Application of Phase Change Materials for Building Energy Retrofits in a Hot Arid Climate

by

Neda Askari Tari

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Graduate Supervisory Committee:

Kristen Parrish, Chair
Harvey Bryan
T. Agami Reddy

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ABSTRACT

In 2018, building energy use accounted for over 40% of total primary energy consumption in the United States; moreover, buildings account for ~40% of national CO2 emissions. One method for curbing energy use in buildings is to apply Demand Side Management (DSM) strategies, which focus on reducing the energy demand through various technological and operational approaches in different building sectors.

This PhD research examines the integration of DSM strategies in existing residential and commercial buildings in the Phoenix, Arizona metropolitan area, a hot-arid climate. The author proposes three different case studies to evaluate the effectiveness of one DSM strategy in buildings, namely the integration of Phase Change Materials (PCMs). PCMs store energy in the freezing process and use that stored energy in the melting process to reduce the energy demand. The goal of these case studies is to analyze the potential of each strategy to reduce peak load and overall energy consumption in existing buildings.

First, this dissertation discusses the efficacy of coupling PCMs with precooling strategies in residential buildings to reduce peak demand. The author took a case study approach and simulated two precooling strategies, with and without PCM integration, in two sample single-family homes to assess the impact of the DSM strategies (i.e., precooling and PCM integration) on load shifting and load shedding in each home.

Second, this research addresses the feasibility of using PCMs as sensible and latent heat storage in commercial buildings. The author documents the process of choosing buildings for PCM installation, as well as the selection of PCMs for retrofitting purposes. Commercial building case studies compare experimental and simulation results, focusing on the impact of the PCMs on reducing the total annual energy demand and energy cost.

Finally, this research proposes a novel process for selecting PCMs as energy efficiency measures for building retrofits. This process facilitates the selection of a building and PCM that are complementary. Implementation of this process has not yet been tested; however, the process was developed based on experimental and simulation results from prior studies, and it would alleviate many of the PCM performance issues documented in those studies.

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CHAPTER 1

INTRODUCTION

Rising fossil fuel prices, energy security, and climate change have led to rapid growth in renewable energy markets and increased the share of renewable energy sources present in the global energy mix. Renewable Energy Sources (RES) are capable of meeting a significant proportion of the energy demand in many countries while reducing greenhouse gas emissions. However, due to their dependency on weather, they are intermittent and therefore, less reliable than non-intermittent energy resources like coal and natural gas. To maximize the utilization of RES as an energy source, users may need to integrate high capacity energy storage and Demand Side-Management (DSM) strategies in buildings; this simultaneously address energy supply and demand (Jan Kays 2016).

Buildings are responsible for consuming 40 % of the world's total energy consumption, 35 % of the world's CO2 emissions, 30 % of the raw material consumption, 50 % of ozone depleting and 40 % of municipal solid waste (Jorgensen 2013). Therefore, using energy efficient devices and integrating new technology solutions in buildings that reduce their energy demand reduces buildings' impact on the environment.

Demand Side Management

DSM is designed to control and manage energy consumption, including the management of seasonal peak load, in order to reduce overall energy demand (Strbac 2008). In other words, DSM provides measures to improve the energy system at the side of consumption; such measures can be varied depending on the timing and the effect on the consumer side (Palensky and Dietrich 2011). According to (Palensky and Dietrich 2011) DSM strategies can be categorized into four groups:

- Energy Efficiency (EE)
- Load-control Program
- Demand Response (DR)
- Spinning and Non-Spinning Reserve (SR)

Demand response, and by extension, peak load shifting through thermal energy storage, are of particular interest for this research.

Demand Response

Research documents demand response strategies that can be applied to commercial and residential buildings (e.g., (Watson, Kiliccote et al. 2006, Batchu and Pindoriya 2015). These strategies are defined as a short-term adjustment of consumers' electricity consumption based on the prices and reliability information, such as overall resource capacity that is available at different times or the impact of the DR strategies on the electricity load before and after the event.

Demand response can be manual, semi-automated, and automated. Automated demand response is capable of controlling the demand and changing the electric load through smart appliances, BMS, and Energy Management and Control Systems (EMCS) (Watson, Kiliccote et al. 2006).

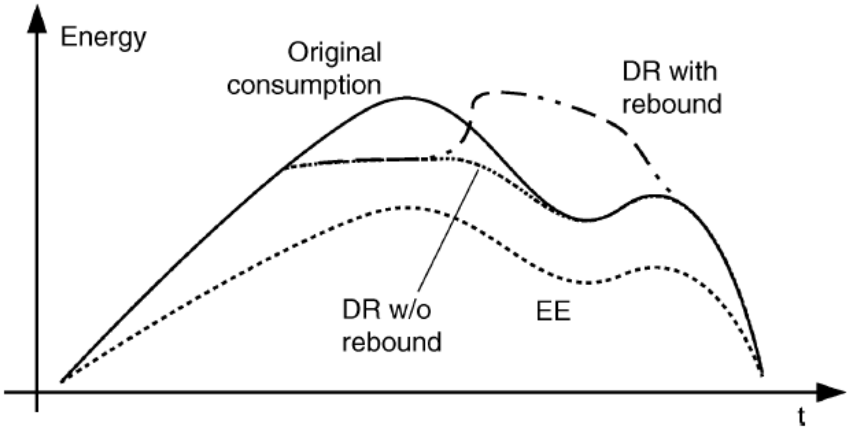


Figure 1. Comparison between Energy Efficiency and Demand Response strategies (Palensky and Dietrich 2011)

