energy storage (thermal and electrical), DSM, advanced control and communication units which are controlled by building energy management systems.

In accordance with the Directive 2019/944 (EU) [10], the definition of *Demand Response* is a change of electricity load by final customers from their conventional or current consumption patterns in response to market signals, such as in response to time-of-use electricity prices, incentive payments, or in response to the acceptance of the final customer's bid to sell demand reduction or increase at a specific price in an organised market [11].

Renewed interest in demand response by balancing the electricity grid supply and demand by a timed increase or decrease is considered as an efficient approach for DSM [12,13], in conjunction with TES to enhance the energy performance of building, has gained an increasing attention for sustainable building design.

Thermal energy storage (TES) is a term used to describe the possibility of storing thermal energy in a building for later use, which would in turn give the desired flexibility to the energy system for a DR event as described by Foteinaki et al. [14]. TES is one possible solution which can provide flexibility to varying energy demands. Hence, this allows for a building to perform more efficiently in times of high peak energy demands as well as benefiting from the low carbon renewable energies that are produced at times of lower demands.

The quality of the building structure can play an important role to improve the energy flexibility of buildings by means of passive TES. Building envelopes with thermal mass can be pre-heated or pre-cooled to give the energy flexibility needed during a DR event, while still maintaining thermal comfort and high thermal efficiency in the building. Aside from simply applying insulation to the building envelope to improve energy performance, the possibility of incorporating additional thermal inertia, by means of PCM-impregnated envelopes thereby increasing both the energy efficiency and enhancing the energy flexibility of a building, could be an option in future home retrofit schemes.

## 2. Literature review

DR in residential buildings can be implemented by considering demand loads according to two categories, namely, non-thermal loads (e.g., lighting and appliances) and thermal loads (e.g., HVAC). A DR event associated with thermal loads can be shifted from high peak times to low peak times by using TES. With TES, it allows the building occupant to charge the storage material during off-peak times and then reduce or shut down HVAC systems during periods of peal electrical demand. The already stored thermal energy from the upward flexibility event can be released and maintain the comfort of the occupants during the DR event [15].

According to Vivian et al. [16], a DR event is an event limited by time where a change in boundary conditions has an effect on both the indoor environment and on the energy consumption pattern of a building. In short, a DR event is a timed change in the increase or decrease of room temperature to offer energy flexibility by powering off the HVAC system at high demand periods. However, it should be noted that *high demand periods* do not refer to the thermal energy demand of a single building, but to the electricity demand of all users connected to the same distribution network.

Buildings with a higher energy flexibility potential will be better suited to participate in DR programmes as the building will meet the storage requirements set out by the system operator or a third party aggregator [16]. Accordingly, it is desirable for buildings to be designed with the optimum passive TES materials in future to be able to participate in a DR event efficiently.

Clauß et al. [17] showed that the use of DR controls reduces energy use for heating at peak times with a particularly efficient margin for direct heating systems. They also concluded that for a building situated in a Norwegian electricity market, that a price based control does not generate cost savings as the lower cost of electricity is outweighed by the increase in the electrical requirement for heating prior to a DR event [17].

These findings show a possible knowledge gap in the literature on optimising demand response strategies for improved energy flexibility in buildings. One option for enhancing the thermal performance and energy flexibility of building envelopes is the use of thermal energy storage materials such as phase change materials as an integrated passive design which will be further studied in this paper.

TES can be used to optimise energy flexibility in a building by charging the available storage during off-peak periods and then dissipating the thermal energy during on-peak periods [15].

The TES of a building is influenced by thermal mass of the building and can be controlled by the building envelope construction properties. The building envelope acts as a passive thermal storage medium. 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 [18,19].

Building construction can be divided into different categories such as light-weight (LW), medium-weight (MW), and heavy-weight (HW) constructions. A high thermal mass (e.g., concrete construction) is considered to have a high TES potential while a lightweight building with a low thermal mass (e.g., metal frame construction) is considered to have a low TES potential [20]. When looking at the passive TES of a construction, it can be termed as sensible heat thermal energy storage when the material temperature rises or falls to store heat, or latent heat thermal energy storage when a material phase change occurs with little to no change in temperature [21]. Sensible heat storage materials for buildings are considered to be concrete, brick and masonry stone [22].

On the other hand, a relatively advanced energy storage material for building application is phase change material (PCM). PCMs are a latent heat storage technology which can store large amounts of heat in mostly isothermal conditions or in a very narrow temperature range [23]. Typical PCMs include water, salt hydrates, eutectics and certain polymers (e.g., paraffin) [24].

The use of PCM to enhance the thermal energy performance in buildings has gained increasing attention in recent years [25]. PCMs can be retrofitted into the walls and ceilings of residential dwellings not only to minimise the fluctuations in indoor ambient temperature but to also reduce heating, cooling, and air-conditioning loads [26]. With the use of latent thermal storage technologies in building structures, it has the potential to offer DR opportunities in supply led electric systems as well as better accommodating a low carbon renewable energy supply [27]. However, there continues to be a lack of research, coupled with uncertainty, in analysing the DR performance of different domestic dwelling building construction such as lightweight (LW) and medium weight (MW) envelope fabrics. Moreover, the use of PCM with varying building thermal masses and demand response strategies have not been considered and is a gap in knowledge that could be addressed.

Rahimpour et al. [28] showed that the selection of PCMs based on the melting point has a significant impact on demand shift time and demand reductions which is of importance to this study when selecting a suitable PCM to be applied to the building envelope. Markarian and Fazelpour [29] also showed that PCM with a low melting temperature of 21 °C is best suited for a building that requires a heating input, while a PCM with a higher melting temperature of 25 °C is more effective for a building that requires a cooling input.

However, Wang et al. [26] showed that a PCM with a melting temperature of 24 °C is more suitable for summertime, while a PCM with a melting temperature of 21 °C is more suitable for wintertime in

Shanghai. In summer, PCM enhanced rooms are understood to raise the indoor temperature less than that of a reference room without PCM in the daytime. The use of PCM as a passive energy storage system was not considered in this study which could be studied further.

Dominković et al. [30] showed that buildings with a high thermal mass of concrete (sensible TES) can tolerate large variations in heat inputs while still maintaining an acceptable indoor thermal condition. Also Foteinaki et al. [14] show that low energy HW buildings can remain autonomous for several hours while maintaining thermal comfort due to their high thermal capacity. The building construction determines the amount of thermal mass and energy storage that is available to the building eventhough heat losses may govern the potential for flexibility.

Becker [20] carried out a study on the retrofitting of the LW, MW, and HW building envelopes with PCM under a Mediterranean climate condition. It was found that the application of PCMs in LW buildings can improve the thermal comfort and reduce the primary energy required for space cooling. However, it was found by Becker [20] that LW buildings with PCM applied was still being outperformed by the no PCM HW building in terms of the increase of the indoor air temperature above 26 °C. The dynamic analysis of the HW building showed that application of PCM in walls can further help the thermal comfort by keeping the surface temperatures below those obtained when no PCM is utilised. For a 2 hour DR event, the heat release ratio for walls and floor is approximately 23.9% and 10.8%, respectively, while for furniture it is 73.2%. This means that a large portion of heat is being maintained in the walls and floors and cannot be released quickly enough to react to a DR event. In this study, the heat release ratio of PCM was not taken into consideration which could be of interest to show the heat release ratio of stored latent heat energy compared to that of stored sensible energy.

Similarly, Wolisz et al. [31] showed that during the DR event that sensible energy stored in the wall mass of a HW building is not sufficient to maintain the internal thermal comfort. Reynders et al. [32] investigated Belgian building typologies (MW and HW) when different demand response events were studied. It was found that the solid concrete wall (HW) had 93% storage efficiency, compared to a cavity wall (MW), which had 81% storage efficiency for a 4 hour DR event. This result is due to a larger thermal mass being available in type one but contradicts the findings of Chen et al. [33] and Wolisz et al. [31]. More information about the storage efficiency can be found in Section 3.7.1.

Foteinaki et al. [14] consider two different types of modulations for a flexibility event. The two modulations considered are an upward flexibility event or a downward flexibility event. In an upward flexibility event, the set point room temperature is increased by approximately 2 °C to charge the thermal mass. However, in a downward flexibility event, the thermostat temperature is decreased by 2 °C, which discharges the thermal mass. During the DR event when the HVAC system is powered off, the energy is either released from the thermal mass or absorbed by the thermal mass depending on the required heating or cooling effect, respectively.

According to the findings of Dominković et al. [30], pre-heating for up to 4 hours before a DR event would have a positive effect on energy flexibility of a high thermal mass building but should be individually evaluated for each construction to be considered for a DR scenario. This is an important gap in research which should be further investigated. The potential for HVAC shut down was longer (6 h) in newer, better developed buildings without compromising thermal comfort compared to older poorly retrofitted buildings. However, Dominković et al. [30] did not consider building envelope passive design with latent thermal storage materials such as PCM.

In another study Reynders et al. [32] showed that the DR efficiency for a demand response event of 4 hours with a set point temperature increase of 2 °C can yield from 12 kWh to 30 kWh thermal storage capacity using the building envelope thermal mass. To prevent a decrease in efficiency of passive thermal storage, the activation of the TES should be limited to short DR events, especially for buildings with radiator heating distribution systems. Also, it was shown that the reference solution with no increase in set point temperature took longer to recover from a previous DR event and therefore could not take part in a close upcoming DR event as the HVAC system was operating at its maximum capacity.

According to Foteinaki et al. [14], the start time of the downward flexibility event has a significant effect on the potential for power curtailment with the results showing that the highest available energy can be curtailed during the night in cooling conditions.

Marin et al. [18] showed that while decreasing HVAC loads throughout the whole year, PCM with a melting temperature of 25 °C could shift peak cooling loads significantly for the whole year in an extremely LW building. In the LW building the cooling load was shifted from 11:00 to between 14:00 and 17:00 thus making PCM effective for DR in this case. Devaux and Farid [34] carried out a similar study, nevertheless, the PCM melting temperature and the DR pre-cooling was not taken into account. This is another knowledge gap worth investigating further in this paper.

In another study, Arıcıet al. [35] showed that the maximum delay in the peak heat fluxes from a PCM layer located in the inner surface of the external wall 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 the reference solution is significant when studying the retrofitting of PCM to enhance the TES of a building for DR events. Taking the delay in heat flux into consideration could prove significant in the timing of the DR event. The thermal conductivity of PCM could also influence the timing for an upward or downward energy flexibility events.

In a numerical study carried out by Rahimpour et al. [28] on LW and HW buildings in five Australian cities. The retrofitting of PCM on ceilings, walls, and floors of a HW building resulted in an overall annual HVAC demand and energy use reduction. It was concluded that as a result of using PCM, a shift in HVAC demand was achieved from between 9–103 minutes for different climates in Australia when the HVAC system was operating based on 24 hour schedule, but setpoint temperature changed (downward flexibility). This is an interesting conclusion which could be further researched by showing how pre-cooling and pre-heating of the building envelope could further shift the HVAC demand. This is another potential knowledge gap which will be investigated in this study.

### 2.1. Contributions of this study

The literature review has shown that, although there is considerable research studies on the application of building integrated passive thermal energy storage for energy performance and thermal comfort improvement, to date a limited number of research papers have been published which show how different dwelling house building envelope enhanced with PCM perform during a specific demand response event. For example, in a recent study, Kishore et al. [36] carried out a parametric and sensitivity analysis for thermal load management in buildings using PCM-enhanced passive envelope technology. Similarly, in another study, Kishore et al. [37] implemented controlled pre-cooling strategies using thermal energy storage materials for thermal load management in residential buildings.

Moreover, to the best knowledge of the authors, the use of pre-heating and pre-cooling of the envelope prior to a demand response event has never been fully investigated for different building constructions where PCM passive technology is implemented, and far too little attention has been paid to this.

