Building Energy Efficiency and Load Flexibility Optimization Using Phase Change Materials Under Futuristic Grid Scenario

Sajith Wijesuriya, Chuck Booten, Marcus Bianchi, and Ravi Anant Kishore*

National Renewable Energy Laboratory, 15013 Denver West Parkway, Golden, CO 80401.

Abstract

This paper investigates the energy saving and load flexibility capacity of phase change material (PCM) integrated into building envelope under a future energy generation scenario, where 80% of the energy load comes from renewable sources. Using community-scale modeling, we first determine the net thermal storage required to fully manage the demand variability at a utility grid, and then using whole-building simulations we optimize operating parameters—such as PCM thickness, latent heat, interior setpoint profile, PCM distribution, and heat transfer coefficient—to determine the optimal conditions required for maximum energy reduction and load flexibility without compromising occupants' thermal comfort. The optimal PCM-integrated envelope proposed in this study can provide annual load flexibility up to 33.6% and annual energy savings up to 10.8% in a lightweight residential building located in Baltimore, MD. This study is relevant given the increasing contributions of renewable energy in the total energy generation mix, leading to a significant time-imbalance between peak energy demand and energy production. While thermal energy storage using PCM is a recognized technique, there is no known prior study dedicated to examining the thermal performance of PCM-integrated envelopes under future energy generation scenarios. This study bridges the research gap by investigating a practical way to implement the PCM in the buildings and maximize the energy efficiency as well as load flexibility related benefits.

* Corresponding author: Ravi.Kishore@nrel.gov

Keywords: load flexibility, grid-interactive efficient buildings, thermal energy storage, building energy, phase change material.

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Nomenclature

PCM	Phase change material	DG_{min}	Minimum dispatchable generation
LH	Latent heat of PCM	Q_{ES}	Total energy storage
HTC	Heat transfer coefficient	$Q_{TES,g}$	Thermal energy storage
t_{pcm}	PCM thickness	ΔE	Change in energy use
τ	Time	T_{vsp}	Variable setpoint temperature
min	Minimum	T_{msp}	Mean setpoint temperature
max	Maximum	T_{sp}	Temperature setpoint
η_{saving}	Energy efficiency	TARP	Thermal Analysis Research Program
$\eta_{flex.}$	Load flexibility	'EW'	Exterior walls
Q_{Total}	Total power demand	'IW'	Interior walls
Q_{VG}	Variable power generation	'C'	Ceiling
Q_{Net}	Net load on the grid	'F'	Floor

1 Introduction

To address concerns related to climate change, interest in renewable energy (particularly wind and solar energy) is rising, leading to considerable reduction in the cost of power generation for these technologies. As more variable renewable and distributed generation sources are integrated into the electrical grid, the difficulties of reliably matching supply and demand increase, leading to the so-called "duck curve" [1] and "Nessie curve" [2]. To minimize the gap between instantaneous energy generation and consumption, the International Energy Agency recommends transitioning from "on-demand power generation" to "on-demand power consumption," and suggests making the energy consumption flexible to keep the energy supply networks stable, reliable, and cost-effective [3].

The building sector worldwide contributes to a significant portion of total global energy consumption [4]. In the United States, approximately 75% of all U.S. electricity consumption and nearly 40% of total U.S. energy consumption is accounted for in buildings [5]. Buildings, therefore, are considered one of the prime sources of cost-effective demand flexibility for the grid, making grid-interactive efficient buildings the focus of research and development in recent years.

Energy storage is a recognized technique to reduce the mismatch between demand and supply on the electricity grid and potentially support the integration of renewable energy sources to the grid [6, 7]. Various energy storage technologies exist: electrochemical storage in electrical batteries [8], thermal energy storage (TES) in phase change materials (PCMs) [9], and pumped hydroelectricity storage in high-elevation water reservoirs [10] are a few examples. These technologies provide temporary storage, when electricity is abundant or less expensive, and dispense the stored energy, when electricity is scarce or more expensive. Because nearly half of the energy used in buildings is related to thermal loads, TES is an attractive candidate in terms of cost and efficiency [11, 12]. Due to their high latent heat capacity, PCMs have been recognized as a very effective TES medium [13]. PCMs can be integrated into building envelopes because they (i) stabilize indoor temperature fluctuations and improve the occupants' thermal comfort [14, 15], (ii) reduce the HVAC energy use, providing energy savings [16, 17], and (iii) modulate the peak energy demand and provide load shedding and shifting capacity [18, 19].

Application of PCMs in buildings is a widely investigated area in the recent literature [20]. Passively implemented PCMs in building envelope has the potential to provide energy saving as

well as load flexibility. Freezing and melting of PCMs by effectively utilizing the diurnal temperature swings reduces thermal loads in the buildings, thereby reducing energy use for heating, ventilation, and air conditioning (HVAC) [20, 21]. Additionally, when the electricity price is low, PCMs can be charged by precooling or preheating using the building HVAC system [22], and the stored energy can be later dispatched when the electricity price is high, providing flexibility to manage the energy demand and reduce the total cost of electricity [19]. While several studies looked at various ways of precooling or preheating PCM in buildings to reduce the stress on the electricity grid during a specified time by peak shifting, the ability of passive thermal storage in a residential building to continuously respond to the variability of grid electricity and provide load flexibility under a high renewable energy generation scenario has not been investigated in the literature. Considering the requirements for grid-interactive buildings, grid flexibility is an important aspect that must be explored. Further, given the increasing interest in the TES technology, there is an urgent need to evaluate PCM's full potential and to support its integration with more intermittent renewable energy sources to the existing grid.

In this study, we performed an analytical and numerical investigation to establish the relationship between PCM-integrated envelopes and the grid's TES requirements in relation to energy savings and demand flexibility. Using ResStock™, a community-scale modeling program, we first calculated the thermal storage required for full demand flexibility at the grid from a cluster of 500 lightweight residential buildings. The total TES requirement is then divided among individual residential homes to evaluate the contribution by each home in meeting the total TES needs. We then formulated an analytical method to quantify the load flexibility of a building. Later, PCM is integrated into the building envelopes to determine if the load flexibility is achieved. We also performed parametric and sensitivity analysis by varying several operating parameters—such as PCM thickness, latent heat, interior temperature setpoint, PCM distribution in the building, and heat transfer coefficients—and calculated the energy saving/penalty due to PCM inclusion to maximize load flexibility.

The main objectives of this study are to (i) quantify the combined annual load flexibility and energy saving potential of PCM-integrated building envelope using numerical modeling, (ii) optimize various PCM thermophysical and operating parameters to maximize its thermal performance, and (iii) identify the sensitivity of PCM properties and other contributing parameters in optimizing the magnitude of load flexibility while assessing HVAC energy savings.

2 Literature Review

PCM inclusion in buildings is an extensively explored research topic. PCMs can be integrated into building components in several possible ways: with HVAC system, in solar water heaters, or in building envelopes [23, 24]. Among the options, building envelopes, such as the wall, roof, and floor, provide the largest distributed surface area for effective heat transfer, making PCM-integrated envelopes a promising solution for thermal storage [25, 26]. This method is particularly effective in lightweight buildings, such as wood-framed constructions [27, 28], because it significantly increases the thermal mass of a building without a major change in actual mass [29, 30]. In this brief literature review, we therefore focus only on lightweight buildings.

Evers et al. [31] reported that PCM-enhanced cellulose insulation in walls provides reductions in the average peak heat flux by up to 9.2% and in the average total daily heat flow up to 1.2%. Kishore et al. [21] noted that depending on the climate, optimized PCMs in U.S. building walls can reduce the annual heat gain up to 47.2% and the annual heat loss up to 8.3%. Prior studies have also reported that PCMs can reduce the buildings' HVAC energy requirements and thus provide significant savings in energy cost. Biswas et al. [16, 17] reported that PCM-enhanced cellulose insulation can reduce electricity consumption for space conditioning by 11%–21.9% In a similar study, Kosny et al. [32] noted that a south-facing vertical wall containing a layer of PCM-insulation mixture provides 20%–35% reduction in peak cooling load and provides load shifting of about 3 hours during summer days. Stovall and Tomlinson [33] noted that a PCM-integrated envelope's effect on the building's energy use depends on the interactions among the exterior climate, thermostat control strategy, PCM transition temperature, and PCM placement in the wall. Neeper [34] stated that the thermal storage capacity of a PCM-integrated wall depends on the PCM melting temperature, the temperature range over which melting occurs, and the latent heat per unit area of the wall.

A key parameter that dramatically affects the performance of PCM is its location within the building envelope. There are several studies that are particularly dedicated to finding the most suitable location for the PCM layer in the envelope [35-37]. For instance, Jin et al. [38, 39] through several experimental and numerical studies concluded that the optimal location of a PCM layer in the wall was affected by the thermal properties of PCM as well as the exterior conditions. The optimal PCM location in the wall moved toward the exterior surface when the PCM thickness,

latent heat, or transition temperature was increased, whereas the optimal PCM location shifted closer to the interior surface when the interior temperature was increased [40, 41]. In a similar study, Fateh et al. [42, 43] reported that the maximum reduction of heat consumption occurred when the PCM was located near center of the wall cavity. Likewise, Lee et al. [44] found that the PCM located at 2/5 of the cavity thickness from the interior in the south-facing wall and 1/5 of the cavity thickness from the interior in the west-facing wall provided maximum peak heat flux reduction. Kosny et al. [45] investigated three configurations of condensed PCM in the ceiling layer and noted that PCM located on the in the middle and on the bottom of the ceiling (attic floor) insulation were the best performing installation strategy for condensed PCM. Tuncbilek et al. [46] concluded that to utilize the latent heat, PCMs layer should be located near the interior while stating that locating the PCM layer near the exterior does not result in any energy savings and may even increase the energy demand. They further suggest that PCM should ideally be placed in a location that maximized thermal interaction with the interior zone. Al-Absi et al. [47] conducted an extensive review of literature which investigate optimum PCM positioning in building envelopes. They concluded that the optimal location of PCM depends on several factors such as application target, weather condition, indoor environment, PCM material properties, and envelope structure and configuration.

While it is well-reported that PCMs integrated into envelopes provide multifold benefits, there are several practical challenges that limits their wide-spread deployment. First, the performance of PCM-integrated envelope depends on multiple factors, including indoor and outdoor temperature conditions and PCM thermophysical properties such as melting temperature, melting temperature range, latent heat, and thermal conductivity of the PCM. All these factors need to be simultaneously optimized to maximize the benefits and least deployment cost [48]. Second, there are material-related concerns that have not been fully addressed. Organic PCMs such as paraffins although highly durable and cost-effective, exhibit low thermal conductivity. Inorganic PCMs such as salt hydrates have relatively higher thermal conductivity but suffer from complex thermal characteristics such as thermal hysteresis and sub-cooling tendencies. Further, since passively applying PCMs in building envelopes requires the material to be integrated with existing material layers as a composite or added as an adjoining layer, the implementation can be restricted by laws or regulations that require the use of non-toxic, non-flammable materials [49]. Due to these reasons, several organic PCMs recently have been hydrogenated and mixed with less flammable

bio-based materials [50]. However, these processes can increase the production cost of the material. The high costs of PCMs, particularly the organic materials, are also driven by the fact that they are mostly crude oil based, and therefore the price greatly depends on oil market [51]. Compared to organic PCMs, inorganic PCMs are less-expensive, non-flammable, and less toxic, but they are corrosive and suffer from phase separation, large volume change, and super cooling causing a significant loss in latent heat enthalpy [9]. Another challenging aspect of passive PCMs is the need for repetitive performance. A recent analysis by Rathore and Shukla [52] reports that PCM must be capable of undergoing more than 5000 thermal cycles.