Figure 1 shows the difference between energy efficiency strategies and demand response strategies. As shown, less energy is consumed after EE improvements are made (e.g., improving insulation, increasing the EER of the HVAC system, LED lighting, etc.); this results in persistent energy and cost savings. However, through demand response strategies, consumers try to use less energy in the peak hours (shown as “DR w/o rebound” in Figure 1) or they will use more energy in the off-peak hours (“DR with rebound” in Figure 1) (Palensky and Dietrich 2011).

Energy Storage

Applying Energy Storage Systems (ESSs) is one DSM strategy to promote balance between demand and supply. This strategy can be very effective in retrofitting existing buildings (Tronchin, Manfren et al. 2018).

Consumption of energy especially electrical energy varies with time of the day and season, therefore controlling the energy consumption especially in the buildings sector can be done by peak shifting behavior (e.g. time-dependent tariffs or precooling) or by technology (e.g. Thermal Energy Storage (TES)). Further, load diversity causes some changes in the shape of the system load. Often, the load reduction period will be followed by load recovery, on the shape of that depends on different forms of energy storage such as thermal, chemical, electrical, and mechanical energy. For DR to be effective, utilities must plan for and manage both load reduction and load recovery (Strbac 2008).

Motivation

The motivation for this dissertation research project is derived from the challenge utilities have been facing in recent years due to high energy generation and low energy demand at certain hours of the day, coupled with the reverse situation later in a day. Integrating RES into the grids increased the energy generation during off peak hours, which results in instability in the grid. In the United States, utilities have tried to manage this mismatch between supply and demand by applying DSM strategies. Utilities are offering electricity pricing paradigms to match flexible, diverse and low- carbon supply with controllable demand with real-time sensing and software (Roberts 2018).

The main purpose of this PhD project is to determine the operational strategies and technologies used to reduce the energy demand and increase the cost savings in existing residential and commercial buildings located in hot arid climates, such as the Phoenix metropolitan area in Arizona. These strategies aim for load shedding, load shifting and finally, load flattening to reduce the electricity bill for the consumers and to minimize the voltage and frequency fluctuation in the grid at multiple time scales. The demand response strategies in the case studies are focused on coupling HVAC control strategies with thermal energy storage systems to shift load off of peak. In particular, this research explores the use of Phase Change Materials (PCMs) for TES. Precooling does not cost anything to implement, and, if effectively coupled with a PCM, it can offer significant energy and cost savings to consumers.

Research Questions

The goal of this dissertation is to study and analyze the integration of PCMs into existing buildings as a DSM strategy that can affect load shifting and load shedding. This research has focused on understanding the process of choosing PCMs and the factors that determine the efficacy of these materials as part of an energy retrofit strategy for existing buildings. This research couples experimental and simulation analyses to provide insights into the efficacy of PCMs as energy retrofit measures. The author uses case studies to identify parameters that determine PCM efficacy. This work can help researchers, engineers, and designers to better understand how PCMs can be used as TES for building energy retrofits. To achieve this goal, this research addresses the following questions:

RQ1: Does the addition of PCMs in single-family homes change the time of day when the home's peak demand (measured in kW) occurs?

RQ2: Does the addition of PCMs in commercial buildings change the time of day when the building's peak demand (measured in kW) occurs?

RQ3: Does plenum type influence the effectiveness of a PCM for TES in commercial buildings in hot arid climates?

RQ4: What factors should be considered when selecting a building for PCM retrofit?

RQ5: What factors should be considered in selecting PCMs?

Organization of this dissertation

The dissertation is organized into chapters, each of which focuses on one or two research questions. Chapter 2 addresses RQ1 and focuses on assessing the efficacy of phase change material with pre-cooling strategies in residential buildings to flatten the duck curve and reduce peak energy demand. Chapter 3 examines the impact of using PCMs in an office building on load shifting, aligning with RQ2. Chapter 4 addresses both RQ2 and RQ3 using case study data and results from PCM integration in two commercial buildings, one with return air ducts in the plenum and another without. After studying the results of all Chapters 2, 3, and 4, the author developed a process for selecting buildings that may be good candidates for PCM integration, and then selecting a PCM for energy retrofits of those buildings; Chapter 5 presents this process and addresses RQ4 and RQ5.

Finally, Chapter 6 presents the findings from implementing PCMs into existing buildings in a hot arid climate and makes recommendations for PCM integration as well as for future research.