Also, the exact timing and duration of a demand response event for different enhanced building typologies have not yet been addressed in detail in the current literature.

Therefore, the main contributions and associated novelty of the current study include: 1—investigation of the effect that PCM-retrofitted building envelope have in both heating and cooling demand response scenarios, 2—assessment of the energy performance of a building when pre-cooling and pre-heating when different time periods prior to a demand response event are deployed, and 3—examination of the energy flexibility potential of different building envelopes through a new proposed *Energy Flexibility* indicator which takes into account pre-cooling and pre-hearing periods prior to a *Demand Response* event.

The methodology proposed in this study can then be utilised to develop timeframe-based daily energy flexibility maps for building and energy engineers, home owners and demand response participants, BMS engineers, and aggregators who may have a portfolio of residential buildings. Such energy flexibility maps will take into account the different construction materials and building envelopes used in the construction of dwelling houses. This study will be carried out for a climatic region that requires both heating and cooling to maintain indoor thermal comfort and can thus be used in both heating-dominant and cooling-dominant climates.

## 3. Methodology

This section provides a detailed description of the research methodologies used in this research. Section 3.1 outlines the different building specifications and procedures used to develop the numerical model used in this study, Section 3.2 describes the building envelopes and construction materials, Section 3.3 gives details on the dynamic simulation tool utilised for modelling and simulation, Section 3.4 outlines the characteristics of the phase change materials used, Section 3.5 identifies different energy flexibility scenarios which are investigated. Section 3.6 discusses in greater detail the procedures used in performing each of the individual analyses of a DR event using automated sensitivity analysis and data analytics, and Section 3.7.1 describes the Demand Response Indicators used to assess the performance and efficiency of different scenarios.

### 3.1. Case study building description, modelling and analysis

The reference building is a residential detached house constructed in 1999. The building has a floor area of 160 $m^2$. 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 v8.7* [38]. The construction geometry considered for analysis can be seen in Fig. 1. For the thermal analysis, the bedroom located on the south façade was investigated, which has an electric air-source heat pump system. This zone was selected because the south and east face walls receive the highest solar radiation over a year where envelope integrated PCM can be used for thermal regulation. The infiltration rate was set to a constant value of 0.5 ACH, and a constant internal load of 1.2 met (70 W/$m^2$) was considered [39]. In this study, neither natural ventilation nor mechanical ventilation were considered.

The software used to develop and analyse the building models were *SketchUp* [40] and *EnergyPlus v8.7* [38], respectively. The software used for the data analysis and data presentation were *Python* [41] and Microsoft Excel. A *Python* [41] code was developed to analyse the data efficiently and apply DR indicators to evaluate the potential for an energy flexibility event. In the simulation setup, 1 minute time step for a run period of three days were utilised.

An electric air-source heat pump with direct expansion (DX) heating and cooling coils serves as the air conditioning system [18]. The heat pump operates 24-h per day throughout the year. To maintain the indoor air temperature within the comfort criteria, a dual set point thermostat with dead-band operative temperature control was selected according to the recommended indoor temperatures for energy calculations of BS EN 15251 [39]. The thermostat control was set to 20 °C for heating and 25 °C for cooling, as recommended for residential buildings and living spaces [39]. Furthermore, relative humidity ratios for dehumidification and humidification were considered to be 60% and 25%, respectively, within the recommended design criteria of BS EN 15251 [39].

The electric heat pump cooling and heating rated coefficient of performances (COP) are 3, and 2.75, respectively. The supply fan total efficiency and motor efficiency are 0.7 and 0.9, respectively. The heat pump gross rated capacity is auto-sized and is based on the maximum heating loads during the heating and cooling design day.

For the analysis of the heating period, weather data was taken for the design day of 21st January and for the cooling period, the design day was 21st July. Fig. 2 shows 3 days plot of outdoor dry bulb temperature and solar radiation data for cooling season July 20–22 2(a) and heating season January 20–22 2(b).

The simulation model uses climatic data made available by *EnergyPlus Weather (EPW) Data Sources* [42]. For the purpose of this research, the climatic region of Madrid, Spain was used as the geographical region. Madrid has a Mediterranean climate (Köppen Climate Classification subtype *"Csa"*) [43] which has moderate winters and very warm summers and therefore, requires heating in winter and cooling in the summer. The main annual climate conditions for the selected city are shown in Table 1. It should be noted that cooling degree days (CDD) and heating degree days (HDD) are calculated on a baseline of 18.3 °C in accordance with ASHRAE climate design data [44].

### 3.2. Building envelope

For the analysis of influence of different construction types on the potential of energy flexibility events, two different construction envelopes were considered; a light weight (LW) building typology and a medium weight (MW) building typology. The difference between the two different construction types is the thermal mass of each envelope. The thermal mass has a significant effect on the TES potential of a building and thus influences the potential for a DR event. The two typologies of building envelope can represent a majority of steel-framed light weight envelope buildings, and building envelopes with brick or concrete with higher thermal mass.

The building envelopes data are extracted from the ASHRAE Materials Dataset [45] which are shown in Table 1. The window U-value was constant for both building constructions with a value of 2.46 $W{\cdot}m^{-2}{\cdot}K^{-1}$. To investigate the effects of retrofitting the internal surfaces (exposed to indoor environment) of the vertical walls with different PCM concentrations, a reference building envelope was created which uses standard gypsum board (GB) as the inner layer of the vertical walls. Table 2 shows the construction details of the case study building, and internal and external areal heat capacity values of different envelopes calculated using the methodology proposed by EN ISO 13786 [46]. In Table 2, $d$ is thickness (m), $\lambda$ is thermal conductivity (W/m·K), $\rho$ is density (kg/$m^3$), $c$ is specific heat capacity (J/kg·K), and $R$ is thermal resistance ($m^2$·K/W).

### 3.3. Dynamic energy simulation

A set of numerical simulations were performed using *EnergyPlus v8.7* dynamic building energy simulation tool [38]. EnergyPlus is an energy simulation program for modelling and simulation of the thermal envelope, HVAC system, lighting, energy management systems, etc. in buildings.

In order to simulate PCM in EnergyPlus, a Conduction Finite Difference (ConFD) solution algorithm is used. This one-dimensional CondFD

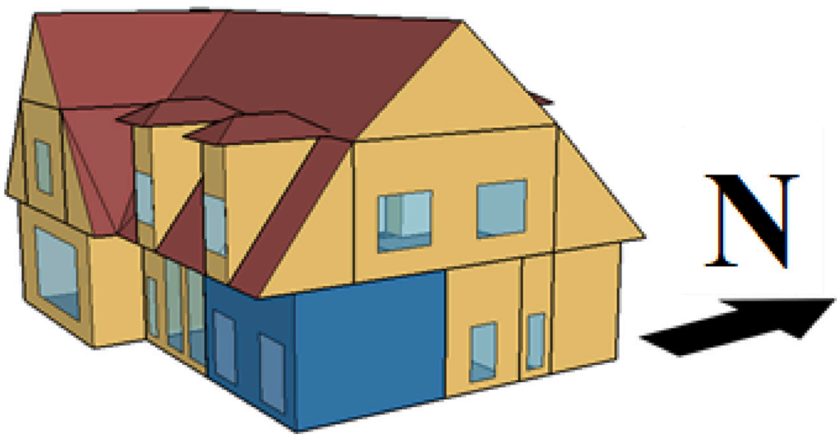


**Fig. 1.** Case study building modelled in SketchUp.

**Table 1**
Climate conditions of Madrid (Latitude: N 40°27′, Longitude: W 3°32′).

| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Ave. dry bulb temperature (°C) | 5.6 | 6.9 | 10 | 11.7 | 16.9 | 20.6 | 25.5 | 24.7 | 20.1 | 14.2 | 9.4 | 5.9 |
| Relative humidity (%) | 72 | 69 | 61 | 55 | 60 | 52 | 40 | 45 | 57 | 70 | 75 | 84 |
| Global ave. solar radiation (Wh/m$^2$) | 1958 | 2767 | 4424 | 5356 | 6169 | 7136 | 7420 | 6387 | 4482 | 3278 | 2222 | 1439 |
| Wind speed (m/s) | 3.1 | 2.6 | 2.7 | 3.6 | 1.9 | 2.2 | 2.7 | 3.2 | 2.8 | 0.9 | 1.5 | 2.2 |
| CDD (°C ) | 398 | 318 | 251 | 189 | 88 | 11 | 1 | 1 | 17 | 113 | 263 | 375 |
| HDD (°C) | 0 | 0 | 0 | 1 | 18 | 110 | 208 | 192 | 78 | 4 | 0 | 0 |

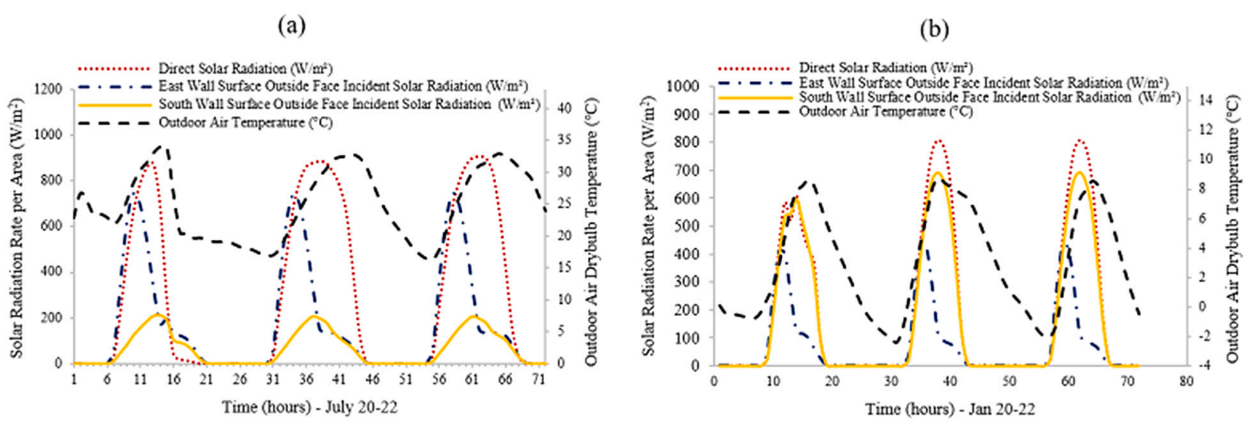


**Fig. 2.** Outdoor air dry bulb temperature and solar radiation data for July 20–22 (a), and for January 20–22 (b).

algorithm discretises building envelope into several nodes, and numerically solves the heat transfer equations by utilising a finite difference method [47,48].

CondFD algorithm uses an implicit finite difference algorithm in EnergyPlus with a fully implicit scheme and is first order in time as shown in Eq. (1).

$$C_p \rho \Delta x \frac{T_i^{j+1} - T_i^j}{\Delta t} = \left( K_W \frac{T_{i+1}^{j+1} - T_i^{j+1}}{\Delta x} + K_E \frac{T_{i-1}^{j+1} - T_i^{j+1}}{\Delta x} \right) \tag{1}$$

$$K_W = \left( \frac{K_{i+1}^{j+1} + K_i^{j+1}}{2} \right) \tag{2}$$

$$K_E = \left( \frac{K_{i-1}^{j+1} + K_i^{j+1}}{2} \right) \tag{3}$$

where, $T$ is node temperature, subscripts $i$ and $i+1$ are node being simulated and adjacent node to interior of construction, $i-1$ is adjacent node to exterior of construction, $j+1$ is new time step, $j$ is previous time step, $\Delta t$ is calculation time step, $\Delta x$ is finite difference layer thickness, $C_P$ is specific heat of material, $K_W$ is thermal conductivity for interface between $i$ node and $i+1$ node, $K_E$ is thermal conductivity for interface between $i$ node and $i-1$ node, and $\rho$ is density of material.