Despite these challenges, the benefits provided by PCM in managing the building energy demand should not be under-estimated. Along with reduction in building energy use, the ability to shift the timing of peak energy demand is a key aspect of PCM-integrated envelopes. When passively controlled, a PCM-enhanced envelope provides 2–3 hours of shift in peak load hour; active control using precooling/preheating techniques can shift this load even further toward off-peak hours. Turner et al. [18] reported that PCM-integrated envelopes with deep precooling strategies could shift up to 99% of the cooling load in the peak period to the off-peak period. In a similar study, Kishore et al. [22] noted that the optimal precooling strategy for PCM-integrated wall can shift the peak heat gain by up to 14 hours, thereby reducing the heat gain during peak period by up to 95%. Wijesuriya et al. [19] reported that the optimal combination of PCMs, convection mode, and precooling schedule can completely shift cooling energy use during a 3-hour demand period, producing maximum cost savings up to 29.4%, while increasing occupants' comfort. Most of the prior studies, however, have focused on the energy savings aspect of PCM-integrated building envelopes. While it has been established that PCM-integrated envelopes provide benefits, its influence on the grid still needs to be established. So, in this study, we investigate the grid flexibility aspects of PCM-integrated envelopes.

3 Methods

The present study was conducted in two stages: (i) the TES requirement for the desired demand flexibility at a utility grid was calculated using community-scale data from ResStock (a cluster of 500 residential buildings) [53], and (ii) PCM-integrated envelopes were optimized using a building-scale model using EnergyPlus® [54] to achieve the desired TES requirement cascaded down to each residential house.

3.1 Determining Grid Needs

Although the analysis is focused on a single residential building, it is important to model the electrical grid at a larger scale to account for variability in energy storage more accurately. Thermal loads in homes are not synchronized, therefore, it is important to model enough individual homes such that, when the loads are aggregated, there is sufficient granularity and the mismatch between the energy load and the power generation on the grid can be accurately defined. Ideally, the entire US electrical grid and all the loads would be modeled. For computational efficiency, we elect to model only enough residential buildings to provide a reasonable approximation of the load variability they represent to the grid. We do not consider commercial or industrial loads; although those are important, the majority of peak loads on the grid are due to residential thermal loads. Therefore, our approach is more tractable while still highlighting the driving factors behind the need for energy storage and grid flexibility: high penetration of renewable energy and residential thermal loads. We made following assumptions to simplify the analysis.

- The grid serves only a cluster of 500 residential buildings that are representative of the features, age, and location of homes in the US
- All buildings are independent
- The TES contribution for each building is proportional to its total annual thermal load.

In this study, we randomly chose 500 buildings from the ResStock library of approximately 350,000 archetype US homes. That number is arbitrary but was chosen to balance computational efficiency with granularity of the results. While the total thermal storage needs at a utility grid will certainly vary with the change in the number of buildings it serves, the procedure established in this paper to calculate PCM requirement, such its material properties, quantity, and location, at an individual residential home would remain unchanged. The second assumption related to the mutual independence of all the residential homes in the cluster is essential and realistic. Currently, the individual homes in most communities in the United States are independent in terms of their energy needs and uses; therefore, the TES contribution of each individual home is expected to be solely dependent on its own thermal load not on the other neighboring homes in the community. The last assumption relating the thermal load and TES contribution was essential to scale the total thermal storage requirement at the grid to each residential building. We have divided the total TES at the grid among the individual buildings based on the proportion of energy demand at a single building

over the total energy demand on the grid. While this method is linear and simple to implement, a complex formulation can also be used without affecting the remaining portion of this study.

We developed a methodology to quantify the impact of temporal control on the ability of buildings to provide flexibility to the grid. Specifically, our method determines how much peak net load on the grid can be reduced due to the load-shifting potential of TES. Net load (Q_{Net}) on the grid is defined as:

$$Q_{Net}(t) = Q_{Total}(t) - Q_{VG}(t) \quad (1)$$

where Q_{Total} is the total instantaneous power demand on the grid and is the sum of all various individual loads, such as space heating and cooling, hot water, lighting, etc., from the buildings. Q_{VG} is the variable power generation from renewable resources.

The total load profiles (Q_{Total}) were obtained from several ResStock simulations, whereas the variable power generations (Q_{VG}) were drawn from the National Renewable Energy Laboratory's reV model [55]. We assumed that 80% of the total power generation comes from variable sources. These are aggressive assumptions that represent a future situation in which the need for storage and the potential for thermal storage are much higher than today [56]. In the absence of time-shifting control in loads, any positive net load must be served by dispatchable generation (e.g., hydroelectric or natural gas power plants), whereas any negative net load implies that there is more variable generation than demand at that moment and therefore some of the variable generation must be curtailed or stored. Additionally, the required amount of dispatchable generation capacity is a function of the peak net load. The greater the peak net load, the more dispatchable generation is required to serve that demand. TES can reduce the peak net load, thereby reducing the amount of required dispatchable generation while still meeting the thermal load demand of end users.

The thermal storage requirement for the entire year was calculated as follows. Because TES only shifts energy, we can theoretically determine a bounding case for the maximum amount of useful energy storage. If the efficiency of the storage is 100%, the entire net load profile could be smoothed out to a single average value. In other words, the minimum possible dispatchable generation (DG_{min}) is equal to the average over the course of the year. In this hypothetical scenario, the dispatchable generation fleet would be running constantly, with TES charging and discharging, serving the time-varying demand.

$$DG_{min} = \frac{1}{\tau}\int_0^{\tau} Q_{Net}(t)\ dt \quad (2)$$

where τ is the total time of the year in hours, which is 8,760 hours.

By comparing the difference between the net load (Q_{Net}) and minimum dispatchable generation (DG_{min}), we can calculate the energy required for charging (Q_{Es}^{+}) and discharging (Q_{Es}^{-}) the overall energy storage system at the grid.

$$Q_{Es}^{+}(t) = Q_{Net}^{+}(t) - DG_{min}(t) \quad (3)$$

$$Q_{Es}^{-}(t) = DG_{min}(t) - Q_{Net}^{-}(t) \quad (4)$$

Note that Q_{ES} is the total energy storage, including thermal storage as well as all other forms of energy storage, such as electrochemical batteries. The thermal component of the energy storage is limited by the fact that thermal storage can only be "discharged" up to the rate of thermal loads in buildings in any given time. That is because thermal storage can only supply thermal loads (thereby offsetting electricity needed to supply those loads). Also, the charging capacity of the TES is limited by the maximum discharging requirements. This was instituted to prevent "oversizing" the TES power requirements based on preventing curtailment rather than on supplying needed thermal energy. Based on the above logic, the TES power ($Q_{TES,g}$) at the grid can be calculated as:

$$Q_{TEs,g}^{-}(t) = min(Q_{Thermal}(t), Q_{Es}^{-}(t)) \quad (5)$$

$$Q_{TEs,g}^{+}(t) = min(max(Q_{TEs,g}^{-}(\tau)), Q_{Es}^{+}(t))) \quad (6)$$

where $Q_{Thermal}$ is the total thermal load in the building connected to the grid at any given time, and $Q_{TEs,g}^{+}$ and $Q_{TEs,g}^{-}$ are the charging and discharging rates of TES. Here subscript "g" has been used to specify the TES requirement at the grid. We will subsequently use subscript "b" to differentiate it from TES contribution by a single building, which can be calculated as:

$$Q_{TES,b}(t) = \frac{Q_b(t)}{Q_{Total}(t)} Q_{TES,g}(t) \quad (7)$$

Here it is assumed that total TES at the grid ($Q_{TES,g}$) is divided among the individual buildings based on the energy demand at a single building ($Q_{TES,b}$) versus the total energy demand at the grid (Q_{Total}).

Figure 1 shows the requirement of thermal storage determined through the method described above for a residential building in Baltimore, Maryland. Figure 1(A) shows the variation in hourly TES

needs for an entire year. The positive values show the charging requirement, and the negative values show the discharging requirement. The total annual TES requirements are 2,772 kWh for charging and 3,684 kWh for discharging. Figure 1(B) zooms in on four days in July (July 1–4) to showcase the variations of charging and discharging requirements. Typically, TES is charged (storing energy) during off-peak hours when demand is small and discharged during peak hours (releasing energy) when demand is high.

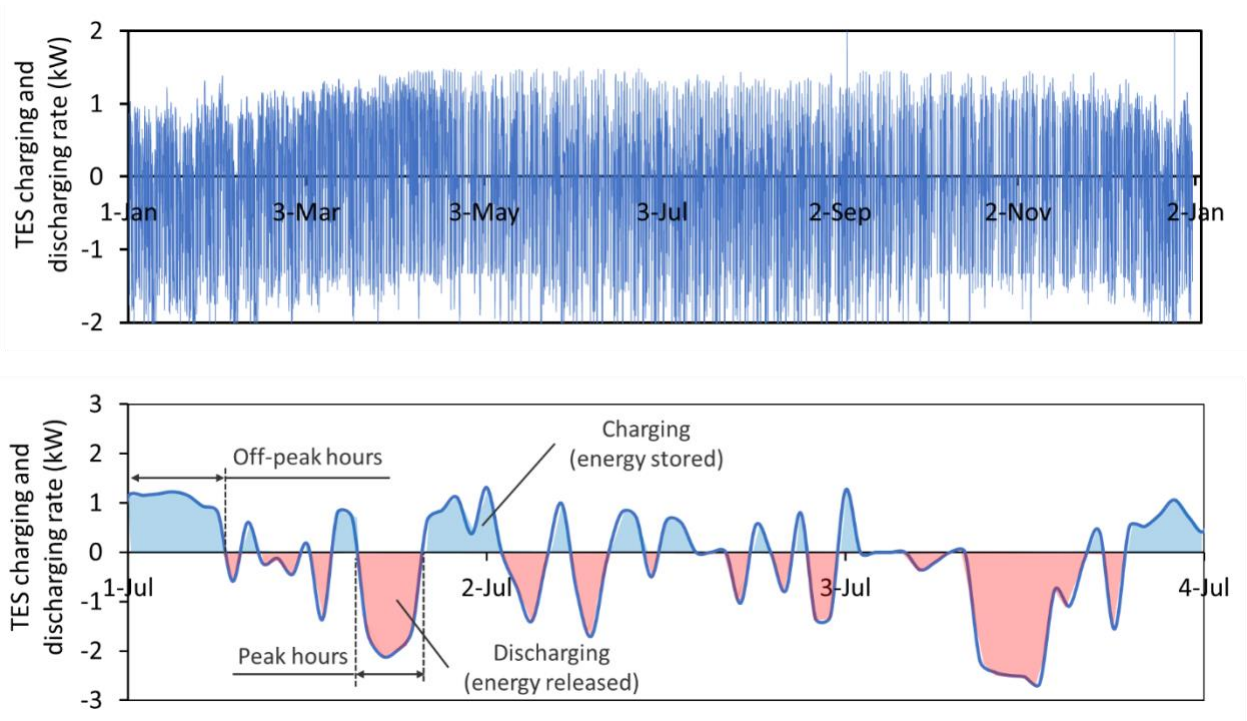

Figure 1. TES charging and discharging rates of a residential building in Baltimore, Maryland for grid flexibility during (A) an entire year, (B) four days, July 1–4.

The energy efficiency of a PCM-integrated building is defined as the reduction in energy use by the PCM-integrated building over the energy use in a reference building with no PCM.

$$\eta_{saving} = \frac{\int_0^\tau \Delta E(t)\, dt}{\int_0^\tau E(t)\, dt} \tag{8}$$

where, $E(t)$ is the energy use in the reference building, and $\Delta E(t)$ is the change (increase or decrease) in energy use caused by the presence of TES in the PCM-integrated building.