CHAPTER 2

EFFICACY OF COUPLING PHASE CHANGE MATERIALS WITH PRECOOLING TO REDUCE RESIDENTIAL PEAK DEMAND

Abstract

The rapid growth of Renewable Energy Systems (RES), especially solar energy systems, results in rapid changes in the load on the grid. The electricity generated from renewable sources occurs at irregular intervals throughout the day and year, making them less reliable sources of power than, for example, a coal-fired power plant. Reverse Demand Response (RDR), like demand response, tries to balance electricity generation with demand. In RDR, consumers increase their consumption in off-peak hours, when generation is peaking, such that they can reduce their demand during on-peak hours, thus helping to "level" the demand. This chapter analyzes one particular (reverse) demand response strategy, precooling, that can be used in single family dwellings in Phoenix, Arizona, a hot-dry climate. Due to higher energy demand in the late afternoon in the summer, the power grid faces a challenge to reliably deliver power, due in part to large fluctuations of demand and supply in the grid. This chapter presents results from a case study where residential customers in the Phoenix area were asked to increase their demand during off-peak hours and store that energy in their home's thermal mass, effectively precooling their homes. That stored energy is then available to be used during the on-peak hours to meet the customer's energy demand. Two different precooling strategies, developed heuristically, were applied to wood frame and block single-family homes, which

represent 55% and 24% of the single-family housing stock in the area, respectively. This chapter compares experimental electricity consumption data from two homes to energy consumption predicted by an EnergyPlus model. Furthermore, this chapter presents simulation results from integration of Phase Chance Material (PCM) into residential buildings and compares the performance of PCMs with different precooling strategies in both wood frame and block residential buildings in a hot arid climate. Finally, this chapter concludes with a discussion of the benefits of increased off-peak energy consumption for utilities seeking load predictability and reliability.

Introduction

The never-ending and ever-increasing demand for energy, alongside concerns about greenhouse gas emissions contributing to global warming, has resulted in greater use of Renewable Energy Systems (RES) to provide power in a cleaner way. Despite the large reduction in CO2 emissions associated with RES, the rapid growth of using RES, particularly solar energy, poses challenges to grid stability, energy capacity and load on the grid in mid-day.

The electricity generated from renewable sources occurs at irregular intervals throughout the day and year. This can cause problems for utilities seeking to reliably provide power to their customers, as it is difficult to reliably predict the amount of power RES will generate on a given day. While the energy produced from RES may vary, in aggregate, the electricity produced from RES creates a so-called “duck curve,” where there is excess power during off-peak hours, but potentially less energy than is required during peak hours (Figure 2) (Denholm, O'Connell et al. 2015, Burnett 2016).

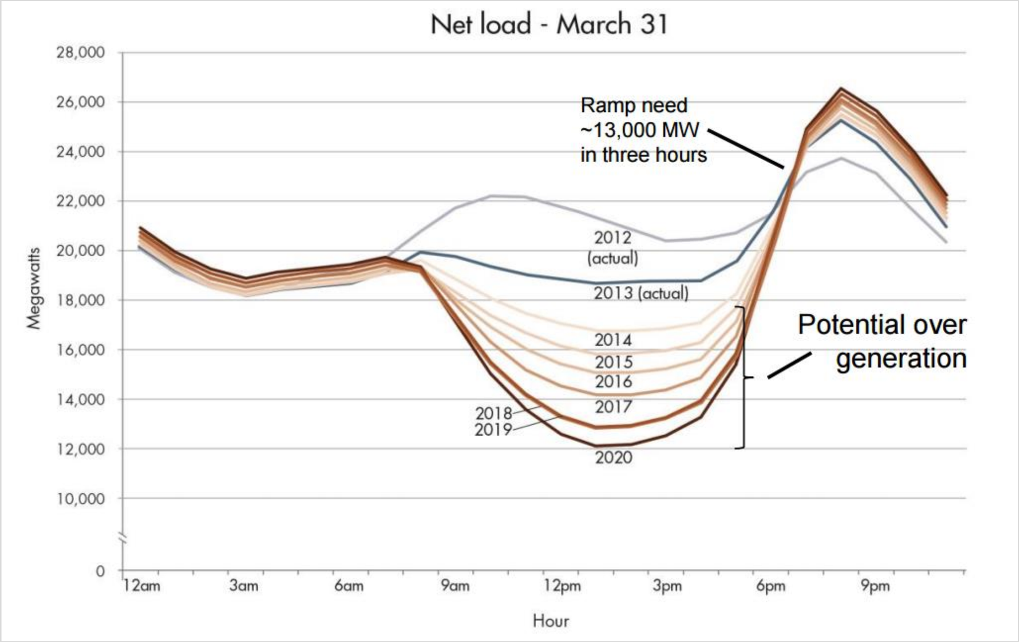


Figure 2. Duck Curve from the California Independent System Operator (Burnett 2016)

RDR combines energy storage and load management. Consumers are essentially incentivized for consuming energy when the grid has energy to spare. While this shows promise for improving some issues with the duck curve, reverse demand response is most impactful when it supports energy storage, rather than simply on-demand energy consumption. This way, utilities are able to make full use of their renewable energy resources when they are producing and avoid needing to operate costly "peaker plants" when renewable generation drops off (Poudineh and Jamasb 2014).

In 2018, buildings accounted for more than 40% of the total primary energy consumption in the United States, which residential buildings account for approximately

21% of the total consumption (Administration 2018). Moreover, residential sector CO2 emission increased by 7.4% in comparison to 2017, due to the colder winter and warmer summer in 2018 (EIA 2018). Therefore, integrating energy storage technologies, i.e., PCMs, in residential buildings can result in a reduction of CO2 emission and assist utilities in leveling demand and mitigating the challenges associated with intermittent supply.