Eq. (4) is used to in the CondFD algorithm to discretise all components, which depends on the thermal diffusivity of the material ($\alpha$), the time step, and the space discretisation constant $c$ which can be set to default value of 3 [47,49].

$$\Delta x = \sqrt{C \ \alpha \ \Delta t} \ = \sqrt{\frac{\alpha \times \Delta t}{F_O}} \tag{4}$$

To simulate PCM and the phase change process, the CondFD algorithm is coupled with an enthalpy-temperature ($h$-$T$) function, as shown in Eq. (5)), which reads the user inputs of $h$-$T$ curve [50]. In each iteration the node enthalpy values are updated and subsequently used to develop an equivalent specific heat $C_P$ at each time step. This is done by considering a third equation for $C_P$ as can be seen in Eq. (6) [49]. This model is a modified version of the enthalpy method which was proposed by Pedersen [50].

$$h_i = HTF(T_i) \tag{5}$$

**Table 2**
Details of construction and materials.

| **Light weight building construction** | | | | | |
|---|---|---|---|---|---|
| External walls | d (m) | λ (W/m·K) | ρ (kg/m$^3$) | c (J/kg·K) | R (m$^2$·K/W) |
| Metal surface (Ext.) | 0.01 | 30 | 7824 | 500 | |
| 50 mm insulation board | 0.05 | 0.03 | 43 | 1210 | |
| Wall air space resistance | | | | | 0.15 |
| 19 mm gypsum board (Int.) | 0.019 | 0.16 | 800 | 1090 | |
| U-Value: 0.47 W/m$^2$·K | | | | | |
| Internal areal heat capacity: 36 kJ/m$^2$·K | | | | | |
| External areal heat capacity: 20 kJ/m$^2$·K | | | | | |
| Internal walls | d (m) | λ (W/m·K) | ρ (kg/m$^3$) | c (J/kg·K) | R (m$^2$·K/W) |
| 19 mm gypsum board (Ext.) | 0.019 | 0.16 | 800 | 1090 | |
| Wall air space resistance | | | | | 1 |
| 19 mm gypsum board (Int.) | 0.019 | 0.16 | 800 | 1090 | |
| U-Value: 0.71 W/m$^2$ | | | | | |
| Internal areal heat capacity: 15 kJ/m$^2$·K | | | | | |
| External areal heat capacity: 18 kJ/m$^2$·K | | | | | |
| Internal ceiling/floor | d (m) | λ (W/m·K) | ρ (kg/m$^3$) | c (J/kg·K) | R (m$^2$·K/W) |
| F16 Acoustic tile (Ext.) | 0.019 | 0.06 | 368 | 590 | |
| Ceiling air space resistance | | | | | 0.85 |
| 100 mm lightweight concrete (Int.) | 0.1 | 0.53 | 1280 | 840 | |
| U-Value: 0.65 W/m$^2$k | | | | | |
| Internal areal heat capacity: 10 kJ/m$^2$·K | | | | | |
| External areal heat capacity: 79 kJ/m$^2$·K | | | | | |
| **Medium weight building construction** | | | | | |
| External walls | d (m) | λ (W/m·K) | ρ (kg/m$^3$) | c (J/kg·K) | R (m$^2$·K/W) |
| 100 mm brick (Ext.) | 0.1016 | 0.89 | 1920 | 590 | |
| 50 mm insulation board | 0.0508 | 0.03 | 43 | 1210 | |
| Wall air space resistance | | | | | 0.15 |
| 19 mm gypsum board (Int.) | 0.019 | 0.16 | 800 | 1090 | |
| U-Value: 0.44 W/m$^2$K | | | | | |
| Internal areal heat capacity: 65 kJ/m$^2$·K | | | | | |
| External areal heat capacity: 20 kJ/m$^2$·K | | | | | |
| Internal walls | d (m) | λ (W/m·K) | ρ (kg/m$^3$) | c (J/kg·K) | R (m$^2$·K/W) |
| 19 mm gypsum board (Ext.) | 0.019 | 0.16 | 800 | 1090 | |
| Wall air space resistance | | | | | 1 |
| 19 mm gypsum board (Int.) | 0.019 | 0.16 | 800 | 1090 | |
| U-Value: 0.71 W/m$^2$k | | | | | |
| Internal areal heat capacity: 15 kJ/m$^2$·K | | | | | |
| External areal heat capacity: 18 kJ/m$^2$·K | | | | | |
| Internal ceiling/floor | d (m) | λ (W/m·K) | ρ (kg/m$^3$) | c (J/kg·K) | R (m$^2$·K/W) |
| Acoustic tile (Ext.) | 0.019 | 0.06 | 368 | 590 | |
| Ceiling air space resistance | | | | | 0.85 |
| 100 mm heavyweight concrete (Int.) | 0.1016 | 1.95 | 2240 | 900 | |
| U-Value: 80 W/m$^2$k | | | | | |
| Internal areal heat capacity: 67 kJ/m$^2$·K | | | | | |
| External areal heat capacity: 154 kJ/m$^2$·K | | | | | |

Where, *HTF* is (*h-T*) function that uses user input data which has to be input accurately. More information on how to construct (*h-T*) curve is given in Section 3.4 and Eq. (7).

$$C_P = \frac{h_{i,\ new} - h_{i,\ old}}{T_{i,\ new} - T_{i,\ old}} \tag{6}$$

The PCM algorithms used in *EnergyPlus* [38] were verified and validated against analytical verification (Stefan Problem), comparative testing (against Heating 7.3) and empirical validation (DuPont Hotbox) by Tabares-Velasco, P. C Christensen, C. Bianchi [51] and Tabares-Velasco et al. [47]. It should be noted that for simulating PCM, and in order to achieve accurate results these three settings must be carefully configured in EnergyPlus model; 1—short time steps equal or less than 3 minutes should be used, 2—PCM with strong hysteresis could not be accurately simulated, and 3—if accurate hourly analysis is needed, smaller node space (equal to 1/3 of the default value) should be used [47]. In this study, in all models the simulation time step was set to 1 minute, the node discretisation value was set to 1, and phase change materials with no hysteresis were used.

### 3.4. PCM characterisation

To investigate the potential of advanced building envelopes thermally enhanced with high latent heat materials, so as to potentially improve energy flexibility in buildings, the gypsum boards of the vertical external and internal walls were replaced with PCM, and installed only on the inner surface of external and internal walls which are in direct contact with building indoor environment [52].

In this study, two different commercially available PCM materials were considered to assess the influence of PCM concentration on the TES of the building and its contribution to a demand response scenario, especially during pre-heating and pre-cooling of the building envelope.

The first PCM is a macro-encapsulated compact storage module (CSM) panel with 100 wt. % concentrated PCM with high latent heat capacity, which is referred to as **PCM-1** in this paper [53]. Each concentrated CSM panel has a total thickness of 10 mm, and a mass of 0.5 kg per panel. The storage capacity of a 10 mm of CSM panel is equivalent to 46 Wh/kg.

**Table 3**
Physical properties of PCM products.

| Physical property | PCM-1 | PCM-2 |
|---|---|---|
| Specific heat | 2 kJ/kg·K | 1.2 kJ/kg·K |
| Thermal conductivity | 0.20 W/m·K | 0.20 W/m·K |
| Peak melting points | 20 °C/heating & 25 °C/cooling | 20 °C/heating & 25 °C/cooling |
| Heat storage capacity (latent & sensible heat) | 200 kJ/kg | 110 kJ/kg |
| Thickness | 10 mm | 12.5 mm |
| PCM concentration | 100 wt% | 30 wt% |
| PCM density | 880 kg/m$^3$ | 800 kg/m$^3$ |

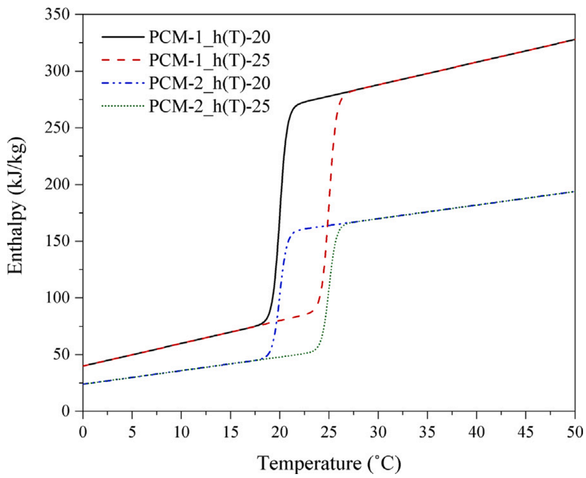


**Fig. 3.** PCM enthalpy-temperature curves.

The second product a PCM-enhanced plasterboard [54–56], suitable for drywall construction applications with about 30 wt% of micro-encapsulated paraffinic PCM, which is referred to as **PCM-2** in this paper. The latent heat capacity of such a product with 12 mm thickness is around 90 Wh/m$^2$.

In order to construct *h-T* curves of each PCM, the enthalpy method was used based on the methodology proposed by Feustel [57] which is shown in Eq. (7), and by introducing physical properties of PCMs which are shown in Table 3.

Two ideal hypothetical PCMs were chosen with 20 °C and 25 °C main peaks with reference temperature at −20 °C and melting range of 4 °C, according to the previous findings of Saffari et al. [58]. Density change due to liquid to solid phase transition was assumed negligible. The specific heat capacity and enthalpy trends as a function of temperature are illustrated in Fig. 3.

$$h\ (T) = C_{p,const}\ T + \frac{h_1 + h_2}{2} \times 1 + \tanh\left[\frac{2\beta}{\tau}\left(T - T_m\right)\right] \tag{7}$$

where $C_p$ is specific heat (kJ/kg·K), $T$ is temperature (°C), $h$ is specific enthalpy (kJ/kg), $\beta$ is inclination, $\tau$ is width of the melting zone (°C), and $T_m$ is peak melting temperature (°C).

### 3.5. 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 thermostat setpoint temperature. To simulate a DR event, pre-heating in winter and pre-cooling in summer were considered, where the building envelope thermal mass was charged by increasing the thermostat setpoint temperature. This is considered to be an upward flexibility event. Immediately after the upward flexibility event, the proposed DR event takes place.

The DR event was simulated for each time frame 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, where both a heating scenario and a cooling scenario was modelled and simulated.

In this study, six different building envelopes were considered for heating and cooling energy flexibility assessment including, light weight building envelope with conventional gypsum board (**LW GB**): this scenario is based on the dwelling envelope specification as per the original construction or reference light weight building; light weight building envelope with 100 wt% concentrated PCM panel (**LW PCM-1**): for this scenario, the conventional gypsum board is replaced with concentrated PCM macro-encapsulated in aluminium cases and installed on the inner surface of external and internal walls which facilitates the heat transfer with the indoor environment; lightweight building envelope with PCM-enhanced gypsum board (**LW PCM-2**): in this scenario conventional gypsum boards are replaced with PCM-impregnated gypsum boards which are installed on the inner surface of the vertical external and internal walls; medium weight building envelope with conventional gypsum board (**MW GB**): this scenario is based on the dwelling envelope specification as per the original construction or reference medium weight building; medium weight building envelope with concentrated PCM panel (**MW PCM-1**): in this scenario conventional gypsum boards are replaced with concentrated PCM macro-encapsulated in aluminium cases on the inner surface of vertical external and internal walls; medium weight building envelope with PCM-enhanced gypsum board (**MW PCM-2**): in this scenario conventional gypsum boards are replaced with PCM-impregnated gypsum boards and installed on the inner surface of external and internal walls.