In this study, the load flexibility potential of the PCM-integrated building is determined by comparing the energy change caused by the PCM against the TES charging/discharging requirements. Mathematically, it can be expressed as:

$$\eta^{+}_{flex.} = \frac{\int_0^{\tau} \Delta E^{+}(t)\, dt}{\int_0^{\tau} Q^{+}_{TES,b}(t)\, dt} \quad (9)$$

$$\eta^{-}_{flex.} = \frac{\int_0^{\tau} \Delta E^{-}(t)\, dt}{\int_0^{\tau} Q^{-}_{TES,b}(t)\, dt} \quad (10)$$

$$\eta_{flex.} = \frac{\int_0^{\tau} \Delta E^{+}(t)\, dt + \int_0^{\tau} \Delta E^{-}(t)\, dt}{\int_0^{\tau} Q^{+}_{TES,b}(t)\, dt + \int_0^{\tau} Q^{-}_{TES,b}(t)\, dt} \quad (11)$$

where ΔE^{+} and ΔE^{-}, respectively, are the increase and decrease in energy loads in a PCM-integrated building compared against the reference building, and $Q^{+}_{TES,b}$ and $Q^{-}_{TES,b}$, respectively, are TES charging and discharging rates associated with the building. $\eta^{+}_{flex.}$ and $\eta^{-}_{flex.}$ represent load flexibility during charging and discharging the TES, whereas $\eta_{flex.}$ is the overall load flexibility by the PCM-integrated building.

Note that the benefits of the PCM integrated into the building walls are not solely due to its latent heat but also because of the added thermal resistance and the heat capacity since it is in addition to existing insulation. As highlighted in the references [46, 57-59], a phase-stabilized material (PSM) wall can be defined that contains the PCM layer but its latent heat is not exploited because the melting and solidification do not occur due to mismatch between transition and operating temperatures. Arici et al. [58] reported that while a PSM wall provides certain energy saving benefits, utilizing PCM latent heat is crucial as it provides substantially higher energy saving. The primary goal of this study is to evaluate the overall benefit of using the PCM; therefore, we have not specifically differentiated between the PSM and PCM walls.

3.2 Building Model

Figure 2(A) shows the single-family residential building model [60] used for the analysis in this study. The building has a floor area of 387 m^2 (4,166 ft^2) and a net conditioned area of 187 m^2 comprising a living area and the garage zone. The living zone is enclosed with six exterior wall surfaces, ceiling, and the floor. Three of the exterior wall surfaces are facing north, and the remaining three wall surfaces are facing east, west, and south. In addition to the conditioned zones, the building includes an unconditioned basement and an unfinished attic.

The climate used this study is Baltimore, MD, USA whose weather file was obtained from Typical Meteorological Year database [61]. Figure 2(B) shows the exterior wall structure of the typical building containing no PCM. The house without PCM is considered the reference case. PCM is added to various assemblies enclosing the living zone in a stepwise manner. Starting with the exterior walls, a PCM layer is included behind the drywall, as shown in Figure 2(C). The PCM location in the wall is a crucial parameter as it determines the extent of its interaction with the interior and exterior environments. When the PCM is placed near the exterior, it interacts very effectively with the exterior environment, but due to the large thermal resistance of the wall insulation, it is unable to effectively transfer the stored energy to or from the interior. On the other hand, when PCM is located near the interior, it interacts effectively with the interior, but it is unable to effectively utilize the benefits of diurnal temperature swings and related free ambient cooling/ heating phenomena. Based on our prior study [48], PCM located near the interior provides maximum load flexibility benefits because of the higher interaction between the interior environment and the PCM that allows controlled phase transition during the charging and discharging processes.

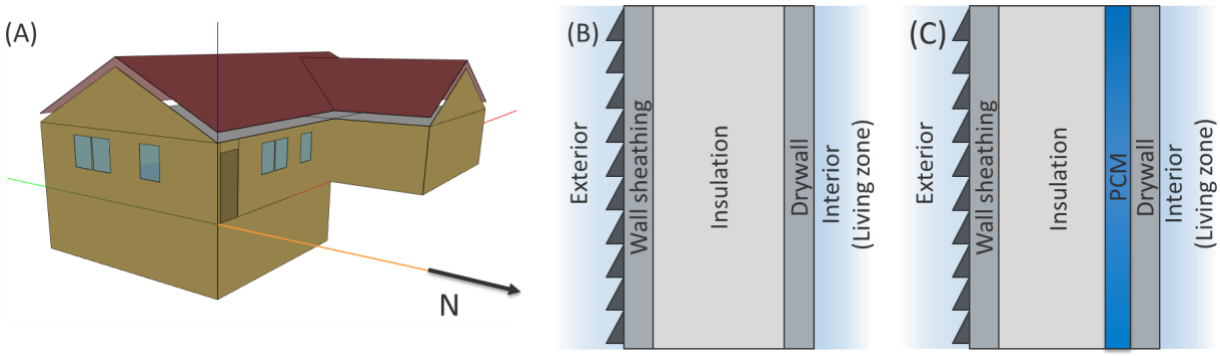

Figure 2. Residential building model: (A) whole-building view, (B) exterior wall structure without PCM, and (C) exterior wall structure with PCM behind the drywall.

All the simulations were performed using EnergyPlus version 9.4, which is an established whole building energy simulation program used to model both energy consumption and water use in buildings [62]. The program employs one-dimensional conduction finite difference (CondFD) algorithm to model the PCMs using two modules called “MaterialProperty: PhaseChange” and “MaterialProperty: PhaseChangeHysteresis”. Since we neglected the hysteresis in the PCMs

considered in this study, we used the first module, "MaterialProperty: PhaseChange", which has been previously validated using multiple other commercial programs [63] as well as against the experimental data [64]. Since more detailed information about CondFD model in EnergyPlus can be easily found in the published literation [65], here we provide only a brief information for brevity of this paper. The CondFD model comprises four different types of nodes: interior surface nodes internal nodes, material interface nodes, and external surface nodes, and uses an implicit finite difference scheme as its solver, which solves the one-dimensional heat transfer equation at each of the nodes indicated above. We used the fully implicit scheme for numerical analysis in this study.

Table 1 lists the various layers of the envelope components in the reference building. The material layers are indicated from exterior to interior. The PCM layer is added in addition to the existing components of the reference building, increasing the total thickness of the envelope.

Table 1. Layer structure of the wall assemblies in the residential building considered in the study.

Layer position	Ceiling	Exterior walls	Floor	Interior walls
1 (Exterior layer)	Additional ceiling insulation	Exterior finish	Drywall	Wall sheathing
2	Truss and insulation	Wall sheathing	Stud and air layer	Wall stud and cavity
3	Drywall	Wall stud and cavity	Floor sheathing	Wall sheathing
4		Drywall	Wood floor	
5			Floor covering	
R-value (°F·ft^2·h/BTU)	13.1	10.1	5.3	9.6
U-value (K·m^2/W)	0.433	0.562	1.071	0.591

Table 2 shows the thermophysical properties of the building materials. We assume that the PCM is macro-encapsulated and used in the form of pouched sheets or shape stabilized layers. The material properties of all components are taken from default material library of EnergyPlus. Prior studies have recommended that the PCM layer used in the envelope should be thin to ensure minimal thermal resistance along the thickness [66]. For the parametric analysis, we have considered PCM thicknesses in the range of 0.64–3.81 cm. PCM latent heat is varied from 50 kJ/kg to 250 kJ/kg, which is within the range of values reported for low-cost commercial PCMs [67, 68]. For simplicity, we ignore the complex PCM behaviors and assume the melting and freezing curves are the same. The thermophysical properties of the PCM were taken from the commercial datasheet of savE® OM series PCMs, which are blend of various organic fatty acids [69]. The PCM was assumed to have transition temperature in the range of 16º–26ºC, which is also consistent with commercially available organic PCMs [69].

Table 2. Thermophysical properties of the building envelope. The information was taken from references: [69, 70].

Layer	Density (kg/m^3)	Thermal Conductivity (W/m·K)	Specific Heat (J/kg·K)	Latent Heat (kJ/kg)	Thickness (cm)
Additional ceiling Insulation	16	0.06	1,047	-	5.08
Drywall	550	0.15	1,089	-	1.30
Floor covering	54	0.04	1,340	-	1.30
Floor sheathing	513	0.12	1,214	-	1.90
Air + stud	68	0.56	1,210	-	14.0
Insulation + stud	162	0.06	1,178	-	8.89
Truss + insulation	51	0.06	1,165	-	8.89

Wall sheathing	512	0.12	1,214	-	1.30
Wood floor	545	0.12	1,211	-	1.60
PCM (solid)	880	0.30	2,750	50–250	0.64–3.81
PCM (liquid)	880	0.10	1,848	50–250	0.64–3.81

Table 3 provides the information related to the thermal loads and the HVAC system in the residential building considered for the analysis. There are two conditioned spaces in the building, the living zone and the garage zone. To apply the envelope modifications, only the living zone is considered in this analysis. The HVAC system in the building comprises of an accessory dwelling unit residential air-source heat pump that provides both cooling and heating to the building. The energy source for the heat pump is electricity. A supplementary heating coil is also electrically powered.

Table 3. HVAC system and loads in the residential building considered in the study.

Items	Description	Specifications
Lighting	Lighting level	258 W
Appliances	Residential ceiling fan	19.3W
	Residential clothes dryer	187 kW
	Residential clothes washer	7.8 kW
	Dish washer	11.7 kW
	Miscellaneous plug loads	270 W
	Range electric	225 W
	Refrigerator	109 W
People	Average number of people	1.32
	Sensible heat fraction	0.57

Cooling	Rated cooling capacity	4.92 kW
	Gross rated cooling COP	4.07
	Rated air-flow rate	0.26 m^3/s
Heating	Gross rated heating COP	3.33
	Rated air-flow rate	0.25 m^3/s
Supplementary heating	Nominal capacity	6.35 kW
	Heating COP	1
Fan	Efficiency	75%
	Maximum flow rate	0.33 m^3/s
Additional Information	Window-to-wall-ratio	0.15
	Living zone floor area	98 m^2
	Living zone vertical surface area	113.5 m^2
	Net-conditioned volume	235.2 m^3
	Air Source Heat Pump	Seasonal Energy Efficiency Ratio (SEER) 13 Heating Seasonal Performance Factor (HSPF) 7.7

3.3 Parametric Analysis

The performance of PCM-integrated envelopes depends on several parameters including the PCM's transition temperature, its thermophysical properties, thickness, location, the interior thermostat control strategy, and the heat transfer coefficient between interior wallboard and indoor air. In this study, we performed a parametric analysis in a predetermined range, which was prepared based on a preliminary analysis and literature review.

Table 4 lists the range of various parameters used in the analysis, which was performed in a stepwise manner by varying one parameter at a time while keeping the remaining parameters

constant. During every optimization step, one parameter was examined and then the optimal value was selected before moving forward to the next one. As mentioned in Section 3.2, the PCM layer's thickness is varied in the range of 0.25–1.50 in. (0.64–3.81 cm). The latent heat of PCM was varied in the range of 50–250 kJ/kg. The heating and cooling setpoints were dynamically varied in accordance with the grid level TES requirements, so that the PCM can be solidified and melted as per TES charging and discharging needs. We define the variable setpoint (T_{sp}) to account for the variation in setpoint temperature to actively charge and discharge the PCM.

$$T_{sp}(t) = T_{msp} \pm \frac{|\,Q_{TES,b}\,(t)|}{max\,(Q_{TES,b})} T_{vsp} \quad (12)$$

The instantaneous TES requirement (Q_{TES}, b) was obtained from equations (5) to (7), and the mean setpoint temperature (T_{msp}) was fixed at 22.8°C for the cooling season and 19.0°C for the heating season. The maximum thermal storage requirement, max ($Q_{TES,b}$), was taken to be 2.0 kW, which is approximately the average of the discharging peaks in Figure 1(A). The variable component of setpoint temperature (T_{vsp}) was varied within the range of 0.5°–2.0°C to ensure thermal comfort of the occupants.