A building’s thermal mass can serve as Sensible Heat Storage (SHS); indeed, a building’s thermal mass affects the total energy consumption of a building and thermal mass also offers potential for load shifting and peak demand reduction (R. Yin 2010). A building’s thermal mass can be used as an energy storage system, particularly when different HVAC control strategies are implemented in the building. Precooling strategies can be used to reduce the peak energy consumption, however studies showed that they often increase the annual cooling energy demand. In a precooling strategy, the building is cooled during off peak hours and energy is stored in the building’s thermal mass; the stored energy is released during the peak hours (Group 2007, William J.N. Turner 2014, W.J.N. Turner 2015).

This chapter begins with a comprehensive literature review of precooling and PCM implementation in residential buildings. It then presents and analyzes two RDR precooling strategies that were developed heuristically and implemented in two sample homes, representing wood frame and block construction, respectively. The authors simulate precooling strategies in these sample buildings to assess their impact on load shifting and customer costs. In the two single-family residential buildings considered, the authors conduct experimental studies to measure the actual impacts of RDR as well, supporting the validation of simulations. Finally, the chapter evaluates the effect of integrating PCMs into the ceiling and exterior walls of the homes via energy simulation, and how PCMs, in conjunction with precooling, impact a home's thermal storage and peak demand.

Literature Review

The research aims to examine the effect of precooling single-family homes with and without PCM integration in a hot arid climate (i.e., Phoenix, AZ) in the summer. These parameters guided the literature review presented herein.

In one study, two precooling strategies were applied to a concrete office building in California that normally operated with a constant set point temperature of 72°F. In the first precooling strategy, temperature dropped to 70°F from 5am to 2pm (i.e., 9 hours prior to the peak) and raised to 78°F from 2pm to 5pm (the peak hours). In the second strategy, the precooling duration was extended and the temperature was set to 68°F from 12am to 5am, raised to 70°F from 5am to 2 pm and then raised to 78°F after 2pm. Applying both precooling strategies in the office building allowed 80-100% of the electric load to shift from on-peak to off-peak hours (Peng Xu 2004).

Yin, Xu et al. conducted a series of tests and developed simulation models for 11 commercial buildings in California to compare different pre-cooling strategies and their effect on reducing peak demand. They found leveraging exponential or step methods for temperature setpoint control reduced the electrical demand during peak hours by 15%-30%. Yin et al. (Rongxin Yin 2010) developed simulation model with DRQAT (a building energy simulation tool), to study the effect of the precooling strategies in the commercial buildings in California. The results indicate that precooling strategies were able to reduce the peak demand and in all test buildings, the electrical demand during the peak period was reduced by 15-30% on automated demand response days.

Different studies have shown that applying different precooling strategies can reduce peak demand in commercial buildings; however, the studies of the effect of precooling in residential buildings are limited. Furthermore, using the building’s thermal mass can impact the heating and cooling load, but to effectively to so requires detailed information about the HVAC control system for the building, weather, occupancy forecast, and information of the thermal comfort of the inhabitant (Kim 2013).

Turner et al. (W.J.N. Turner 2015) studied two different precooling strategies, using temperatures of 72°F and 74°F for precooling (77°F was the “base temperature”). They simulated different residential buildings with low thermal mass in 12 climate zones in the United States with three precooling windows for each precooling temperature (i.e., 72°F and 74°F); 3h (13:00-16:00), 5h (11:00-16:00), and 8h (08:00-16:00). Prior to precooling, all residential buildings operated at 77°F from 4pm to 7am and 80°F from 7am to 4pm. Their results illustrate that at least 50% of the on-peak electricity consumption in a home can be shifted to off peak hours. However, comparing the effect of precooling strategies in different climate zones showed that the ratio of off-peak cooling load increase to on-peak cooling load decrease in Phoenix (climate zone 2B) is lower than that same ratio in other climate zones.

Katipamula and Lu (2006) studied four control strategies that can be implemented for HVAC system in single family homes. These strategies compared the average demand reduction during the peak hours (from 3-7 pm) and prioritized the comfort level of the occupants and energy costs for three population sizes, consisting of 10, 100, and 1000 homes, respectively. They compare four scenarios: (1) a constant temperature setpoint of 75°F, (2) total curtailment during peak price periods, (3) temperature reset control (an increase from 75°F to 80°F during the peak price period, (4) 10°F precooling (decrease from 75°F to 65°F) for a few hours before the peak price period and allow the temperature to rise to 80°F during the peak hours (temperature setpoint is 75°F at all other times). The authors also tested a modified precooling strategy where they gradually step the temperature down over several hours rather than doing a 10°F drop at the start of the precooling period.

Results from Katipamula and Lu (2006) showed that curtailment control has the most impact on average demand reduction during the peak hours and the average demand relief of curtailment control is 20%- 25% higher than the modified precooling control for most cases. However, in this strategy, the indoor temperature quickly becomes uncomfortable for occupants. The modified precooling strategy can have a significant impact on the average demand reduction, although it can cause energy and cost penalties compared to total curtailment. The temperature reset strategy reduced the average demand, but the average daily cost ($/day) of this strategy is higher than precooling and curtailment. Comparing all strategies suggests that modified precooling may be a suitable strategy if demand needs to be reduced for several hours.