When examining the building thermal sensitivity to an energy flexibility event, it is important to consider the indoor thermal comfort and temperature fluctuation within the zone of the building both during pre-cooling and pre-heating stages as well as demand response events. Simulation results of this study, for both heating and cooling scenarios show that all operative temperature fluctuations of the indoor environment due to DR events are within the recommended threshold and less than the maximum operative temperature change allowed for different time periods shown in Table 4, and fully comply with ASHRAE Standard Thermal Environmental Conditions for Human Occupancy [59]. The maximum operative temperature change allowed within the dwelling over a time period is shown in Table 4.

### 3.6. Automated parametric schedule and data analysis

A sensitivity analysis algorithm has been programmed in *EnergyPlus v8.7* [38] Energy Management System (EMS) using EnergyPlus Runtime Language [60]. This facilitates the automation of DR thermostat modulation with high frequency thermostat modulation and accelerated modelling. The modulating process was repeated for each time interval of the day to numerically investigate what is the optimum pre-heating and pre-cooling time of the day, as well as demand response duration for each building envelope. For the simulations to be run for each desired time of the day, a parametric thermostat setpoint schedule in *EnergyPlus v8.7* [38] was developed. This is to allow for many simulations to be run using just one initial "*.idf*" file.

**Table 4**
Allowed operative temperature change in a thermal zone [59].

| Time period | 0.25 h | 0.5 h | 1 h | 2 h | 4 h |
|---|---|---|---|---|---|
| Max. operative temperature change allowed | 1.1 °C | 1.7 °C | 2.2 °C | 2.8 °C | 3.3 °C |

The exported simulations data included time of day, site outdoor air dry-bulb temperature, zone mean air temperature, zone operative temperature, zone thermostat setpoint temperature and the HVAC power consumption. With this parametric analysis tool, an array of Excel spreadsheets was exported from *EnergyPlus v8.7* [38] for each different duration of the energy flexibility event.

To process this wide array of data, Python scripts were developed which allowed for DR indicators (as discussed in Section 3.7) be applied to the data. The development of the Python scripts allowed each of the parametric runs exported by *EnergyPlus v8.7* [38] calculation engine to be analysed quickly and filter the twenty-four Excel files into one Excel file with the DR indicators applied to the desired data sample. This desired sample of data included the duration of the energy flexibility event and within this data sample, the pre-heating and pre-cooling events, DR event, and the rebound effect event were analysed.

### 3.7. Scenario simulations

For the reference case simulations, each of the six building envelopes are simulated separately where the room setpoint temperature is held constant throughout the three-day period at the reference zone thermostat temperature of 20 °C (for heating) and 25 °C (for cooling). The simulation data for each of these reference cases are used as a reference HVAC power input for each building envelope and can be compared to the modulating case.

For each of the modulating simulation levels in a heating scenario, the thermostat setpoint temperature is increased from 20 °C to 22 °C for either 0.5 hours (short pre-heating), or 2 hours (long pre-heating). This is known as the pre-heating period. It is followed immediately by a DR event where the setpoint temperature decreases to 18 °C for either 1 hour (short DR), or 4 hours (long DR) before setting back the thermostat setpoint to the normal operative comfort temperature of 20 °C.

Following the same methodology as the heating case, in the cooling scenario, the thermostat setpoint temperature is decreased from 25 °C to 23 °C for either 0.5 hour (short pre-cooling), or 2 hours (long pre-cooling) for the pre-cooling of the envelope followed immediately by a DR event where the thermostat setpoint temperature increases to 27 °C for either 1 hour (short DR), or 4 hours (long DR) before setting back the thermostat setpoint to the normal operative comfort temperature of 25 °C. It should be noted that selection of each of these demand response scenarios is highly dependent on the actual constraint on the electricity network and demand-side management strategy of the building BMS managers and/or aggregator as well as the actual thermal storage capacity of buildings.

A schematic is shown in Fig. 4 which illustrates the overall methodology used for heating and cooling energy flexibility assessment and analysis. This includes, building envelope typology, air conditioning system thermostat set point for heating and cooling, PCM type, pre-heating and pre-cooling modes, and demand response periods.

#### 3.7.1. Demand response indicators

Reynders et al. [32] defined three indicators for quantifying energy flexibility in a DR event. These are: storage capacity ($C_{ADR}$), rebound effect ($RE_{ADR}$) and storage efficiency ($\eta_{ADR}$). To apply these performance indicators, the difference in HVAC power usage between the modulating building zone and reference building zone is calculated using Eq. (8):

$$P_{diff} = \left(P_{mod} - P_{ref}\right) \tag{8}$$

where $P_{diff}$ is difference in HVAC power consumption (W), $P_{mod}$ is modulating HVAC power consumption (W), and $P_{ref}$ is reference HVAC power consumption (W).

The available energy storage capacity (SC) is defined as the maximum amount of energy that can be stored during the pre-heating or pre-cooling phases prior to the DR event, without interfering with the indoor thermal comfort of the building as shown in Fig. 5 and can be calculated using Eq. (9). Also, it should be highlighted that the maximum available storage capacity of the envelope varies depending on the thermal inertia of the envelope, and more importantly, in PCM-enhanced envelopes it depends on the indoor and outdoor temperature, as well as PCM charging phase (solid or liquid).

$$SC = \int_0^{DR} |P_{diff}|\, dt \tag{9}$$

where *SC* stands for the 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 DR event has passed and is given by Eq. (10):

$$RE = \int_{Post-DR}^{\infty} |P_{diff}|\, dt \tag{10}$$

where *RE* stands for the rebound effect (kWh). For the purpose of this study, the rebound effect for six hours after the DR event was taken into consideration because the difference between the modulating case and the reference case after the six-hour duration was found negligible.

It should be highlighted that, an indicator that is not considered by Reynders et al. [32] is the power curtailed (here referred to as *PC*) during the DR event. This is an indicator needed to define the amount of energy that can potentially be curtailed during the DR event and is shown in Fig. 5.

$$PC = \int_{DR}^{Post-DR} |P_{diff}|\, dt \tag{11}$$

where *PC* stands for the power curtailment (kWh).

It is also required to define the storage efficiency of the building. According to Reynders et al. [32], the storage efficiency is described as the fraction of the heat that is stored during the active demand response event, and can be utilised subsequently to reduce the heating power required to maintain indoor thermal comfort temperature and is given by Eqs. (12) and (13):

$$\eta_{DF} = 1 - \frac{\int_{Post-DR}^{\infty} |P_{mod} - P_{ref}|\, dt}{\int_0^{DR} |P_{mod} - P_{ref}|\, dt} \tag{12}$$

$$\eta_{UP} = \frac{\int_{Post-DR}^{\infty} |P_{mod} - P_{ref}|\, dt}{\int_0^{DR} |P_{mod} - P_{ref}|\, dt} \tag{13}$$

where $\eta_{DF}$ is the efficiency of a downward demand response event, and $\eta_{UF}$ is the efficiency of an upward demand response event. In Eqs. (12) and (13) the integral in the denominator is the available storage capacity, and the integral in the numerator is the fraction of the heat stored during the active demand response event that is not recovered after a long period as described by Reynders et al. [32].

However, due to the complexity of the energy flexibility event considered in this study, the storage efficiency indicator defined by Reynders et al. [32], does not take into consideration energy flexibility events where either a pre-heating phase or pre-cooling phase and a DR event are implemented. Therefore, in this study, the efficiency indicator has been further improved to take into account the pre-heating and pre-cooling DR events to store thermal energy in the building envelopes, especially when integrated construction materials with high latent heat