We also varied the PCM distribution in the building as follows. First, PCM was added in the exterior walls (EW). Later, in addition to the exterior walls, PCM was included in the ceilings (C), floors (F), and interior walls (IW). The PCM layer is added behind the drywall of the exterior walls and ceiling; for the floor, the PCM layer is added underneath the wood floor, and for the interior walls, PCM layers are placed behind the drywall on either side of the wall stud and cavity layer.

Lastly, we examined the effect of different heat transfer coefficients. TARP is the default natural convection model used in this study and is a built-in function in EnergyPlus [71], which calculates variable convection coefficients at the interior surfaces based on the temperature difference between the surface and zone air [72]. Figure 3 shows the annual convection coefficient variation for different surfaces within the occupied zone with TARP model. Note that convection coefficient on all the surfaces remains lower than 2.5 W/m^2·K throughout the year. The energy Management System (EMS) modeling environment of EnergyPlus allows users to override the convection coefficients at the interior surfaces of the building model. During the parametric analysis, we varied the heat transfer coefficient in the range of 2.5–10 W/m^2·K in 2.5 increments to implement

mixed and forced convection conditions assuming the operation of ceiling fans and compared the performance against the TARP model [73].

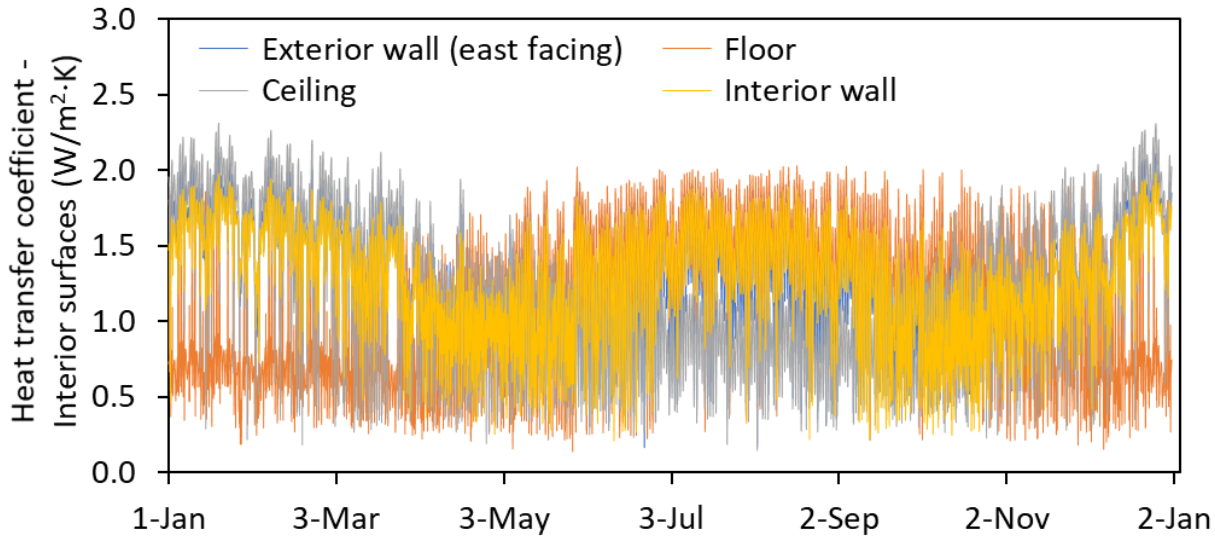

Figure 3. Convection coefficient variation at each interior surface with TARP model

The effectiveness of PCM-integrated envelopes toward achieving the grid's TES requirements was determined by comparing the HVAC related electricity use in buildings with and without PCMs. The energy use in the building without PCM (the reference house) was considered the baseline. For the reference case, a constant cooling setpoint of 73°F (~22.8°C) and a constant heating setpoint of 66°F (~19.0°C) was considered along with the TARP convection model at the interior surface of the exterior walls. The difference of the energy consumption between the reference building and PCM-integrated buildings is calculated at each 1-hour interval. The positive value indicates the energy penalty (extra energy consumed by the PCM-integrated building), whereas the negative value infers an energy savings (less energy consumed by the PCM-integrated building by minimizing the energy use by HVAC).

Table 4. Various parameters, their default value and the range used for the parametric analysis.

Parameters	Units	Default Value	Investigated Values
PCM thickness (t_{pcm})	cm	0.64	0.64 ,1.27, 1.91, 2.54, 3.18, 3.81
Latent heat (LH)	kJ/kg	100	50, 100, 150, 200, 250

Variable setpoint temperature (T_{vsp})	°C	2.0	0.5, 1.0, 1.5, 2.0
PCM distribution	-	Exterior walls (EW)	Exterior walls (EW), Exterior walls + Ceiling (EW + C), Exterior walls + Ceiling + Floor (EW + CF), Exterior walls + Ceiling + Floor + Interior Walls (EW + CF + IW)
Heat transfer coefficient (HTC)	W/m^2·K	TARP	TARP, 2.5, 5.0, 7.5, 10.0

Figure 4 illustrates a flowchart summarizing the steps used during the parametric analysis. Each parameter indicated in the Table 4 was varied while keeping the other parameters constant at a default value. After every step of the parametric analysis, the optimum value of a certain parameter was selected and later used in the subsequent steps. The baseline case represents the operating conditions of the reference building used to compare and calculate the annual load flexibility and energy savings in a PCM-integrated building. As shown, during the first four steps of the parametric analysis (used to optimise PCM thickness, latent heat, VSP, and PCM locations), a common baseline case comprising no PCM, no VSP, and a constant heat transfer coefficient (TARP) was used. However, in the final step of the analysis, the heat transfer coefficient was varied in the reference as well as PCM-integrated building.

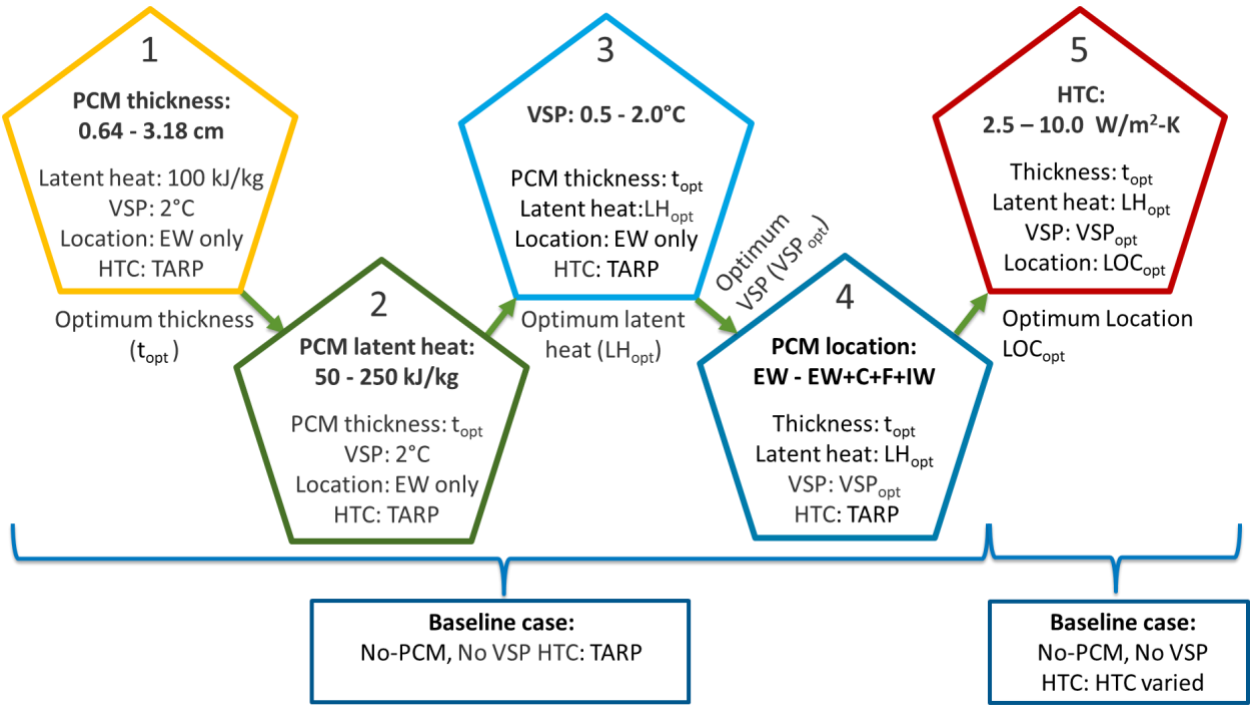

Figure 4. Flowchart illustrating the steps used during the parametric assessment.

4 Results and Discussion

4.1 Load Flexibility by a PCM-Integrated Building

As explained in Section **Error! Reference source not found.**, determining load flexibility and energy savings in the PCM-integrated building requires comparing it against the energy use in the identical reference building containing no PCM or VSP. Figure 5 shows the procedure used to obtain the change in HVAC energy use (ΔE^+ and ΔE^-) in the PCM-integrated building in comparison to the reference building. For illustration, we have shown only the first four days of July, but this procedure was followed for the entire year. As shown in Figure 5(A), a constant temperature setpoint depicted as "baseline" was used in the reference building, whereas the setpoint temperature in the PCM-integrated building was altered in accordance with TES variations (shown in Figure 1) to allow controlled charging and discharging of the PCM. Due to the influence of the PCM, the energy use profile of the PCM-integrated building varies substantially from that of the reference building, as shown in Figure 5(B). When energy use in the PCM-integrated building is higher than the reference building, it is considered an energy penalty even though this is eventually used to charge the PCM. Likewise, when energy use in the building

is lower than that of the reference building, it is considered an energy savings, as the surplus energy is provided by the PCM during discharging. The positive and negative differences in the energy use, shown in Figure 5(C) and (D), eventually provide the load flexibility, which can be calculated using equations (9) to (11) described in Section **Error! Reference source not found.**.