Sun, Wang et al. (Yongjun Sun 2012) compare the impact of precooling strategies in buildings without active thermal storage capacity (i.e., a passive building) to those with active thermal energy storage (TES), in this case, Phase Change Materials (PCMs). Using PCM as TES in buildings increases their heat capacity; thus, buildings are able to store energy during high energy generation and use that stored energy during peak loads. Sun, Wang et al. (2012) compared three different cases; the first case is pre-cooling in a passive building without implementing a Proportional–Integral–Derivative (PID) peak demand limiting algorithm for HVAC setpoint control, the second is pre-cooling in a passive building **with** implementation of PID for HVAC setpoint control, and the last case is pre-cooling in a building that includes PCM (melting point temperature 73.4 °F and attached to the inside wall) and implements PID for HVAC setpoint control. Results show that coupling PID control and PCM support up to 38% reduction in peak demand, compared to a 19% reduction in the passive building implementing PID control.

Abuzaid and Reichard (Abdullah I. Abuzaid 2016) studied the effect of PCMs on the electricity consumption and thermal performance of residential buildings in the United States using simulation tools. In their study, they document that PCMs may result in increasing the electricity consumption for the charging period, depending on the building design and operating context. According to their study, in hot dry regions, such as Phoenix, Arizona, using PCMs is an appropriate solution for reducing the daytime heat gain and improving the thermal comfort for the building occupants. Due to the energy required for charging, they conclude it may be beneficial to charge the PCM in the off-peak hours (when electricity costs are relatively low) and use the stored energy in the peak hours for cooling; this finding aligns with other research. Finally, their study documents the effectiveness of off-peak PCM charging for load shifting or load shedding.

Berardi and Soudian (Umberto Berardi 2018) studied a hybrid PCM system consisting of two types of Bio-PCM, one with a 23°C melting point and the other with a 25°C melting point. The 2cm thick hybrid PCM was integrated on the walls and ceiling of the high-rise apartments to study the PCM performance for both heating and cooling purposes in two cities, Toronto and Vancouver, in Canada. In both cities, the buildings considered were high-rise apartments constructed of reinforced concrete using flat slabs with steel studs and gypsum board for the interior walls. In Vancouver, the PCM composite system had a significant effect on average cooling energy; reducing it by up to 50% in the summer season. Furthermore, in their study they illustrated that in both cities, the Bio-PCM with melting point of 23°C is more efficient in reducing cooling energy, as the desired indoor temperature is closer to 23°C in summer seasons. In Toronto, the highest energy savings were in the shoulder seasons (i.e., fall and spring) for heating.

Methodology

The overarching aim of this chapter is to analyze the impact of PCMs on TES in single-family homes. This study comprises experimental work on precooling as well as simulation modeling for precooling and PCM installation to develop calibrated energy models for each home. Experiments were conducted in two single-family homes, representing about 70% of the residential stock in the Phoenix metropolitan area, in July 2019. Figure 3 describes the analysis approach for experimental and simulation analysis.