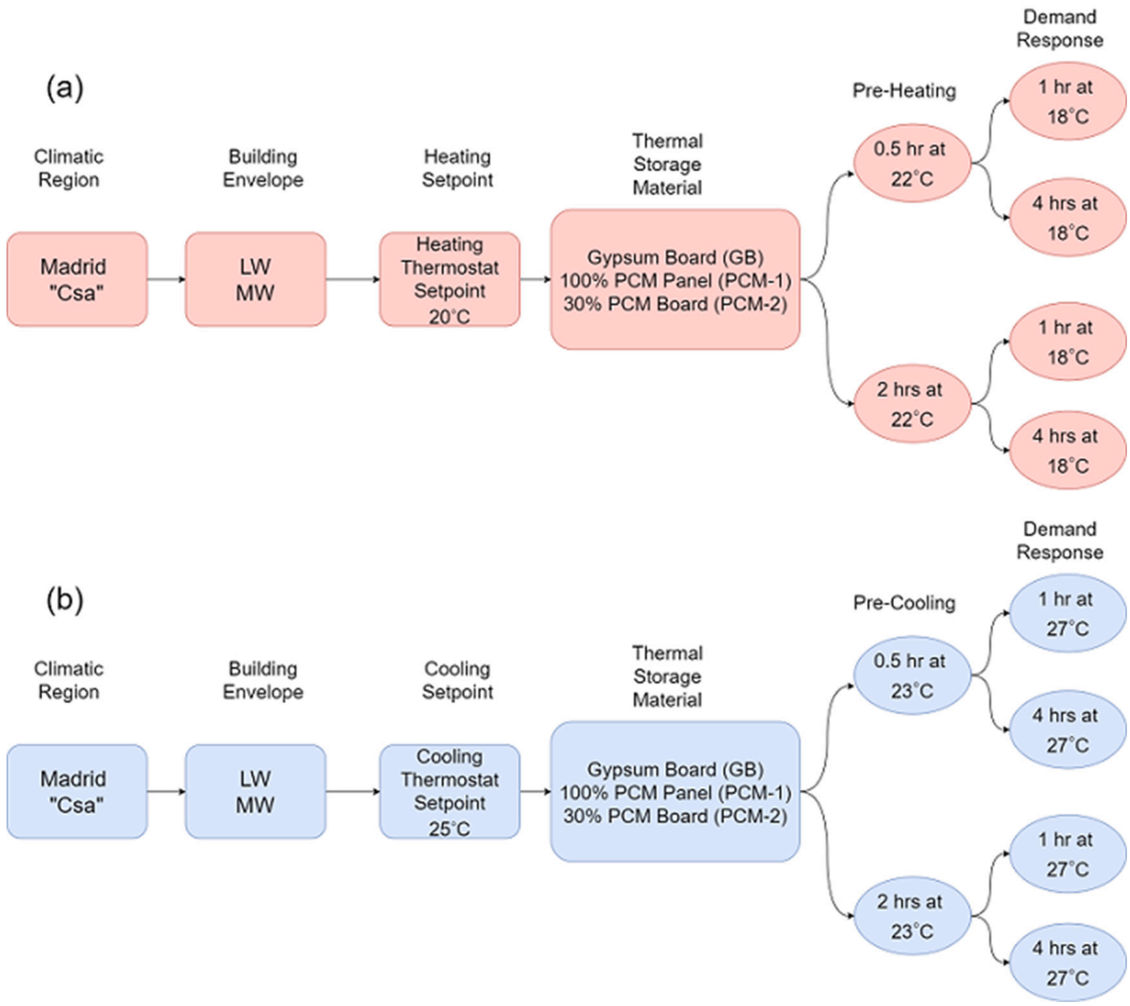


**Fig. 4.** Simulation scenarios for heating (a) and cooling (b).

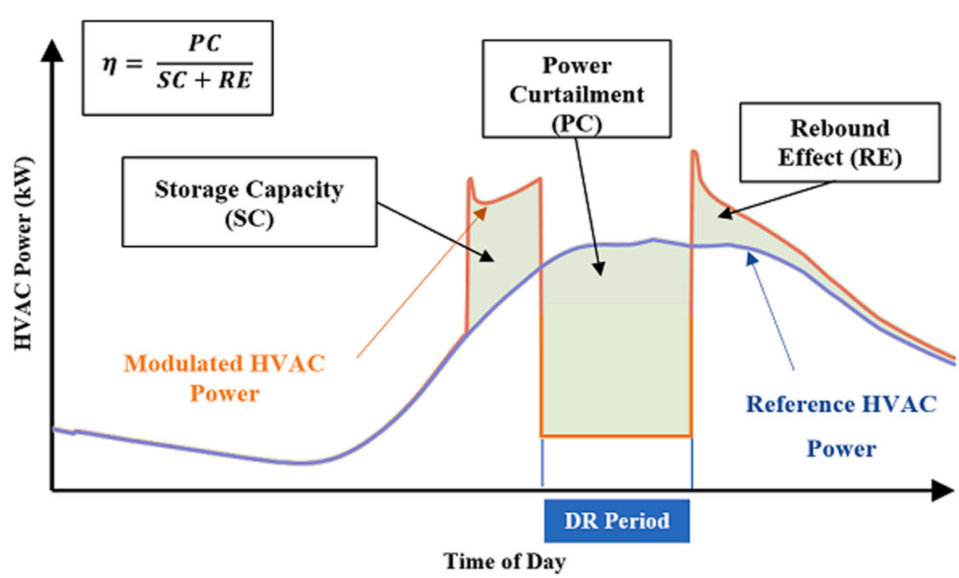


**Fig. 5.** Schematic of energy flexibility indicators.

**Table 5**
Summary of all demand response scenarios analysed in this study.

| Envelopes | **Demand response strategies for heating** | | | |
|---|---|---|---|---|
| | Short pre-heating-Long DR | Long pre-heating-Long DR | Short pre-heating-Short DR | Long pre-heating-Short DR |
| LW GB<br>LW PCM-1<br>LW PCM-2<br>MW GB<br>MW PCM-1<br>MW PCM-2 | 0.5 h pre-heating at 22 °C–<br>4 h DR with TSTAT at 18 °C | 2 h pre-heating at 22 °C–<br>4 h DR with TSTAT at 18 °C | 0.5 h pre-heating at 22 °C–<br>1 h DR with TSTAT at 18 °C | 2 h pre-heating at 22 °C–<br>1 h DR with TSTAT at 18 °C |
| | **Demand response strategies for cooling** | | | |
| | Short pre-cooling-Long DR | Long pre-cooling-Long DR | Short pre-cooling-Short DR | Long pre-cooling-Short DR |
| LW GB<br>LW PCM-1<br>LW PCM-2<br>MW GB<br>MW PCM-1<br>MW PCM-2 | 0.5 h pre-cooling at 23 °C–<br>4 h DR with TSTAT at 27 °C | 2 h pre-cooling at 23 °C–<br>4 h DR with TSTAT at 27 °C | 0.5 h pre-cooling at 23 °C–<br>1 h DR with TSTAT at 27 °C | 2 h pre-cooling at 23 °C–<br>1 h DR with TSTAT at 27 °C |

are utilised, such as PCM. The new **Energy Flexibility Efficiency Indicator** proposed in this study takes into account the overall energy flexibility event as shown in Fig. 5. This *Flexibility Efficiency Indicator* ($\eta$) is defined as shown in Eq. (14) and can have values less than or greater than 1.0, depending on applicable boundary conditions for each scenario examined. It should be noted that the storage capacity (SC) in this equation is the thermal energy that the building envelope can store during pre-cooling or pre-heating period and it varies depending on the pre-cooling or pre-heating duration, and the available passive thermal storage capacity of the envelope. The rebound (RE) value is influenced by the available heat stored in the building envelope and heat dissipation during and/or after the demand response period which depends on the available thermal storage capacity of the envelope, pre-cooling and pre-heating duration and thermostat set point temperature, and DR duration and thermostat set point modulation. This study gives insights into the various building envelope design and demand response control strategies when PCM is used to identify potential energy flexibility of buildings.

$$\eta = \frac{PC}{SC + RE} \tag{14}$$

## 4. Results

This section presents the results and analysis of heating and cooling energy flexibility of different scenarios. Six different building envelopes and four different demand response strategies were analysed and their results are discussed in this section. There are a total of 24 scenarios for heating and 24 scenarios for cooling which are summarised in Table 5.

### 4.1. Heating flexibility efficiency analysis

This section analyses the flexibility efficiency for each demand response event for different pre-heating periods and different DR duration periods. As an example, Fig. 6 shows a 24 h comparison of the heat pump energy use and indoor temperature of the LW GB scenario without DR and LW PCM-1 scenario with DR at 10 a.m. From the modulated heat pump energy use it can be seen that during pre-heating phase from 9:30 h to 10:00 h, the energy use increases followed by a zero energy consumption during the DR phase from 10:00 h to 11:00 h.

#### 4.1.1. Short pre-heating period, long DR period

Fig. 7 shows the flexibility efficiency for a pre-heating event of 0.5 hours and a 4 hour DR event. The maximum efficiency value is found to be 356% and is associated with the LW PCM-2 envelope (purple line) and with the energy flexibility event starting at 07:00 on the design day. The maximum efficiency is observed here due to the rebound effect of the energy flexibility event being significantly lower as the outdoor temperature is rising at the end of the DR event which limits the amount of HVAC power required to bring the zone ambient temperature back to 20 °C. The worst performing building envelope for this particular energy flexibility event is seen to be the LW GB building envelope (blue line) with a maximum efficiency observed to be just 245%. The lower efficiency of the LW GB envelope suggests that not a sufficient amount of thermal mass is available to maintain the thermal energy for a DR event of 4 hours. This is due to the short pre-heating event prior to the DR event. It can be seen that in order for the LW GB to perform efficiently, a long pre-heating event is required. Also, the LW GB building has the largest temperature fluctuations during the DR event which suggests that an insufficient amount of thermal inertia is available to maintain the internal environment over the long DR event.

It could be suggested here that, to reach the highest efficiencies in short pre-heating and long DR events, an optimum envelope design with PCM is required. A building with higher thermal inertia is understood to perform more efficiently in this type of energy flexibility event. Looking at the storage capacity heatmap in Fig. 8, it can be seen that the LW gypsum board envelope has a larger thermal storage capacity. This is due to a fall in outdoor ambient temperature while the onset of an energy flexibility event resulting in the LW building requiring more heat to remain at the zone setpoint temperature. As the LW building has a low thermal inertia and no initial thermal storage to counteract the quick change in outdoor temperature, this results in a HVAC energy consumption to charge the building at the onset of the energy flexibility event.

In the later part of the day, the energy flexibility efficiency is greatly reduced due to the effects of solar gain. Here, the storage capacity remains relatively high, but the power curtailment is seen to drop significantly due to reduced need for HVAC operation in the dwelling house zone. Similar trends are seen by Devaux and Farid [34], which observed that the evening time load shift was not as effective in DR.

Considering the storage capacity for this energy flexibility event in Fig. 8, it can be observed that the storage capacity remains at zero for the LW and MW GB envelope after midday. This trend is due to the higher temperatures experienced in the building during the day due to solar gain. These higher temperatures seen within the dwelling are undesirable due to the compromise in thermal comfort. This also effects the ability for these envelopes to perform in late evening energy flexibility events. Another important observation can be made at around 07:00 for the LW GB envelope when the storage capacity rises to 0.1003 kWh. At this time, the outdoor ambient air temperature is at the lowest point, resulting in a significantly higher storage capacity, which results in a lower efficiency for the DR event.

LW and MW GB building envelopes have a high associated rebound effect value (between 0.096 kWh to 0.1273 kWh). This suggests that the

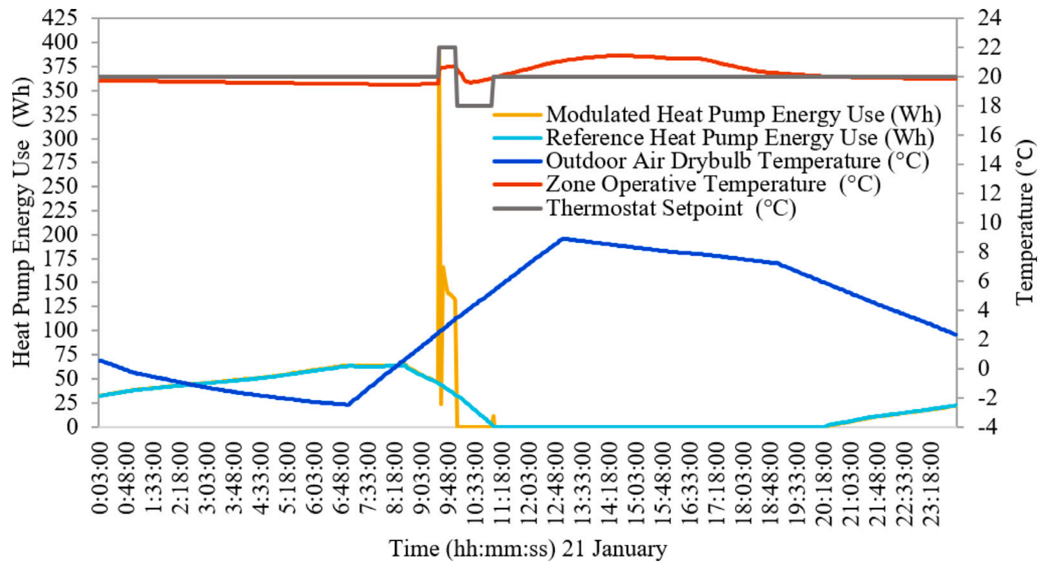


**Fig. 6.** Heat pump energy use comparison of the reference LW GB scenario without DR vs. LW PCM-1, pre-heating at 22 °C for 0.5 h, DR at 18 °C for 1 h.