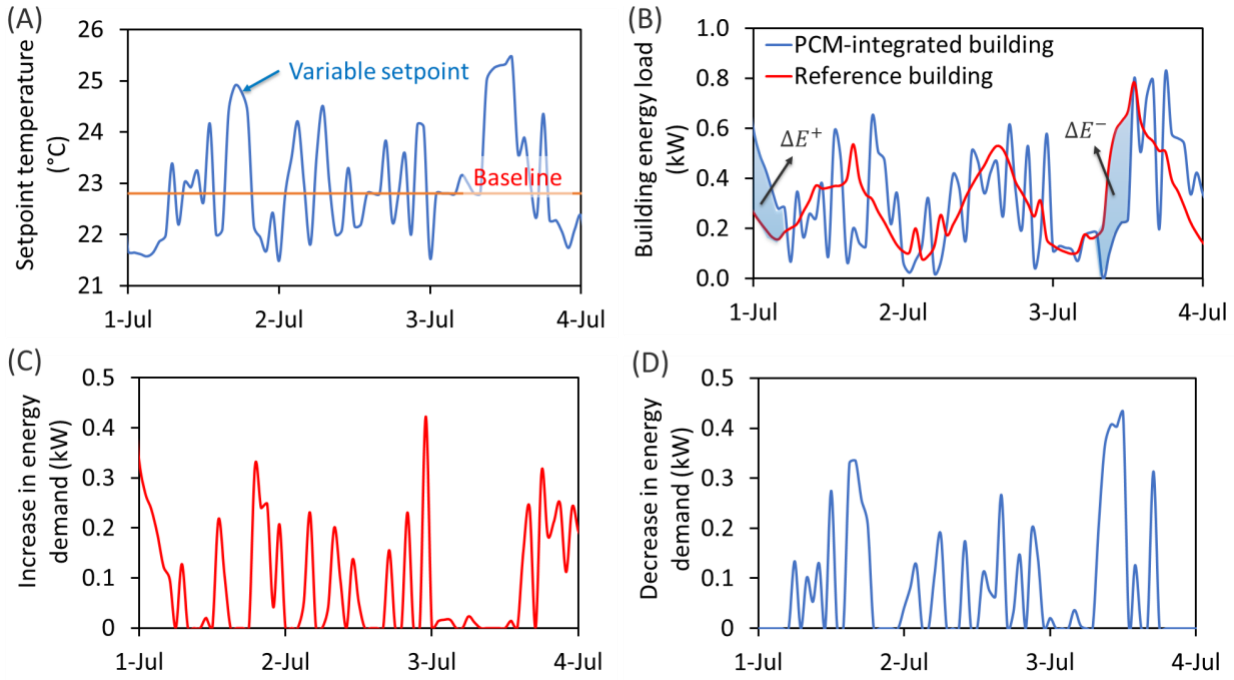

Figure 5. Steps used to obtain change in HVAC energy use (ΔE^+ and ΔE^-) in the PCM-integrated building. (A) Variable temperature setpoint used to controllably charge and discharge the PCM. (B) Energy use in the PCM-integrated building versus energy use in the reference building containing no PCMs. (C) Increase in energy use due to energy storage in PCM. (D) Decrease in energy use due to energy released by PCM.

Figure 6 compares the TES charging energy ($Q^+_{TES,b}$) and discharging energy ($Q^-_{TES,b}$) needed for demand flexibility versus change in energy (ΔE^+ *and* ΔE^-) provided by the PCM. The energy penalty (ΔE^+) and energy savings (ΔE^-) signify the contribution by the PCM-integrated building in meeting demand flexibility. Comparing the TES charging and discharging needs and variable energy use in the PCM-integrated building in Figure 6(A) and (B), we can see that the PCM-integrated building can reproduce the continuous variability needed for grid flexibility; however, the magnitude is nearly one order lower, which is expected considering the small amount of PCM used in the building envelope. The total TES charging and discharging energy needed for full load

flexibility is 2,772 kW-h and 3,682 kW-h, respectively, whereas the positive and negative change in energy use in the PCM-integrated building is 553 kW-h and 658 kW-h, respectively. In other words, the PCM-integrated building in the given case can meet 19.9% of the total TES charging requirement and 17.9% of the total TES discharging requirement. Overall, the PCM-integrated building in the given case provides an annual load flexibility of 18.8% and an annual energy savings of 3.5%. Note that the results shown in Figure 6 are for a sample case, where the PCM in the exterior walls has a thickness of 0.64 cm, and latent heat of 100 kJ/kg. The variable setpoint point (T_{vsp}) is 2°C and the convection model used is TARP. We will see in the subsequent sections that load flexibility and energy savings can be substantially enhanced by parametric optimization.

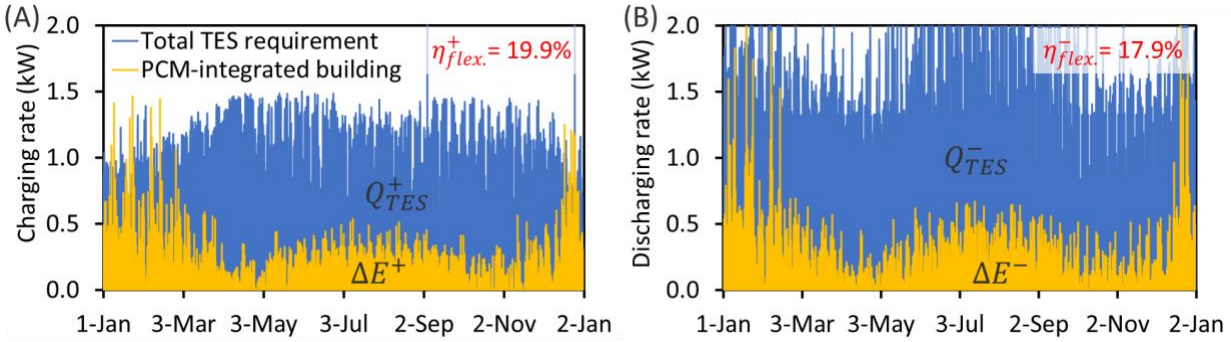

Figure 6. Accessing total TES requirements versus change in energy use for (A) charging, and (B) discharging in a PCM-integrated building.

4.2 PCM Thickness

Figure 7 shows the effect of PCM thickness on the annual load flexibility and energy savings in a PCM-integrated building. The PCM thickness is varied from 0.64 cm to 3.81 cm, while keeping latent heat fixed at 100 kJ/Kg, T_{vsp} = 2°C, convection model as TARP, and PCM included in the exterior walls only. As shown in Figure 7(A), the effect of PCM on load flexibility is prominent when its thickness is increased from 0.64 cm to 1.91 cm, providing an increase in load flexibility from 18.8% to 19.3%. However, increasing PCM thickness beyond this value provides no major benefits in terms of load flexibility. Figure 7(B) shows the effect of PCM thickness on annual energy savings. Annual energy savings increase from 3.5% to 7.4% with increase in PCM thickness from 0.64 cm to 3.81 cm; however, there are diminishing returns. This happens despite the higher energy storage capacity provided by a thicker PCM layer. Prior studies have reported that interior temperature fluctuations are smaller when the PCM thickness is large [74, 75],

implying that its utilization reduces as thickness increases. That indicates that though the thermal storage capacity of the PCM increases with increase in its thickness, additional PCM remains unutilized when the thickness is greater. Consequently, load flexibility as well as energy savings first increase with an increase in PCM thickness because it helps in achieving higher energy storage; however, beyond a certain limit, additional energy storage capacity remains unutilized, providing limited benefits. Because the focus of this study is load flexibility, we select a PCM thickness of 2.54 cm for the remaining analysis in the paper.

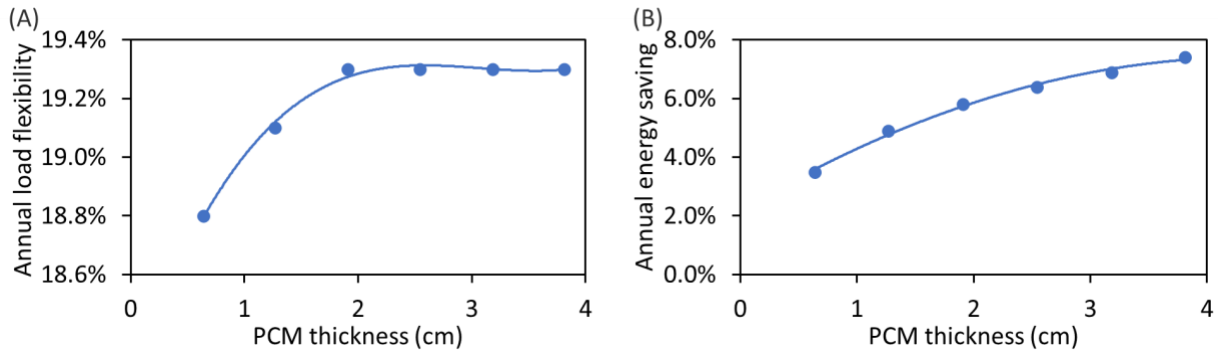

Figure 7. PCM thickness versus the (A) annual load flexibility and (B) annual energy savings in the PCM-integrated building.

4.3 PCM Latent Heat

Figure 8 shows the effect of PCM latent heat on the annual load flexibility and energy savings potential of the PCM-integrated building. Latent heat is increased from 50 kJ/kg to 250 kJ/kg, while keeping thickness fixed at 2.54 cm, T_{vsp} = 2 °C, convection model as TARP, and PCM included in the exterior walls only. The effect of latent heat is like that of PCM thickness because both these factors affect the heat capacity of the PCM. Increase in latent heat leads to an increase in load flexibility as well as energy savings; however, there are diminishing returns. Load flexibility nearly saturates at 19.5% beyond latent heat of 200 kJ/kg. Annual energy savings, on the other hand, continues to increase from 5.8% to 7.4% with increases in latent heat from 50 kJ/kg to 250 kJ/kg; however, the benefit is reduced. Like PCM thickness, increase in latent heat reduces the interior temperature fluctuations and, therefore, the variation of melting fraction of the PCMs. In other words, utilization of PCM reduces with increases in its latent heat capacity. This infers that part of the PCM's heat capacity remains unutilized when the latent heat is high, thereby

resulting in diminishing benefits. Based on these observations, we selected latent heat of 200 kJ/kg for the remainder of this study.

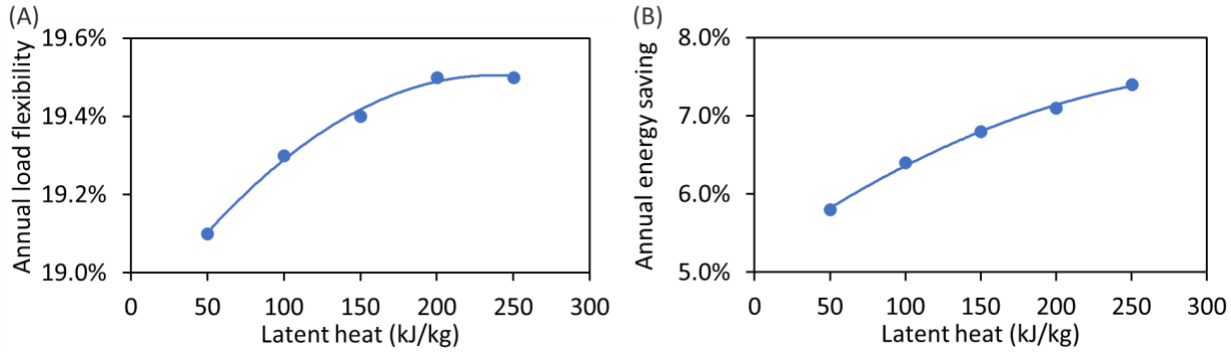

Figure 8. PCM latent heat versus the (A) annual load flexibility and (B) annual energy savings in the PCM-integrated building.

4.4 Variable Setpoint Temperature

Figure 9 shows the effect of variable temperature setpoint (T_{vsp}) on the annual load flexibility and energy savings. T_{vsp} is increased from 0.5°C to 2.0°C, keeping PCM thickness fixed at 2.54 cm, latent heat at 200 kJ/kg, convection model as TARP, and PCM included in the exterior walls only. Increase in T_{vsp} results in higher interior temperature fluctuations, which eventually drive higher utilization (melting/freezing) of the PCM, causing an increase in both charging- and discharging-related energy. As shown in Figure 9(A), load flexibility increases almost linearly from 7.1% at T_{vsp}= 0.5°C to 19.5% at T_{vsp}= 2.0°C. Increasing T_{vsp} beyond this value can further increase load flexibility; however, because the interior temperature affects the occupants' comfort, there is a limit beyond which variable setpoint range cannot be increased. ASHRAE Standard 55-2010 [76] specifies that the operative temperature may not change more than 2.2°C (4.0°F) during a 1-hour period. If variations are created because of control or adjustments by the user, higher values may be acceptable. We note that the largest change of temperature within an hour is ~2.7°C when T_{vsp} = 2°C, which is slightly higher than the value specified in the standard; therefore, we selected T_{vsp} = 2°C for further analysis in this paper.