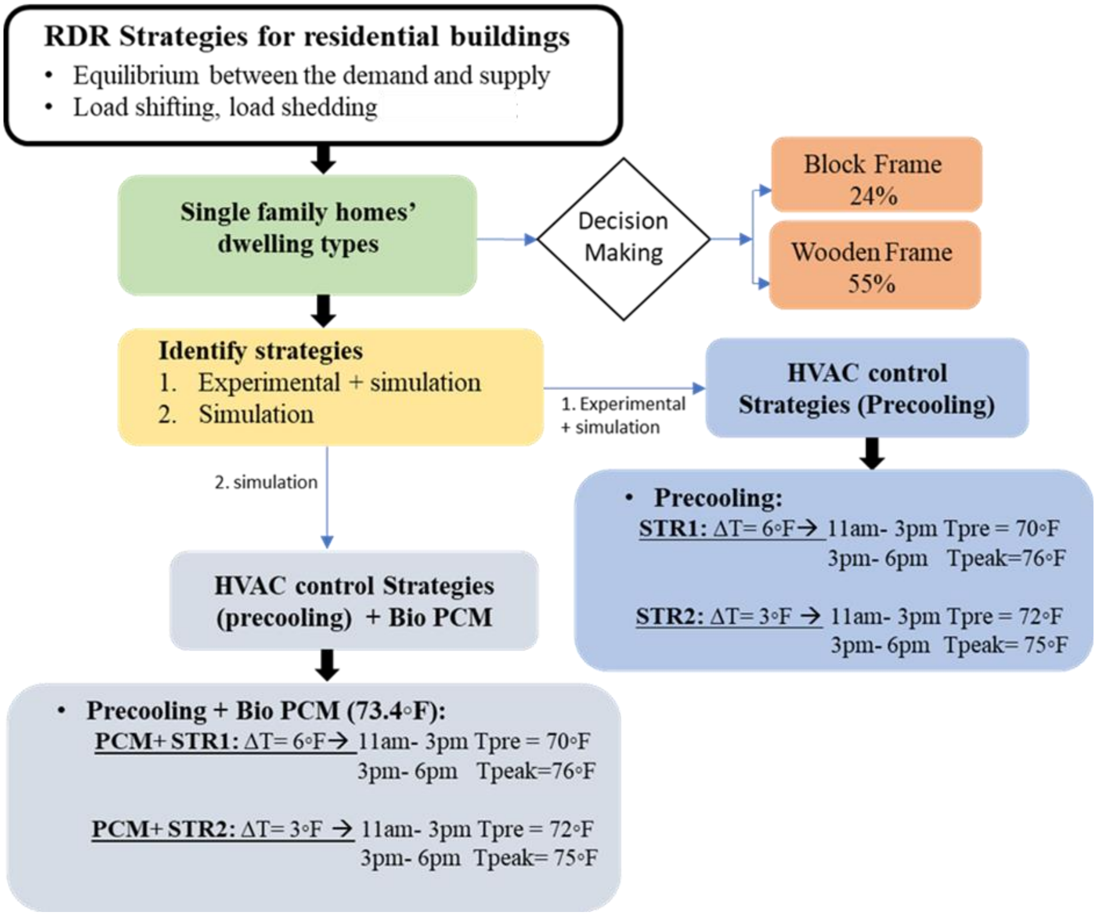


Figure 3. Analysis Approach in this Case Study

Energy modeling

Based on the dwelling type information from the utility provider (SRP), 55% of the single-family homes in their territory are wood frame and 24% are made of concrete block ("block"). As such, the authors selected one wood-frame single family home and one block single family home for the experimental work. The authors developed energy models of both homes using Google SketchUp for energy modeling and EnergyPlus and

OpenStudio software for energy simulation analysis. The methodology used in this study is described as follows and is shown in Figure 4:

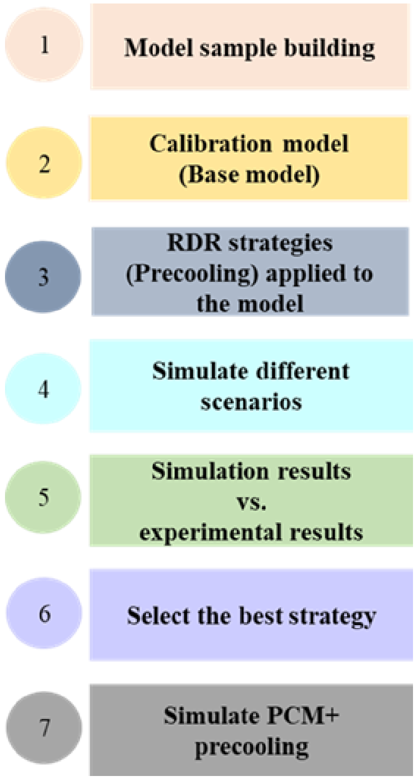


Figure 4. Energy Modeling in this Study- Residential Buildings

1. In order to simulate the precooling strategies, the thermodynamics model for each of the selected homes were created using the geometry and HVAC setpoint temperature provided by the homeowners.
2. Both models were calibrated using the hourly electricity consumption (kWh) for two weeks prior to the precooling experiment. The thermal comfort, thermostat setpoint and occupancy schedule in both homes were completely different.

Moreover, due to the homes using different setpoint temperatures in May, June, and July, the authors calibrated both models for the first two week in July 2019, immediately prior to the experimental period. Therefore, the base model is based on the setpoint temperature schedule of each of home during the period of July 1st through July 15th.

3. The first precooling strategy was applied in both homes in the third week of July (17th -23rd) and the second strategy was tested in the last week of July (24th - 30th). In order to maintain thermal comfort while also supporting energy storage, the authors limit the precooling to 6°F, and analyze precooling strategies that leverage temperature setpoints 3°F and 6°F below the typical household temperature for four hours prior to the peak hours – in this case, the precooling period is from 11am – 3pm, while the peak period is from 3pm – 6pm. Table 1 presents the precooling strategies implemented. Based on the setpoint temperature (base temperature) in each home, two options were considered for the first precooling strategy (ΔT: 6◦F). If the base temperature in a home was lower than 76◦F, the precooling temperature should not be lower than 70◦F from 11 am until 3 pm, and the temperature could increase up to 76◦F in the peak hour (option I). If the base temperature is higher than 76◦F, the precooling temperature should be 6◦F lower than the base temperature from 11 am until 3 pm and it will be back to the base temperature from 3 pm to 6 pm (option II).

Table 1. Precooling Strategies Used in this Case Study

Experimental date	Strategies	
07.17.2019- 07.23.2019	**ΔT: 6◦F**	**I) Base Temp ≤ 76◦F** → T_{pre} = 70◦F for *11 am- 3pm* *3pm- 6pm* → T_{peak}=76◦F **II) Base Temp > 76◦F** → T_{pre} = T_{Base}- 6◦F for *11 am-3pm* *3pm- 6pm* → T_{peak} = back to the base temperature
07.24.2019- 07.30.2019	**ΔT: 3◦F**	ΔT_{pre} = T_{Base}- 3◦F for *11 am- 3pm* *3pm- 6pm* → back to the base temperature

4. The base temperature in both selected sample homes was 75◦F, therefore, the option I was selected for the first precooling strategy (T_{pre}=70◦F and T_{peak}=76◦F). In the second precooling strategy, the precooling temperature was set to 72◦F from 11 am until 3 pm and 75◦F from 3 pm to 6 pm.
5. All results from simulation were compared to the experimental data. In addition, both precooling strategies were simulated for each sample home from June 2019 until September 2019 to evaluate the effect of the precooling and the RDR strategy in the summer periods, which are the most important months from the utility point of view.
6. Due to the different construction material and setpoint temperature in each of the sample buildings, the energy savings were different in each precooling strategy. Based on the goals of this project, i.e., balance the electricity generation with demand, the proper precooling strategy was selected for each of the dwelling types.