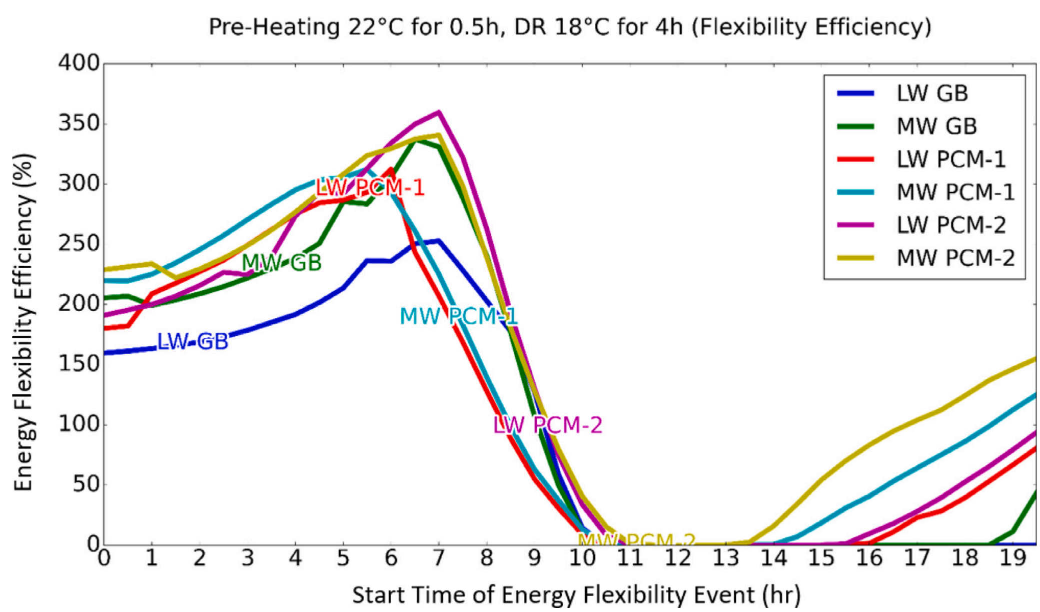


**Fig. 7.** Heating flexibility efficiency for each building envelope in a short pre-heating–long DR Event.

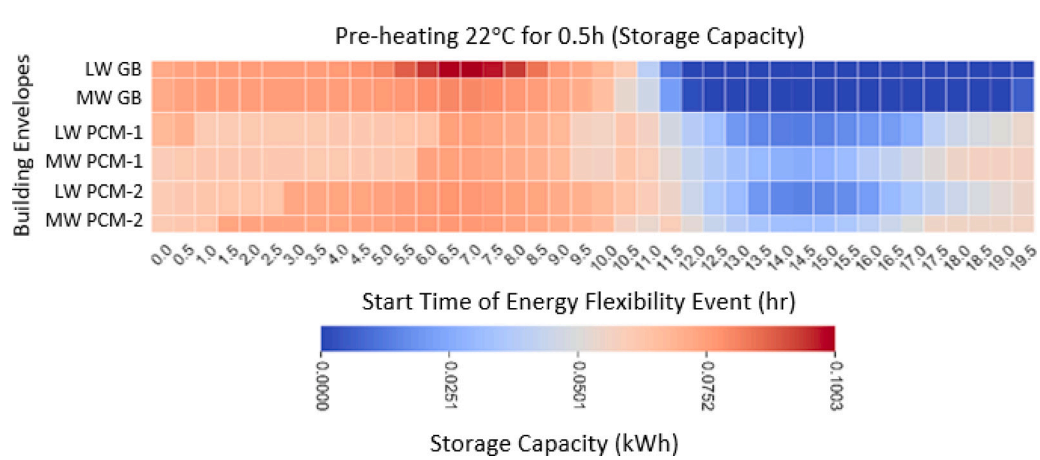


**Fig. 8.** Heating storage capacity in a short pre-heating event.

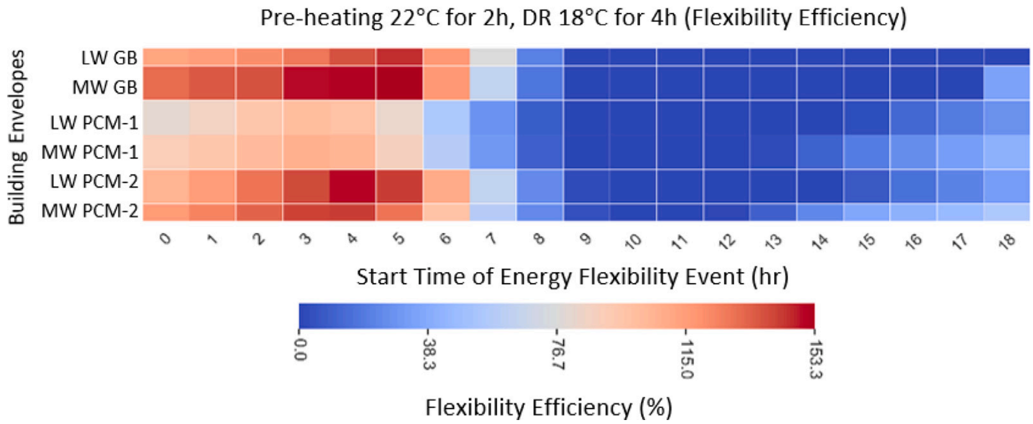


**Fig. 9.** Heating flexibility efficiency in a long pre-heating–long DR event.

thermal inertia that they have associated with them is not sufficiently large enough to complete a long DR event. Here, the sensible TES envelopes alone would not be fit to participate in another closely timed DR event. PCM-1 envelopes have a rebound effect value lower than 0.032 kWh due to its high thermal inertia. This would minimise the need for HVAC power input after the DR event and hence would allow for the building envelope with PCM-1 to participate in another energy flexibility event as described by Reynders et al. [61].

*4.1.2. Long pre-heating period, long DR period*

Fig. 9 shows the flexibility efficiency for a 2 hour pre-heating event and a 4 hour DR event. It can be observed that the efficiency decreases significantly with an increase in length of the pre-heating event. PCM-1 applied to both the LW and MW envelopes have the largest decrease in efficiency. This is due to a larger amount of TES and a significant amount of heat being transferred into the layers of the wall during long pre-heating events, which was also investigated by Wolisz et al. [31]. PCM-1 is outperformed in early hours of the day especially when the pre-heating time increases to 1 hour and 2 hours, for any of the heating scenarios. It is shown to be least efficient and has the least power curtailment potential associated with it, although the initial energy input is the lowest for the PCM-1 envelopes.

Maximum efficiency values for each envelope are seen to be occurring earlier in the morning due to the longer pre-heating event, hence shifting the DR event later into the day. For this length of a pre-heating event, it is shown that the MW GB envelope acts as the most efficient TES medium in the early hours of the morning with a maximum efficiency value of 153% starting at 05:00 as shown in Fig. 9. The LW PCM-2 envelope is shown to be the second-best performer with 150% starting at 04:00.

Finally, for this event it is observed that the evening time efficiency performance drops similarly to all the other situations. The envelopes with just sensible TES are seen to be effective at later times in the day. This is due to the building still recovering from the higher radiative temperatures reached during the midday hours.

*4.1.3. Short pre-heating period, short DR period*

The flexibility efficiency for a 0.5 hour pre-heating and changing the DR length to 1 hour sees the overall efficiencies of the events drop significantly. Interpreting Fig. 10, it is shown that the MW GB envelope performs in an early morning energy flexibility event with the highest efficiency. At 08:00, the MW GB envelope reaches an efficiency of 111%.

For the MW GB board building, the efficiency drops when the energy flexibility starts at 07:00 due to the ambient outdoor temperature being lowest at this point. This low ambient temperature for a period of time causes the structure to be discharged and at the time of the energy flexibility event (07:00), it requires large amounts of energy to re-charge the building to 22 °C during the pre-charge phase. This has a similar effect to each of the other building envelopes although they happen at different times due the thermal inertia of the buildings. For the short DR events, the power required to pre-charge the envelopes is nearly proportional to the amount of power curtailed. Studying the heatmap in Fig. 10, the optimum time for the energy flexibility event to occur is 07:30 for MW GB building and 08:30 for the LW GB building. It should be noted that for the larger TES medium (PCM-1), the energy flexibility event should occur at an earlier time of 05:30.

*4.1.4. Long pre-heating period, short DR period*

In Fig. 11(a), it can be seen that the flexibility efficiency is at a minimum for an event that uses a long pre-heating time of 2 hours followed by just a short DR event. For this type of event, the DR period is too short to recover all the stored energy in the building envelope as a long pre-heating period is applied.

The LW and MW GB envelopes appear to be most efficient as the sensible heat is recovered quicker. This agrees with an observation of Hirmiz et al. [15] which notes that PCM has a relatively low thermal conductivity which may have an effect on the rate of charging and discharging of thermal energy which could be considered as a drawback for a DR event. PCM-enhanced building envelopes have a zero-rebound effect as they do not dissipate the stored thermal energy throughout the DR event due to a low discharge rate. On the other hand, the sensible TES envelopes (gypsum board) have a rebound effect associated with them as their envelopes are discharged more quickly.

Another aspect that influences the flexibility efficiency is the thermal storage capacity of the envelope. Fig. 11(b) shows that, the pre-heating storage capacity is greatest for buildings passively enhanced with PCM. This allows the building to store large amounts of energy during the first phase of the event but as mentioned earlier, it cannot be recovered quickly enough for the 1 hour DR period. It should be noted that for short demand response events, PCM-enhanced buildings are not an efficient solution as it is outperformed by the standard gypsum board finished buildings for early morning demand response events. However, later in the day the flexibility efficiency is greater for the PCM enhanced envelopes which follows previous trends seen.

*4.2. Cooling flexibility efficiency analysis*

This section describes the results of cooling energy flexibility efficiency analysis for each energy flexibility event. As an example, Fig. 12 shows a 24 h comparison of the heat pump energy use and indoor temperature of the LW GB scenario without DR and LW PCM-1 scenario with DR at 10 a.m. in July 21st. In Fig. 12, it can be seen that the thermostat set point decreases from 25 °C to 23 °C to pre-cool the building envelope. From the modulated heat pump energy use it can be seen that during pre-cooling phase the energy use increases followed by a zero energy consumption during the DR phase when the thermostat set point temperature is set at 27 °C.