As shown in Figure 9(B), the effect of T_{vsp} on energy savings is different than load flexibility. Annual energy savings first increase from 5.6% at T_{vsp} = 0.5°C to 7.9% at T_{vsp} = 1.0°C, but this decreases with further increase in T_{vsp}. This is expected because energy savings by PCM requires

stable interior temperature to reduce HVAC operation. Alternatively, load flexibility requires variable interior temperatures to maximize PCM charging and discharging. Increase in T_{vsp} beyond 1.0°C significantly increases HVAC operation, causing higher energy use and thus lower energy savings. Because in this study our primary focus is to enhance load flexibility, we have considered T_{vsp} = 2.0°C for the subsequent analysis.

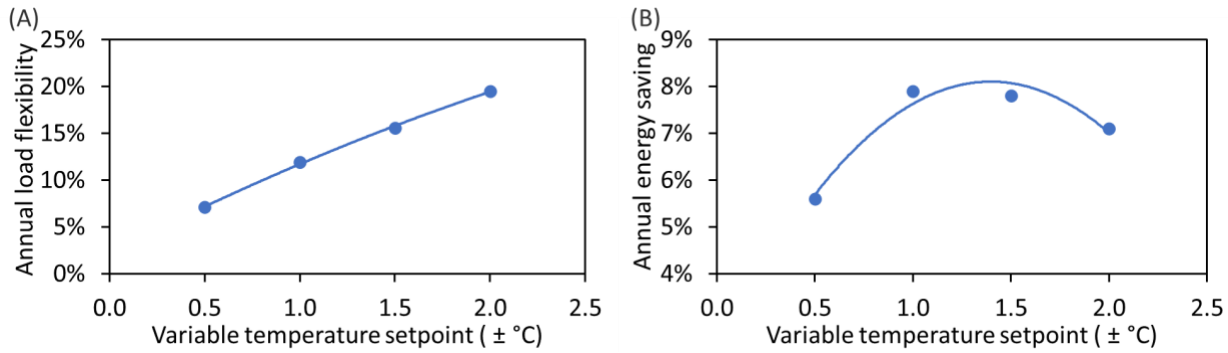

Figure 9. Variable setpoint temperature versus the (A) annual load flexibility and (B) the annual energy savings potential of the PCM-integrated building.

4.5 PCM Distribution

Figure 10 shows the effect of PCM distribution on the annual load flexibility and energy savings. PCM distribution in the building envelope is increased by adding PCM in the external walls (EW), ceiling (C), floor (F), and internal walls (IW). The remaining parameters remain unchanged: PCM thickness is 2.54 cm, latent heat is 200 kJ/kg, T_{vsp} = 2°C, and the convection model is TARP. Increasing PCM distribution, in general, increases load flexibility as well as energy savings. However, it is not certain that an increase in PCM quantity in the building would always enhance energy saving and load flexibility. As shown in Figure 10, adding PCM in the ceiling enhances thermal performance of the building; however, the same quantity of PCM in the floor does not provide any benefit. We attribute this to the low R-value of the floor, which is about three times lower than that of the exterior walls, leading to large thermal losses. Overall, as shown in Figure 10(A), load flexibility in the PCM-integrated building increases from 19.5% for EW-only case to 22.3% for EW + CF + IW case. As shown in Figure 10(B), energy savings increase from 7.1% for the EW-only case to 11.4% for the EW + CF + IW case.

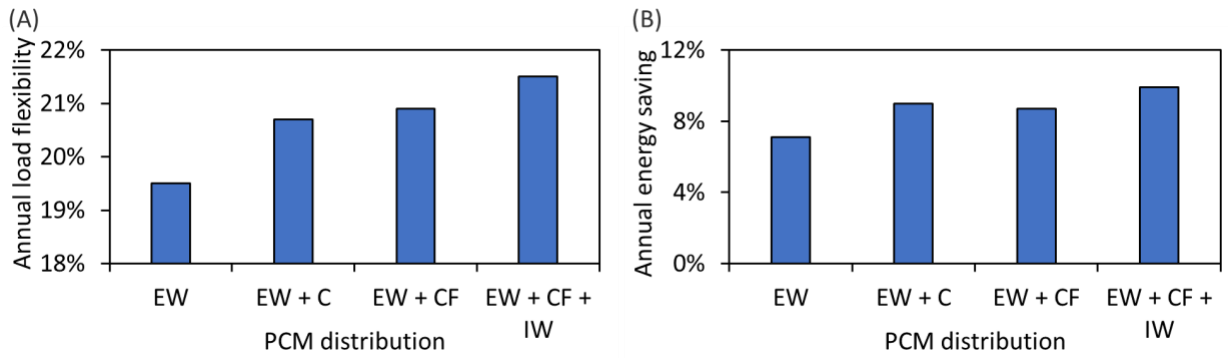

Figure 10. PCM distribution versus the (A) annual load flexibility and (B) the annual energy savings potential of the PCM-integrated building.

4.6 Heat Transfer Coefficient

Figure 11 shows the variation in the annual load flexibility and energy savings with an increase in the heat transfer coefficient at the inner surfaces. For these simulations, PCM thickness is 2.54 cm, latent heat is 200 kJ/kg, $T_{vsp} = 2$°C, and PCMs are added to exterior walls, floor, ceiling, and the interior walls. The first case shows the default TARP model, where the convection coefficient changes through the year (as shown in Figure 3), but it always remains lower than 2.5 W/m^2·K. The remaining cases illustrate the constant heat transfer coefficients: 2.5, 5, 7.5, and 10 W/m^2·K. The effect of increasing the heat transfer coefficient on load flexibility and energy savings is nearly the same as that of variable setpoint temperature; both these factors eventually increase the heat interaction between energy storage in PCM and indoor air. As shown in Figure 11(A), increasing the heat transfer coefficient from TARP to 10.0 W/m^2·K linearly increases load flexibility from 21.5% to 33.6%. On the other hand, energy savings first increases from 9.9% to 11.7% with the increase in the heat transfer coefficient from TARP to 5.0 W/m^2·K, but it gradually decreases beyond this point. As explained in the case of variable temperature setpoint, operating conditions that provide high load flexibility also result in large interior temperature fluctuations, which eventually increases HVAC operation, reducing energy savings.

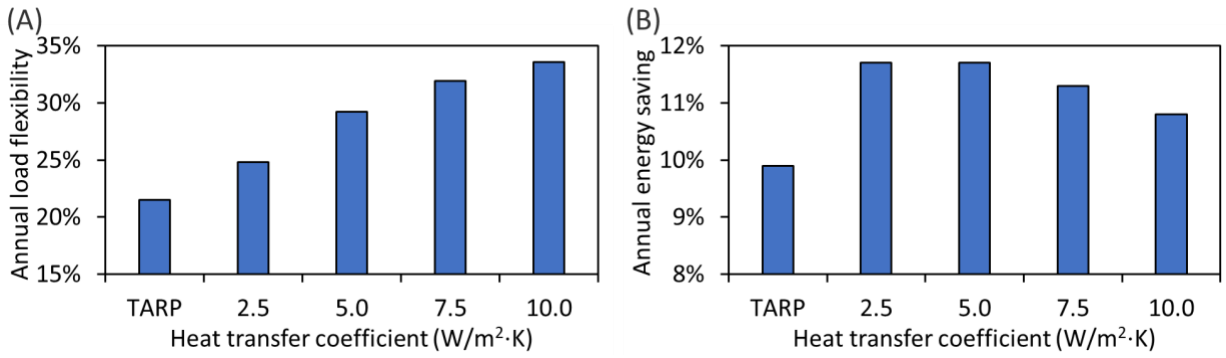

Figure 11. Heat transfer coefficient versus the (A) annual load flexibility and (B) the annual energy savings potential of the PCM-integrated building.

4.7 Comparison to Reference Building with Variable Setpoint Strategy

Discussions in the previous sections suggest that control strategies like variable setpoint temperature and operational parameters such as heat transfer coefficient have a strong effect on load flexibility. In this section, we compare the performance of the PCM-integrated building and the reference building having variable setpoint temperature, $T_{vsp} = 2$°C and an enhanced heat transfer coefficient. All other parameters remain fixed as used in Section 4.6. Figure 12 shows the annual load flexibility and annual energy savings versus different heat transfer coefficient for the PCM-integrated building and the reference building having variable setpoint temperature (VSP). As shown in Figure 12(A), the PCM-integrated building provides 3.9% to 8.5% higher load flexibility than the reference building with the same VSP. This indicates that comparing against load flexibility by the reference building, the PCM-integrated building provides 22%–33% higher load flexibility. Additionally, as shown in Figure 12(B), the reference building results in a negative energy savings, which means there is an energy penalty, whereas the PCM-integrated building provides energy savings of 9%–12% along with load flexibility. The reference building with its low thermal mass is unable to store the thermal energy and eventually contributes toward thermal losses, leading to some energy penalties. The PCM-integrated building, on the other hand, contributes toward TES and results in energy savings along with higher load flexibility.

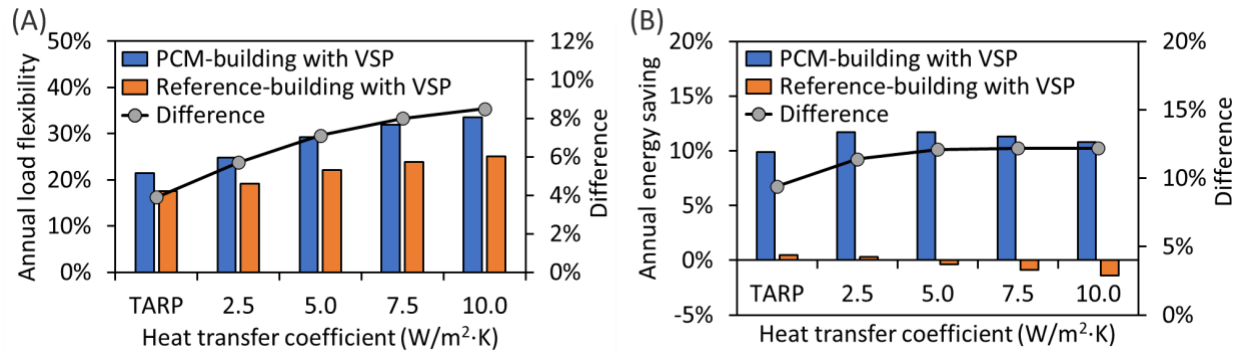

Figure 12. Annual (A) load flexibility and (B) energy savings for a PCM-integrated building and a reference building with the same variable setpoint temperature and heat transfer coefficient.

4.8 Sensitivity Analysis

There are several parameters that collectively affect load flexibility and energy savings potential of the PCM-integrated building. Although it is practically difficult to change all the parameters, a sensitivity analysis is necessary to determine the most crucial parameters that have a significant effect. Table 5 lists all the parameters and shows the factorial change relative to the base value. Note that while the factorial change in the first four parameters (latent heat, PCM thickness, setpoint temperature, and heat transfer coefficient) are quantitative, the factorial change in PCM distribution is taken only for the qualitative assessment.

Table 5. Various parameters and the factorial change used in the sensitivity analysis.