7. After analyzing the precooling strategies, a PCM with 73.4◦F melting point was integrated into the base model and the precooling strategies were again simulated. The PCM was integrated on the ceiling above the lumber and in the exterior walls directly behind gypsum board. The purpose of simulating both locations was to compare PCM performance in the two locations, and assess the energy saving potential of PCMs, to determine if PCMs should be incorporated into new homes or added to existing homes to support energy efficiency.

Data collection and analysis

Case study building characteristics

The following table (Table 2) shows the specification of each of the sample homes included in this case study; these represent over 50% of the single-family homes in the Phoenix metropolitan area.

Table 2. Energy Characteristics of the Sample Buildings

Input parameters	**Sample home 1**	**Sample home 2**
Total floor area	185 m^2 (1978 ft^2)	178 m^2(1914 ft^2)
Floor height	2.7m (9ft)	2.4m (8ft)
Exterior wall U-value	0.42(W/ m^2 -K)	0.78(W/ m^2 -K)
Floor U-value	0.63(W/ m^2 -K)	0.97(W/ m^2 -K)
Roof U-value	0.12(W/ m^2 -K)	0.17(W/ m^2 -K)
Window U-value	2.72(W/ m^2 -K)	2.72(W/ m^2 -K)
HVAC coefficient of performance (COP)	3.5	3
HVAC Energy Efficiency Ratio (EER)	12	10.23
Lighting power density	14 W/ m^2 (1.3 W/ ft^2)	8 W/ m^2 (0.74 W/ ft^2)
Plug loads power density	4 W/ m^2 (0.4 W/ ft^2)	.87 W/ m^2 (0.36 W/ ft^2)
People	46 m^2/person (495f ft^2/person)	35 m^2/person (376 ft^2/person)
Construction Type	Wood, 2-story	Block, 1-story

BioPCM location

Figure 5and Figure 6 illustrate BioPCM locations within ceiling and wall assemblies. Clearly, integrating PCMs into the ceiling is easy to do without a major renovation; conversely, including PCMs in the exterior walls would require a major renovation (though it would be straightforward to include PCMs in exterior walls for new construction). Table 3 lists the PCM properties that were used for EnergyPlus modeling.

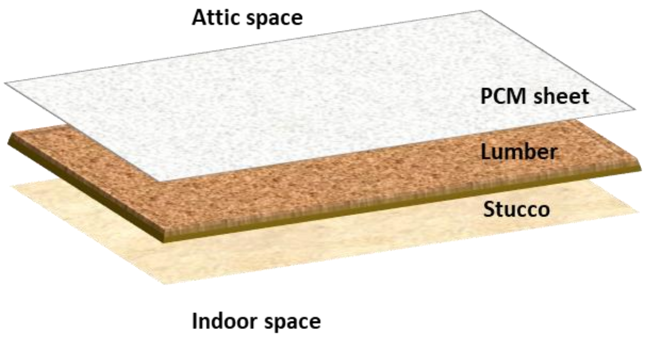


Figure 5. BioPCM Location on the Ceiling

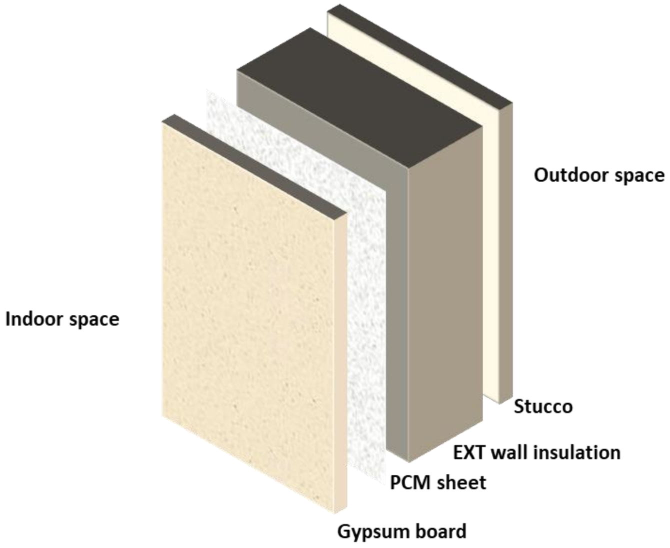


Figure 6. BioPCM Location in the Exterior Wall

Table 3. BioPCM Physical and Chemical Properties

	SI-Unit	Imperial units
Melting point	23 °C	73.4 °F
Latent Heat	210-250 J/g	90- 110 BTU/lb
Energy Storage Capacity	400- 1250 kJ/m2	35- 110 BTU/sqft
specific Heat	2.2 - 4.5 J/gK	0.6- 1.1 BTU/lb °F
Thermal Conductivity	0.15-2.5 W/mK	0.09-1.45 BTU/ft hr °F
Relative density	0.85- 1.4 g/mL	53- 87 lb/ ft3
Thickness	6 mm	0.24 inch