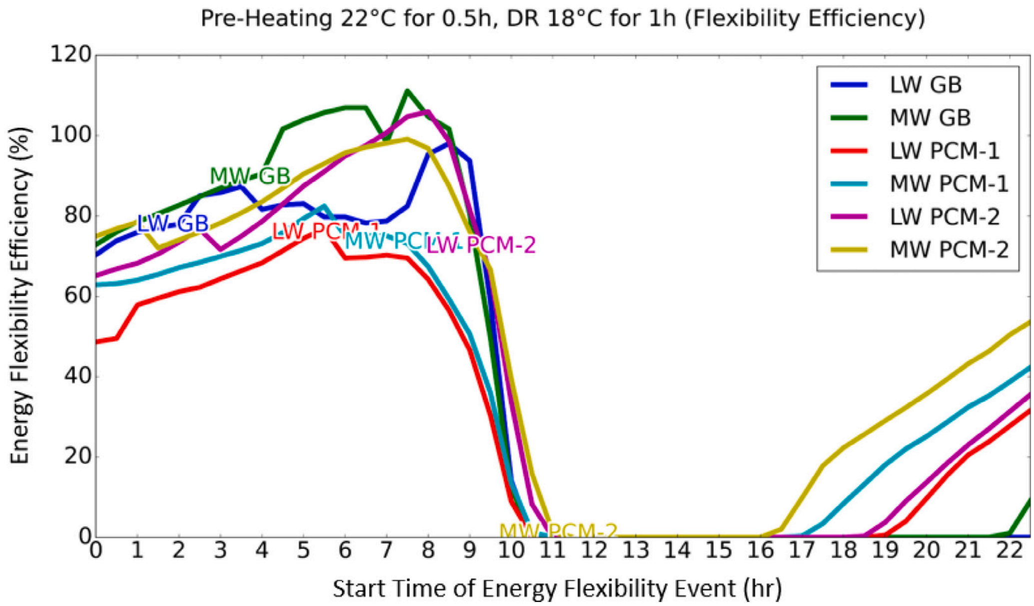


**Fig. 10.** Heating Flexibility efficiency in a short pre-heating–short DR event.

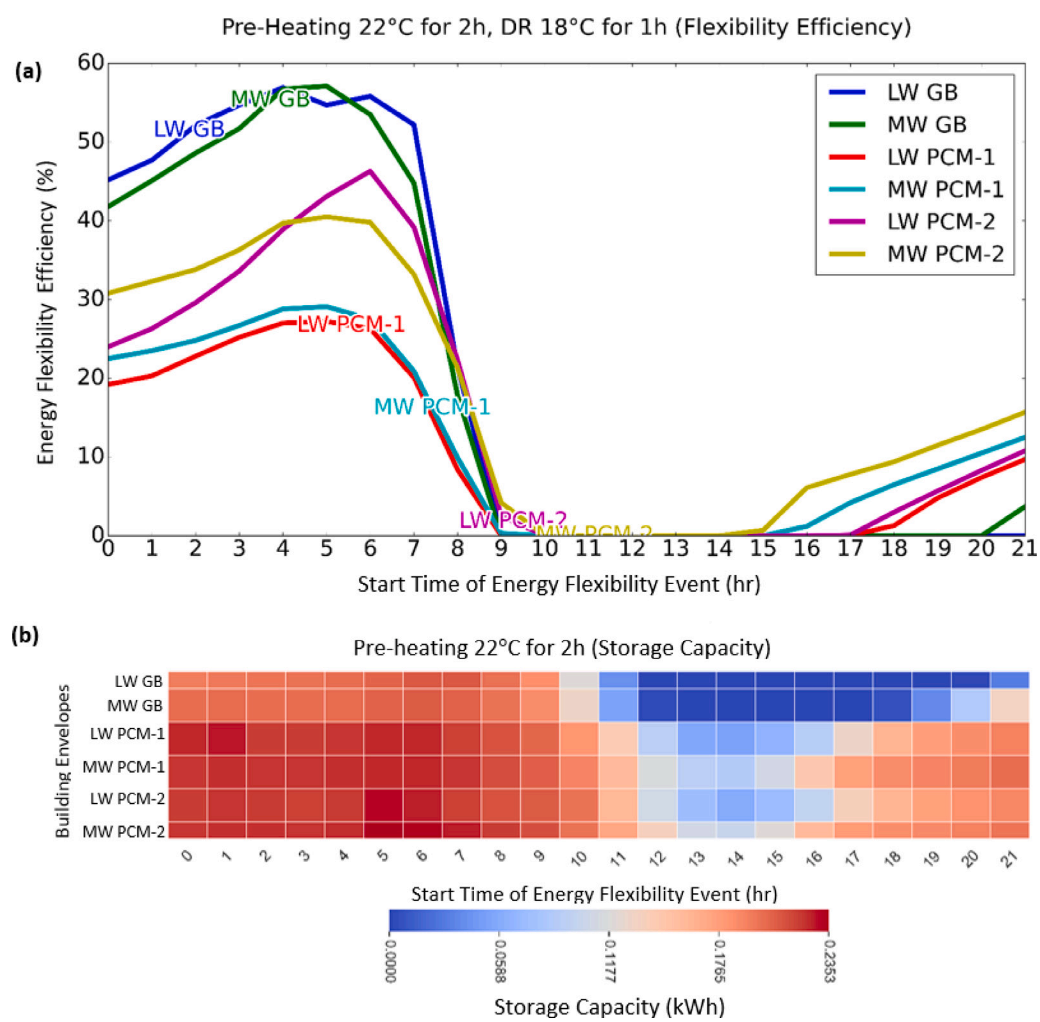


**Fig. 11.** (a) heating flexibility efficiency for long pre-heating and long DR, and (b) Storage capacity at 22 °C long pre-heating.

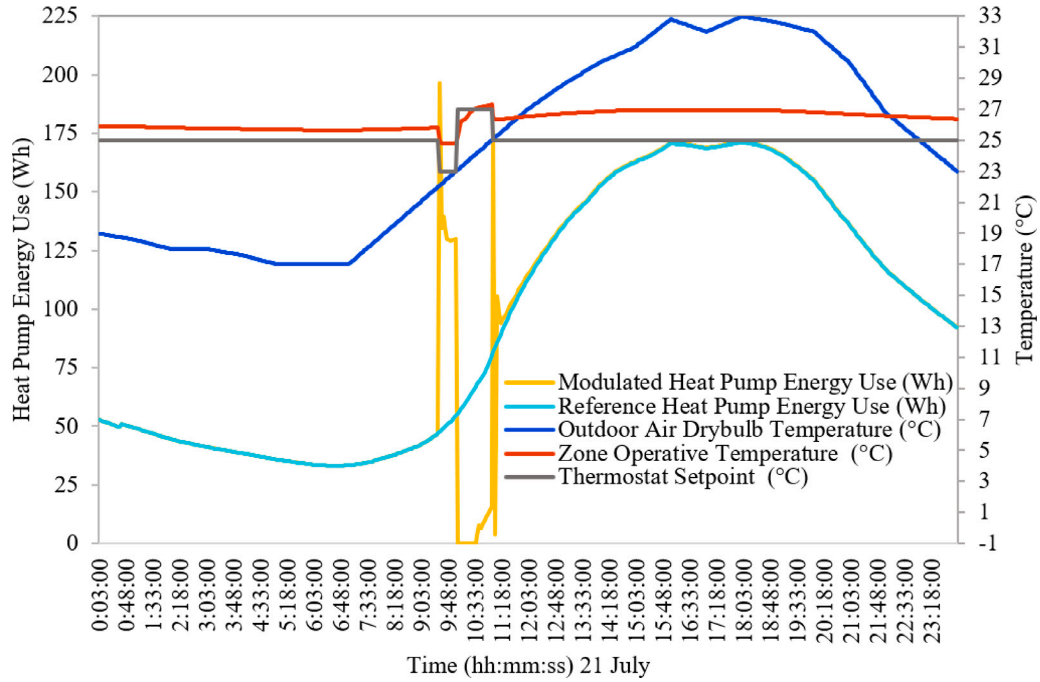


**Fig. 12.** Heat pump energy use comparison of the reference LW GB scenario without DR vs. LW PCM-1, pre-cooling at 23 °C for 0.5 h, DR at 27 °C for 1 h.

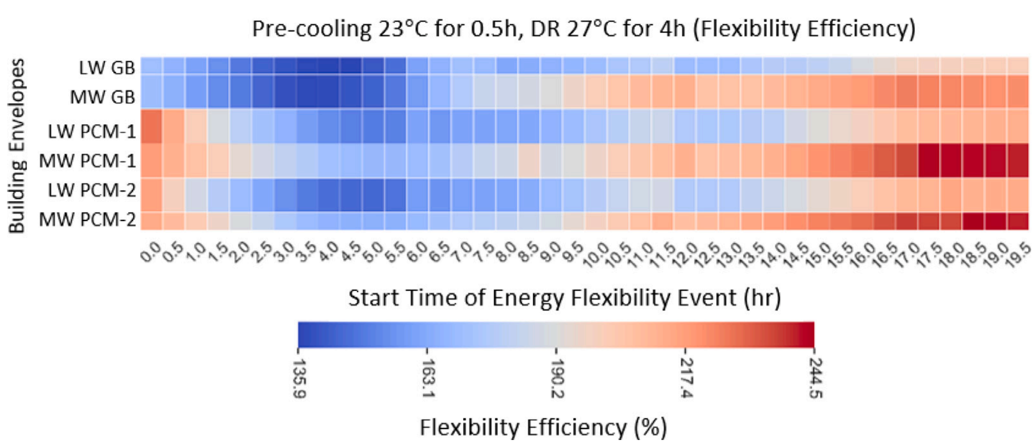


**Fig. 13.** Cooling flexibility efficiency in a short pre-cooling–long DR event.

*4.3. Short pre-cooling period, long DR period*

This scenario investigates the 0.5 hour pre-cooling event followed by a 4 hour DR event. Fig. 13 shows that the flexibility efficiency is at a maximum in the evening time, while the morning time sees the minimum efficiency values. It is shown that the MW PCM-1 envelope has the highest efficiency with a value of 244.5% with an energy flexibility event start time of 17:30. This is closely followed by the MW PCM-2 building envelope which has an efficiency value of 244% with a slightly later time of 18:00. The MW GB building is seen to have a high efficiency value of 220% with an earlier start time of 16:30. The LW PCM-2 building envelope has the next highest efficiency which occurs at 17:30 with a value of 210%. The LW PCM-1 has a similar outcome, however the highest efficiency is not seen until the start time of the event at 19:30. The LW GB envelope is seen to be the lowest energy flexibility performer overall with an efficiency value of 200%.

MW envelopes offer the greatest energy flexibility efficiency for this duration of an energy flexibility event. It also shows that the latent TES has a significant positive influence on the efficiency of an energy flexibility event when it is retrofitted to all envelopes. It can be seen that the LW envelopes efficiency values are much lower.

Considering the storage capacity results in Fig. 14, it can be observed that the largest storage capacity is achieved after midday for each envelope. This is due to building envelope being at a higher temperature due to the considerable amount of solar gains to the building. This results in a higher HVAC consumption to reduce the indoor temperature to the required temperature of 23 °C for the pre-cooling period. The LW PCM-1 building is seen to require the largest amount of power to reduce the indoor temperature. For the MW buildings however, the envelope can maintain the indoor temperature from rising by having a higher sensible thermal inertia.

*4.3.1. Long pre-cooling period, long DR period*

Considering next a 2 hour pre-cooling event followed by a 4 hour DR event, it is clear that the increase in pre-cooling length by 1.5 hours has a negative influence on the flexibility efficiency. Examining Fig. 15, the maximum flexibility efficiency is seen to be given by the MW GB building. This 138% efficiency is associated with a start time of 09:00. The maximum efficiencies seen for the MW PCM-1 and PCM-2 envelopes are slightly lower with values of 132% at 10:00 and 135% at 12:00, respectively. However, when looking at the early hours of

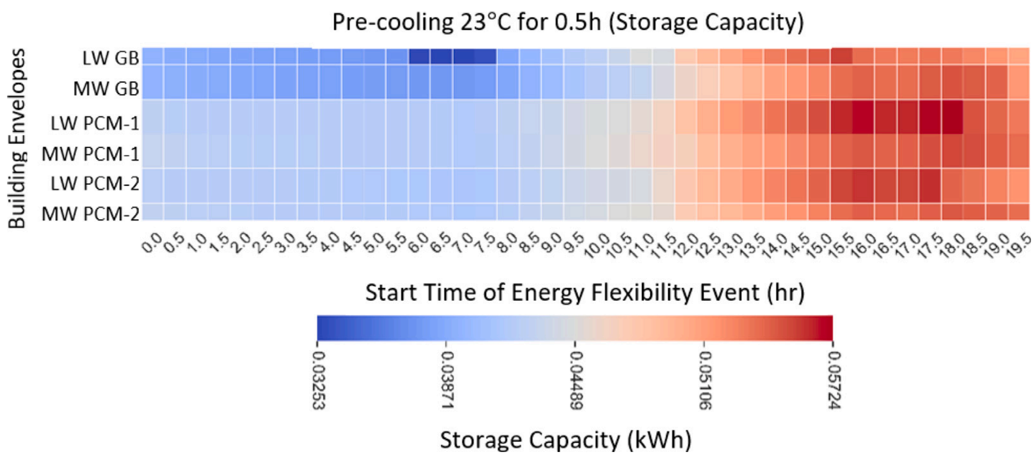


**Fig. 14.** Cooling storage capacity in a short pre-cooling event.

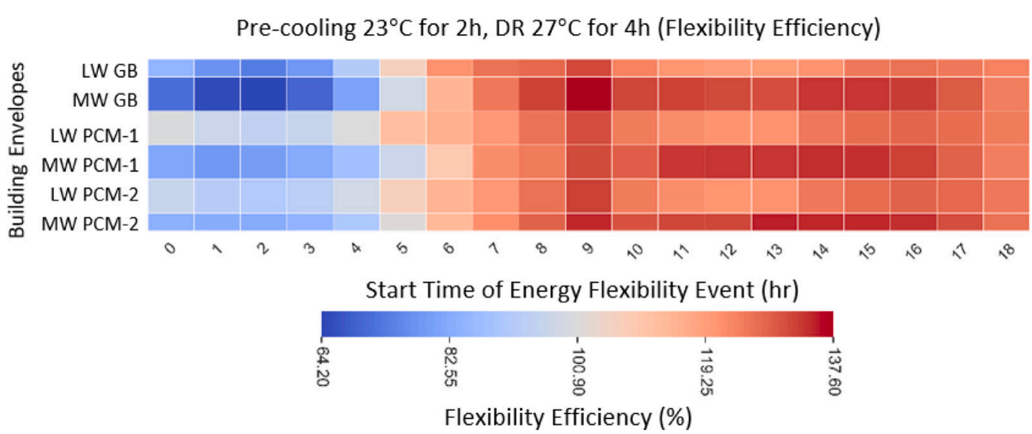


**Fig. 15.** Cooling flexibility efficiency in a long pre-cooling–long DR event.

the day, it can be observed that the LW PCM-1 and PCM-2 building envelopes offer a greater efficiency.