Factorial change	Latent heat (kJ/kg)	PCM thickness (cm)	Variable temperature setpoint (°C)	Heat transfer coefficient ($W/m^2 \cdot K$)	PCM distribution
1	50	0.64	0.5	2.5	EW
2	100	1.27	1.0	5.0	EW + C
3	150	1.91	1.5	7.5	EW + CF
4	200	2.54	2.0	10.0	EW + CF + IW

Figure 13 shows the sensitivity analysis, which shows the resultant change in the annual load flexibility and energy savings versus factorial change in various parameters. As shown in Figure 13(A), variation in setpoint temperature is the strongest parameter affecting load flexibility, followed by heat transfer coefficient, PCM distribution, PCM thickness, and latent heat. Notably, operational parameters like setpoint variation and heat transfer coefficients are more important for load flexibility than PCM parameters like latent heat and thickness. However, as shown in Figure 13(B), PCM parameters like thickness are more important for energy savings. Operational parameters like heat transfer coefficients are still important because its effect becomes negative beyond a certain value.

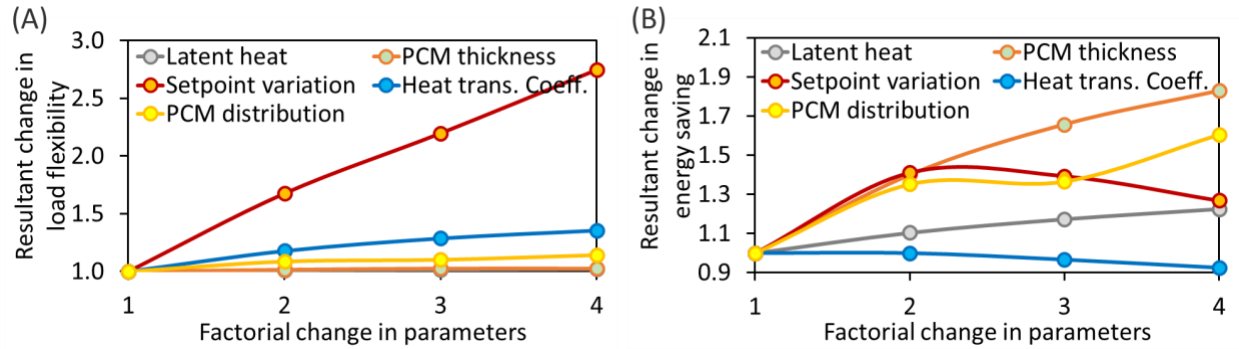

Figure 13. Sensitivity analysis illustrating relative the effect of various parameters on the annual (A) load flexibility and (B) energy savings.

4.9 Comparison with the Published Literature

While there are numerous studies related to PCM-integrated building envelope in the published literature, the current study is unique because it focuses on a future renewable energy scenario. Additionally, most studies in the past primarily focus the energy savings benefits of the PCM-integrated building, whereas this paper aims to collectively maximizes both energy saving as well as load flexibility by optimizing various operational and material parameters. Broadly, it has been observed by many prior researchers that the optimal thermophysical parameters of the PCM in the building envelope varies based on the interior and exterior atmospheric conditions as well as the building type and optimization goal [47]. Therefore, while it is difficult to make the exact comparison between the current and the prior studies, here we briefly review a few key parameters. Arici et al. [58] conducted an optimization study on maximum activation of latent heat for PCMs included at the three different locations in external building walls in Turkey. The study noted that

the annual energy saving is maximum with 2.0 cm thick PCM placed between the insulation and exterior plaster in heating season and between the interior plaster and concrete in the cooling season. Tunçbilek et al. [46], on the other hand, reported that to fully utilize the latent heat storage capacity of PCM, the PCM layer should be located near the interior. Likewise, Kishore et al. [48] reported that PCM located near the interior provides the maximum load flexibility benefits because of the higher interaction between the interior environment and the PCM for controlling its phase change and thus charging and discharging processes. In this study, we noted the optimal thickness of the PCM as 2.54 cm (1-inch) placed behind the drywall of the envelope, which agrees with the findings in the prior studies. Latent heat capacity of PCMs in the building envelope have been reviewed in the detail by Cai et al [77]. Based on the studies by various researchers such as Kuznik et al. [78], Xu et al. [79], and Zhang et al. [74], higher latent heat was reported to provide lower indoor air temperature fluctuations and thus lower HVAC energy use. However, considering the costs, Kosny et al. [80] suggested that the acceptable PCM price should be between 3.50 and 4.00 $/lb for the microencapsulated products with enthalpies between 190 and 220 kJ/kg. The optimal latent heat of 200 kJ/kg noted in this study is thus within the recommended limit. Regarding variable temperature setpoint, Dreau and Heiselberg studied energy flexibility in the residential buildings using active preheating during the time of excess energy, where the optimum variable setpoint value of ± 2 °C was suggested to ensure thermal comfort of the occupants. ASHRAE Standard 55-2010 [76] specifies that the operative temperature should not change by more than 2.2°C during a 1-hour period of operation for ensuring the occupants' thermal comfort. Using variable setpoint temperature of ± 2°C in this study, we noted that the largest temperature change within an hour is about 2.7°C, which is slightly higher than the recommended value.

5 Conclusions

This paper presents an investigation to establish the effect of integrating PCMs in building envelopes on energy saving and demand flexibility under a futuristic energy generation scenario, where 80% of the energy load comes from renewable energy. While it is well-reported that PCMs integrated into envelopes provide multifold benefits, the ability of PCMs in a residential building to continuously respond to the variability of grid electricity and provide load flexibility under a high renewable energy generation scenario has not been investigated in the literature. This study bridges the research gap by investigating a practical way to implement, optimize, and quantify the

TES benefits for PCM-integrated buildings in relation to their energy savings and demand flexibility capacity.

The key findings of the study are summarized below:

- Energy storage capacity of the PCM-integrated envelope increases with an increase in the PCM thickness. However, load flexibility saturates beyond 1.91 cm, and energy savings exhibit diminishing returns with an increase in PCM thickness.
- Energy storage capacity increases with an increase in PCM latent heat. Load flexibility saturates beyond 200 kJ/kg, and energy savings show diminishing returns with an increase in latent heat.
- Load flexibility increases linearly with an increase in variability in the temperature setpoint due to increased utilization of the PCM. However, setpoint variation beyond ±2°C should be avoided to maintain occupants' thermal comfort. Energy savings peak at setpoint variation of 1°C.
- Load flexibility as well as energy savings increase with an increase in PCM distribution in the building envelope, such the exterior and interior walls, ceiling, etc. Adding PCM to the floor, however, does not provide a major benefit due to the small R-value.
- Heat transfer coefficient between inner surfaces and indoor air plays an important role in enhancing interaction between PCM and interior. Load flexibility increases almost linearly with increase in heat transfer coefficient. However, energy savings peak at 5 $W/m^2 \cdot K$.
- A sensitivity analysis shows that operational parameters like setpoint variation are most important for load flexibility, whereas PCM parameters like thickness are crucial for energy savings.

Overall, we noted that the PCM-integrated envelope is quite effective in providing the desired load flexibility. Compared against a reference building containing no TES, the optimized case comprising a 1-in. (2.54 cm) PCM layer having 200 kJ/kg latent heat, included in all living zone envelopes and with increased convection coefficients of 10 $W/m^2 \cdot K$, provides annual load flexibility up to 33.6% and total annual energy savings up to 10.8% for a residential building located in Baltimore, USA. One key limitation of the current study is that it is limited to a single climate. Our future study plans include extending the analysis to other climates and quantifying their respective PCM benefits. Further, we plan to incorporate a more complex load distribution

model from grid to residential buildings in place of the linear model used in the current study. Lastly, this study is limited to a lightweight residential building. A more compressive study needs to be conducted in future that includes different types of residential, commercial, and industrial buildings connected the utility grid.

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References

[1] California-ISO. What the duck curve tells us about managing a green grid. https://www.caiso.com/Documents/FlexibleResourcesHelpRenewables_FastFacts.pdf. 2016.

[2] St. John J. Hawaii's solar-grid landscape and the 'nessie-curve'. https://www.greentechmedia.com/articles/read/hawaiis-solar-grid-landscape-and-the-nessie-curve. Green Tech Media. 2014;10.

[3] Marszal-Pomianowska AJ, Johra H, Knotzer A, Salom J, Péan T, Jensen SØ, et al. Principles of Energy Flexible Buildings: Energy in Buildings and Communities Programme Annex 67 Energy Flexible Buildings. 2020.

[4] Zhu N, Ma Z, Wang S. Dynamic characteristics and energy performance of buildings using phase change materials: a review. Energy Conversion and Management. 2009;50:3169-81.

[5] EIA.gov. How much energy is consumed in U.S. residential and commercial buildings? Accessed on July 06, 2019. https://www.eia.gov/tools/faqs/faq.php?id=86&t=1. .

[6] Speidel S, Bräunl T. Leaving the grid—The effect of combining home energy storage with renewable energy generation. Renewable and Sustainable Energy Reviews. 2016;60:1213-24.

[7] Nair N-KC, Garimella N. Battery energy storage systems: Assessment for small-scale renewable energy integration. Energy and Buildings. 2010;42:2124-30.

[8] Alotto P, Guarnieri M, Moro F. Redox flow batteries for the storage of renewable energy: A review. Renewable and Sustainable Energy Reviews. 2014;29:325-35.

[9] Sharma A, Tyagi VV, Chen CR, Buddhi D. Review on thermal energy storage with phase change materials and applications. Renewable and Sustainable Energy Reviews. 2009;13:318-45.

[10] Rehman S, Al-Hadhrami LM, Alam MM. Pumped hydro energy storage system: A technological review. Renewable and Sustainable Energy Reviews. 2015;44:586-98.

[11] calmac.com. A close look at thermal versus battery energy storage for commercial applications. http://www.calmac.com/energy-storage-articles-a-close-look-at-thermal-versus-battery-energy-storage-for-commercial-applications. Accessed on Jan 21, 2020.

[12] greentechmedia.com. How Does Thermal Energy Storage Reach Scale? https://www.greentechmedia.com/articles/read/how-does-thermal-energy-storage-reach-scale. Accessed on Jan 21, 2020.

[13] Lizana J, Chacartegui R, Barrios-Padura A, Valverde JM. Advances in thermal energy storage materials and their applications towards zero energy buildings: A critical review. Applied Energy. 2017;203:219-39.

[14] Kuznik F, Virgone J, Noel J. Optimization of a phase change material wallboard for building use. Applied Thermal Engineering. 2008;28:1291-8.

[15] Nghana B, Tariku F. Phase change material's (PCM) impacts on the energy performance and thermal comfort of buildings in a mild climate. Building and Environment. 2016;99:221-38.

[16] Biswas K, Abhari R. Low-cost phase change material as an energy storage medium in building envelopes: experimental and numerical analyses. Energy Conversion and Management. 2014;88:1020-31.

[17] Biswas K, Lu J, Soroushian P, Shrestha S. Combined experimental and numerical evaluation of a prototype nano-PCM enhanced wallboard. Applied energy. 2014;131:517-29.

[18] Turner WJN, Walker IS, Roux J. Peak load reductions: Electric load shifting with mechanical pre-cooling of residential buildings with low thermal mass. Energy. 2015;82:1057-67.

[19] Wijesuriya S, Brandt M, Tabares-Velasco PC. Parametric analysis of a residential building with phase change material (PCM)-enhanced drywall, precooling, and variable electric rates in a hot and dry climate. Applied Energy. 2018;222:497-514.

[20] Lamrani B, Johannes K, Kuznik F. Phase change materials integrated into building walls: An updated review. Renewable and Sustainable Energy Reviews. 2021;140:110751.