In early morning situations, it can be noticed that the LW and MW GB envelopes have low efficiency with values of 75% and 65%, respectively, compared to the buildings retrofitted with the PCMs. This would suggest at times where there is no solar gain, such as 02:00, there is a strong dependence on the high thermal inertia in the form of latent TES to participate in the long DR events. Here, the long pre-cooling events allows for the higher TES envelopes to exhibit greater cooling storage potential, while the envelopes with only sensible energy storage have both poor power curtailment and lower efficiencies.

For this energy flexibility event, when the operative air temperature is sufficiently high in the zone of the building, the LW building envelope for each material class has a high rebound effect. This is due to a combination of a long DR event and poor sensible energy storage. The building envelope has become over discharged due to the long DR event and poor thermal inertia resulting in the HVAC system operating longer in order to restore the zone to its equilibrium position. The MW buildings are seen to have a low rebound effect as they are fit to store larger amounts of energy during the pre-cooling phase resulting in a better energy discharge characterisitc during the DR period while maintaining indoor thermal comfort. This would allow MW buildings to participate in many energy flexibility events which are closely followed by each other as described by Reynders et al. [32].

### 4.3.2. Short pre-cooling period, short DR period

In Fig. 16, it can be observed that the flexibility efficiency for a 0.5 hour pre-cooling and changing the DR length to 1 hour sees the overall efficiencies drop by about 100%. For this energy flexibility event, the LW and MW GB envelopes see the overall minimum efficiencies in early morning. However, moving later into the day, the LW GB envelope is seen to give the maximum efficiency with a value of 125% at a start time of 11:00. After the start time of 11:00, all the LW envelopes suffer a decrease in efficiency. This decrease in efficiency is due to a large rebound effect which suggests that not enough TES is charged during the pre-cooling phase as well as the outdoor environment effect on the LW envelopes as discussed in previous sections. For early morning energy flexibility events of this nature, it can be observed that the buildings with latent TES outperform the buildings which have just sensible TES available to them. For example, at 05:30, the LW PCM-1 building has an efficiency of 85%, while the MW GB building only sees an efficiency of 38%. Taking this into consideration, it is suggested not to have an energy flexibility take place in buildings which have only sensible TES, as the amount of power curtailed would not justify the amount of power taken to pre-charge the building. The MW PCM-2 envelope performs with the highest efficiency starting at 22:00 due to the rebound effect being minimal which therefore suggests that this type of envelope has the optimum TES to perform in short pre-cooling events regardless of DR event length.

### 4.3.3. Long pre-cooling period, short DR period

From Fig. 17, it is clear that the flexibility efficiency is minimum where a long pre-cooling time of 2 hours is used, followed by just a 1 hour DR event. Extremely low flexibility efficiency is seen for this energy flexibility event in early morning (04:00 to 05:00), meaning that any energy that is stored in the envelopes is not recovered during the DR event. The LW GB board envelope with only the use of sensible TES is seen to be the most efficient performer (66.6%) in this event starting

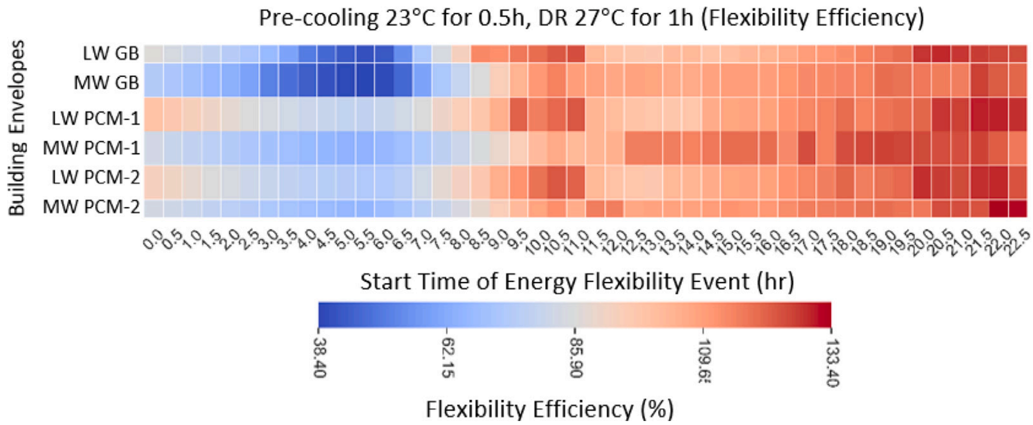


**Fig. 16.** Cooling flexibility efficiency heatmap for each building envelope in a short pre-cooling–short DR event.

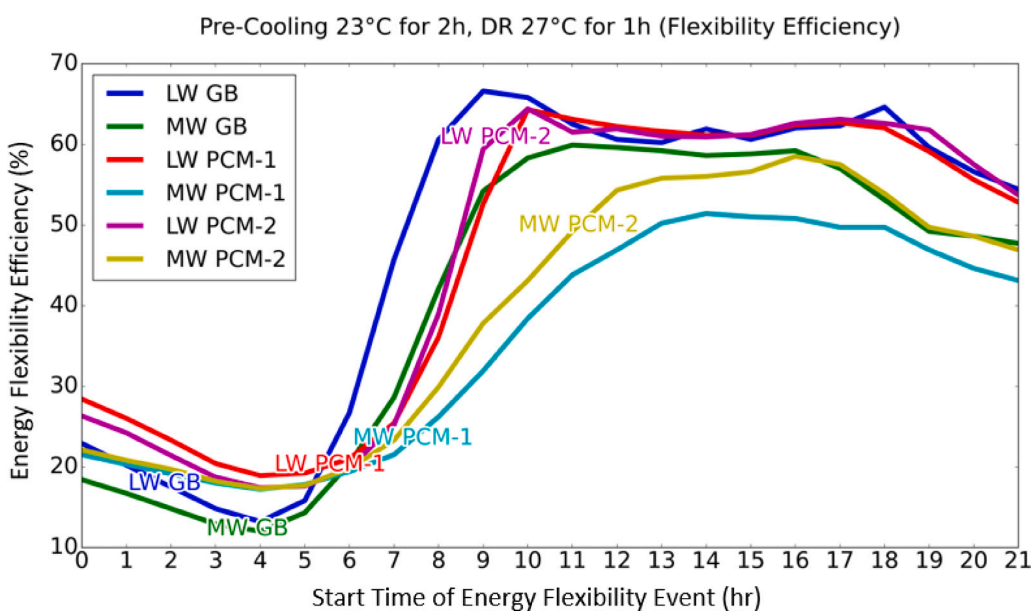


**Fig. 17.** Cooling flexibility efficiency heatmap for each building envelope in a short pre-cooling–short DR event.

at 09:00. For an energy flexibility event of this type, it is clear that the best envelope performer is the LW GB envelope. This is because of the low thermal inertia being charged during the long pre-cooling event which has a lesser amount of HVAC power consumption. The other envelopes especially the MW PCM-1 and PCM-2 envelopes have a large TES which as a result require a large amount of power to be used during the pre-cooling stage. This energy that is in the building envelope cannot be re-released quick enough in the DR event to allow for a greater efficiency. Barzin et al. [62] concluded in their study that early morning pre-cooling is most effective for a cooling DR event and similar trends can be seen here.

An energy flexibility event like this also shows that buildings with a higher thermal inertia has a poor ability to perform as evident in Fig. 17. This is due to the large storage capacity available during the pre-cooling time, which increases the HVAC consumption over the 2 hour period to charge this large thermal inertia. It can be seen that the MW PCM-1 envelope, having the largest thermal inertia is most difficult to charge resulting in a large HVAC consumption. The results from this energy flexibility event suggest that an event like this should not be undertaken to avoid low efficiencies.

## 5. Discussion

In general, for both heating and cooling, changing the length of the DR phase has a significantly higher impact on flexibility efficiency than changing the length of the pre-heating phase. This suggests that the length of DR event is the driving variable to be considered when implementing an energy flexibility event. Moreover, for heating, it can be concluded that the DR period of the energy flexibility event where a thermostat is modulated to 18 °C is of more benefit to energy flexibility event than when a thermostat is modulated to 22 °C during the pre-heating event. Similarily, for cooling, a thermostat modulation from 25 °C to 23 °C in the pre-cooling phase is less effective than changing the thermostat from 25 °C to 27 °C in the DR phase.

This research shows that aside from increasing a buildings thermal performance by just thermal retrofitting using thermal insulation, the application of thermal mass retrofitting can increase both the energy efficiency of the house and energy flexibility of buildings. Allocating financial support to this innovative solution could be one step towards de-fossilisation of the residential building stock while providing additional energy flexibility to national grids.

## 6. Conclusions

This study aimed to identify the most suitable type of building envelopes, which incorporate PCM passive design, to participate in energy flexibility events, with different demand response periods in a climatic zone where both heating and cooling are required. The current literature lacks research on the application of passive thermal storage envelope optimisation with different demand response techniques. The main contribution of this study is to investigate the impact of PCM-enhanced envelopes and different demand response strategies on the overall energy flexibility of the building through a new indicator which takes into account pre-heating and pre-cooling of the building envelope. With the findings of this study, an energy flexibility map for residential electricity aggregators can be developed to include building envelopes, energy flexibility start times and energy flexibility durations for the climates considered.

The main findings from the heating scenarios suggest that:

1. Evening time energy flexibility events should have a short pre-heating time and a long DR time to gain the most efficient evening energy flexibility event where there are PCMs retrofitted within the building envelope. Buildings with only sensible TES cannot participate in evening energy flexibility events due to the influence from peak external temperature throughout the day.
2. Gypsum board enhanced with PCM-2 retrofitted on the LW and MW envelopes are shown to give an overall good energy flexibility efficiency and power curtailment compared to the other building envelopes for all energy flexibility events. It was also concluded that the MW PCM-2 envelope was the most efficient type to participate in both morning energy flexibility events and evening energy flexibility events.
3. For buildings which have only sensible TES, long DR events should be avoided to maintain thermal comfort and hence should be replaced with events which have a short DR phase as these events can still achieve high efficiencies and power curtailment when implemented at the correct times of day.

The main findings from the cooling scenarios are as follows:

1. In early morning periods, no pre-cooling phase should be implemented, as the cooler external temperature conditions are generally sufficient to pre-cool the building envelope for a DR event.
2. When comparing different envelopes for DR periods, it was observed that LW envelopes which had both integrated PCM or gypsum boards, suffered undesirable temperature fluctuations and therefore long DR events should not be implemented on LW buildings during a cooling scenario. However, when an energy flexibility event is implemented at the optimum time for a long pre-cooling event combined with short DR event, the LW GB envelope can have the highest energy flexibility efficiency.
3. MW buildings were shown to have more independence from the external environment and this allowed the MW envelopes to perform within the temperature limits during long DR events of 4 hours. Therefore, MW building envelopes outperformed LW building envelopes when a long DR event was activated making them the better choice.
4. For shorter DR events, the LW sensible TES is shown to be most effective as the storage capacity can discharge faster over the short DR period. The PCM enhanced envelopes are marginally better than the gypsum envelope when the pre-cooling periods are shorter.

## 7. Future work

The investigations carried out in this study show that environmental and geographical conditions highly influence the performance of PCM-enhanced envelopes and correspondingly energy flexibility. Thus, it would be beneficial to implement the same methodology proposed in this study to further analyse the energy flexibility and demand response scenarios in buildings located in other geographical regions. This would give an overall insight into the impact that climatic conditions would have on the participating of a dwelling house in a demand response event.

With the methodology proposed in this study, an energy flexibility map for each climatic region could then be developed. This would ensure the efficient participation of residential building stock in energy flexibility events while still providing flexibility to the national electric grid systems.

In this study, the influence of variable occupancy, internal heat gains, natural ventilation, and different PCM melting ranges have not been investigated. Further research is required to understand the influence of these factors on the energy flexibility efficiency and the overall energy performance of buildings, where demand response scenarios prevail.

## Declaration of competing interest

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## Data availability

The data that has been used is confidential.

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