[21] Kishore RA, Bianchi MVA, Booten C, Vidal J, Jackson R. Optimizing PCM-Integrated Walls for Potential Energy Savings in US Buildings. Energy and Buildings. 2020:110355.

[22] Kishore RA, Bianchi M, Booten C, Vidal J, Jackson R. Modulating Thermal Load Through Lightweight Residential Building Walls Using Thermal Energy Storage and Controlled Precooling Strategy. Applied Thermal Engineering. 2020:115870.

[23] Zhang Y, Zhou G, Lin K, Zhang Q, Di H. Application of latent heat thermal energy storage in buildings: State-of-the-art and outlook. Building and Environment. 2007;42:2197-209.

[24] Heier J, Bales C, Martin V. Combining thermal energy storage with buildings–a review. Renewable and Sustainable Energy Reviews. 2015;42:1305-25.

[25] Akeiber H, Nejat P, Majid MZA, Wahid MA, Jomehzadeh F, Famileh IZ, et al. A review on phase change material (PCM) for sustainable passive cooling in building envelopes. Renewable and Sustainable Energy Reviews. 2016;60:1470-97.

[26] Liu Z, Yu ZJ, Yang T, Qin D, Li S, Zhang G, et al. A review on macro-encapsulated phase change material for building envelope applications. Building and Environment. 2018;144:281-94.

[27] Naji S, Çelik OC, Alengaram UJ, Jumaat MZ, Shamshirband S. Structure, energy and cost efficiency evaluation of three different lightweight construction systems used in low-rise residential buildings. Energy and buildings. 2014;84:727-39.

[28] Kosny J, Petrie T, Gawin D, Childs P, Desjarlais A, Christian J. Thermal mass-energy savings potential in residential buildings. Buildings Technology Center, ORNL. 2001.

[29] Zhou D, Zhao C-Y, Tian Y. Review on thermal energy storage with phase change materials (PCMs) in building applications. Applied Energy. 2012;92:593-605.

[30] Tyagi VV, Kaushik SC, Tyagi SK, Akiyama T. Development of phase change materials based microencapsulated technology for buildings: a review. Renewable and Sustainable Energy Reviews. 2011;15:1373-91.

[31] Evers AC, Medina MA, Fang Y. Evaluation of the thermal performance of frame walls enhanced with paraffin and hydrated salt phase change materials using a dynamic wall simulator. Building and Environment. 2010;45:1762-8.

[32] Kosny J, Kossecka E, Brzezinski A, Tleoubaev A, Yarbrough D. Dynamic thermal performance analysis of fiber insulations containing bio-based phase change materials (PCMs). Energy and Buildings. 2012;52:122-31.

[33] Stovall TK, Tomlinson JJ. What are the potential benefits of including latent storage in common wallboard? 1995.

[34] Neeper DA. Thermal dynamics of wallboard with latent heat storage. Solar energy. 2000;68:393-403.

[35] Li ZX, Al-Rashed AAAA, Rostamzadeh M, Kalbasi R, Shahsavar A, Afrand M. Heat transfer reduction in buildings by embedding phase change material in multi-layer walls: Effects of repositioning, thermophysical properties and thickness of PCM. Energy Conversion and Management. 2019;195:43-56.

[36] Sharma V, Rai AC. Performance assessment of residential building envelopes enhanced with phase change materials. Energy and Buildings. 2020;208:109664.

[37] Saffari M, De Gracia A, Fernández C, Cabeza LF. Simulation-based optimization of PCM melting temperature to improve the energy performance in buildings. Applied Energy. 2017;202:420-34.

[38] Jin X, Medina MA, Zhang X. On the importance of the location of PCMs in building walls for enhanced thermal performance. Applied energy. 2013;106:72-8.

[39] Jin X, Medina MA, Zhang X. Numerical analysis for the optimal location of a thin PCM layer in frame walls. Applied Thermal Engineering. 2016;103:1057-63.

[40] Jin X, Shi D, Medina MA, Shi X, Zhou X, Zhang X. Optimal location of PCM layer in building walls under Nanjing (China) weather conditions. Journal of Thermal Analysis and Calorimetry. 2017;129:1767-78.

[41] Jin X, Zhang S, Xu X, Zhang X. Effects of PCM state on its phase change performance and the thermal performance of building walls. Building and Environment. 2014;81:334-9.

[42] Fateh A, Klinker F, Brütting M, Weinläder H, Devia F. Numerical and experimental investigation of an insulation layer with phase change materials (PCMs). Energy and Buildings. 2017;153:231-40.

[43] Fateh A, Borelli D, Devia F, Weinläder H. Summer thermal performances of PCM-integrated insulation layers for light-weight building walls: Effect of orientation and melting point temperature. Thermal Science and Engineering Progress. 2018;6:361-9.

[44] Lee KO, Medina MA, Raith E, Sun X. Assessing the integration of a thin phase change material (PCM) layer in a residential building wall for heat transfer reduction and management. Applied Energy. 2015;137:699-706.

[45] Kośny J, Fallahi A, Shukla N, Kossecka E, Ahbari R. Thermal load mitigation and passive cooling in residential attics containing PCM-enhanced insulations. Solar Energy. 2014;108:164-77.

[46] Tunçbilek E, Arıcı M, Krajčík M, Nižetić S, Karabay H. Thermal performance based optimization of an office wall containing PCM under intermittent cooling operation. Applied Thermal Engineering. 2020;179:115750.

[47] Al-Absi ZA, Mohd Isa MH, Ismail M. Phase change materials (PCMs) and their optimum position in building walls. Sustainability. 2020;12:1294.

[48] Kishore RA, Bianchi M, Booten C, Vidal J, Jackson R. Parametric and Sensitivity Analysis of a PCM-Integrated Wall for Optimal Thermal Load Modulation in Lightweight Buildings (Submitted). Applied Thermal Engineering. 2020.

[49] Mehling H, Cabeza LF. Heat and cold storage with PCM: Springer; 2008.

[50] Kosny J, Yarbrough DW, Riazzi T, Leuthold D, Smith JB, Bianchi M. Development and testing of ignition resistant microencapsulated phase change material. p. 14-7.

[51] Kośny J. Short history of PCM applications in building envelopes. PCM-Enhanced Building Components: Springer; 2015. p. 21-59.

[52] Rathore PKS, Shukla SK. Potential of macroencapsulated PCM for thermal energy storage in buildings: A comprehensive review. Construction and Building Materials. 2019;225:723-44.

[53] Wilson EJ. ResStock-Targeting Energy and Cost Savings for US Homes. National Renewable Energy Lab.(NREL), Golden, CO (United States); 2017.

[54] Crawley DB, Lawrie LK, Winkelmann FC, Buhl WF, Huang YJ, Pedersen CO, et al. EnergyPlus: creating a new-generation building energy simulation program. Energy and Buildings. 2001;33:319-31.

[55] Maclaurin G, Lopez A, Grue N, Buster G, Rossol M, Spencer R. Open Source reV (The Renewable Energy Potential Model). National Renewable Energy Lab.(NREL), Golden, CO (United States); 2020.

[56] Kroposki B, Johnson B, Zhang Y, Gevorgian V, Denholm P, Hodge B-M, et al. Achieving a 100% renewable grid: Operating electric power systems with extremely high levels of variable renewable energy. IEEE Power and Energy Magazine. 2017;15:61-73.

[57] Tunçbilek E, Arıcı M, Bouadila S, Wonorahardjo S. Seasonal and annual performance analysis of PCM-integrated building brick under the climatic conditions of Marmara region. Journal of Thermal Analysis and Calorimetry. 2020;141:613-24.

[58] Arıcı M, Bilgin F, Nižetić S, Karabay H. PCM integrated to external building walls: An optimization study on maximum activation of latent heat. Applied Thermal Engineering. 2020;165:114560.

[59] Mazzeo D, Oliveti G, Arcuri N. Definition of a new set of parameters for the dynamic thermal characterization of PCM layers in the presence of one or more liquid-solid interfaces. Energy and Buildings. 2017;141:379-96.

[60] Wilson EJ, Christensen CB, Horowitz SG, Robertson JJ, Maguire JB. Energy Efficiency Potential in the US Single-Family Housing Stock. National Renewable Energy Lab.(NREL), Golden, CO (United States); 2017.

[61] energyplus.net/. Weather Data. https://energyplusnet/weather-location/north_and_central_america_wmo_region_4/USA/MD/USA_MD_Baltimore-WashingtonIntlAP724060_TMY3.

[62] EnergyPlus. https://energyplus.net/.

[63] Tabares-Velasco PC, Griffith B. Diagnostic test cases for verifying surface heat transfer algorithms and boundary conditions in building energy simulation programs. Journal of Building Performance Simulation. 2012;5:329-46.

[64] Wijesuriya S, Tabares-Velasco PC, Biswas K, Heim D. Empirical validation and comparison of PCM modeling algorithms commonly used in building energy and hygrothermal software. Building and Environment. 2020;173:106750.

[65] Al-Janabi A, Kavgic M. Application and sensitivity analysis of the phase change material hysteresis method in EnergyPlus: A case study. Applied Thermal Engineering. 2019;162:114222.

[66] Ismail K, Castro J. PCM thermal insulation in buildings. International Journal of Energy Research. 1997;21:1281-96.

[67] Wijesuriya S, Tabares-Velasco PC. Experimental apparatus and methodology to test and quantify thermal performance of micro and macro-encapsulated phase change materials in building envelope applications. Journal of Energy Storage. 2020;32:101770.

[68] Tyagi VV, Buddhi D. PCM thermal storage in buildings: A state of art. Renewable and sustainable energy reviews. 2007;11:1146-66.

[69] pluss.co.in. TECHNICAL DATA SHEET OF savE® OM21: https://www.pluss.co.in/upload/technical-datasheets/2019/Doc%20443%20TDS_OM21.pdf. Accessed on June 15, 2021.

[70] ASHRAE. 2005 ASHRAE Handbook : Fundamentals. 2005.

[71] Bigladdersoftware.com. Coils: Engineering Reference—EnergyPlus 8.2. 2015.

[72] Walton GN. Thermal analysis research program reference manual. National Bureau of Standards, March. 1983.

[73] energyplus.net/. U.S. Department of Energy EnergyPlus engineering reference: the reference to EnergyPlus calculations. 2009.

[74] Zhang YP, Lin KP, Yang R, Di HF, Jiang Y. Preparation, thermal performance and application of shape-stabilized PCM in energy efficient buildings. Energy and Buildings. 2006;38:1262-9.

[75] Osterman E, Tyagi VV, Butala V, Rahim NA, Stritih U. Review of PCM based cooling technologies for buildings. Energy and Buildings. 2012;49:37-49.

[76] ASHRAE-Standard. Standard 55-2010, Thermal environmental conditions for human occupancy. American Society of Heating, Refrigerating and Air Conditioning Engineers. 2010.

[77] Cai R, Sun Z, Yu H, Meng E, Wang J, Dai M. Review on optimization of phase change parameters in phase change material building envelopes. Journal of Building Engineering. 2021;35:101979.

[78] Kuznik F, Lopez JPA, Baillis D, Johannes K. Phase change material wall optimization for heating using metamodeling. Energy and Buildings. 2015;106:216-24.

[79] Xu X, Zhang Y, Lin K, Di H, Yang R. Modeling and simulation on the thermal performance of shape-stabilized phase change material floor used in passive solar buildings. Energy and Buildings. 2005;37:1084-91.

[80] Kosny J, Shukla N, Fallahi A. Cost analysis of simple phase change material-enhanced building envelopes in southern US climates. National Renewable Energy Lab.(NREL), Golden, CO (United States); 2013.