Price plan

To assess the impacts of precooling and PCMs on energy costs, the authors leverage three price plans for a local utility in the Phoenix, AZ area. In all plans, summer is defined as the May, June, September and October billing cycles. Summer Peak is defined as the July and August billing cycles. Winter is defined as November through April billing cycles. The price plans are as follows (SRP 2019):

E21 (EZ3): Peak hours are 3 pm to 6 pm year-round. Off-peak all day on holidays and weekends.

E23 (Standard): Subject to seasonal price change. Price plans based on the monthly usage, with higher prices imposed as customers use more electricity in any given month.

E26 (Time of Use): Subject to seasonal price change. Peak hours are 1 pm to 8 pm during the summer and summer peak seasons and 5am to 9 am/5 pm to 9 pm during winter season. Figure 7 illustrates the daily average energy consumption for a July 2018 day for each of the price plans considered. The goal of the precooling strategies was to encourage more uniform energy consumption across the year.

Both sample buildings in this case study subscribe to the EZ3 price plan. Table 4 describes the details of this price plan, which are also used in calculating the cost savings associated with the suggested precooling strategies from June until September.

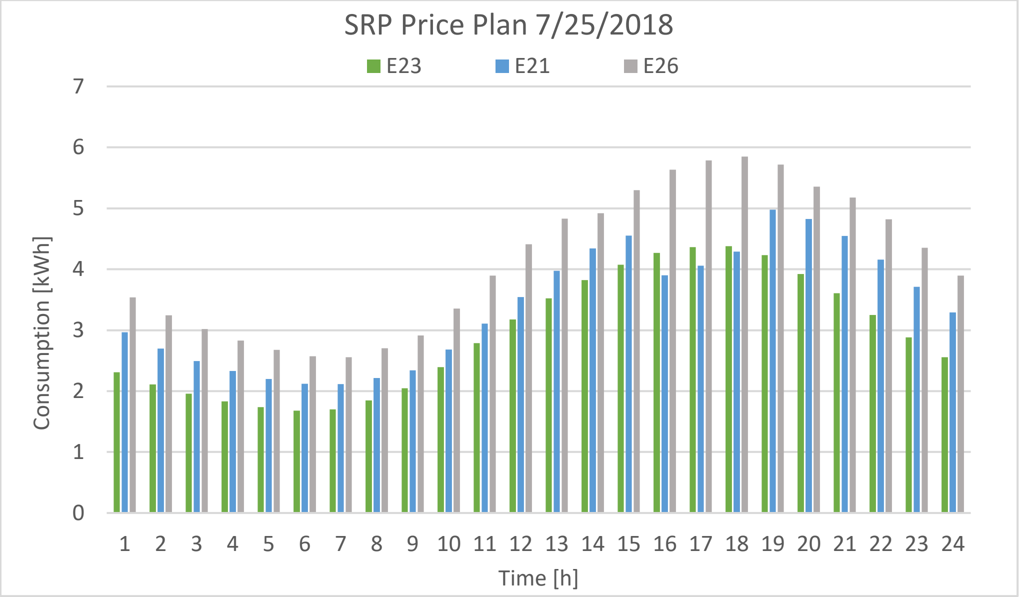


Figure 7. SRP Price Plan in Residential Buildings

Table 4. EZ3 SRP's Price Plan for Residential Customers

	Off-Peak	**On peak**	**Off-Peak**
	1am-3pm	**3pm-6pm**	**6pm-12am**
January	7.38¢	10.63¢	7.38¢
February	7.38¢	10.63¢	7.38¢
March	7.38¢	10.63¢	7.38¢
April	7.38¢	10.63¢	7.38¢
May	8.29¢	28.95¢	8.29¢
June	8.29¢	28.95¢	8.29¢
July	8.53¢	34.44¢	8.53¢
August	8.53¢	34.44¢	8.53¢
September	8.29¢	28.95¢	8.29¢
October	8.29¢	28.95¢	8.29¢
November	7.38¢	10.63¢	7.38¢
December	7.38¢	10.63¢	7.38¢

Results and discussion

This section explains different precooling strategies implemented in the simulation and discusses the results for each strategy. Table 5 lists the HVAC setpoint temperatures for the sample homes.

Table 5. Setpoint Temperature of Sample Buildings for the Base Model

	1am-12pm	12pm-3pm	3pm-6pm	6pm-12am
Sample home 1 (wood)	75◦F	72◦F	82◦F	75◦F
Sample home 2 (block)	75◦F	75◦F	75◦F	75◦F

In order to calibrate both homes, the schedule of both homes prior to precooling was considered as a baseline for simulation. Sample home 1 is a two-story wood frame home and has four schedules per day. In July, this house was operating a precooling strategy with a 10°F temperature gradient; that is, the homeowner precooled their home for 3 hours at 3°F and allowed the temperature to reach a setpoint 10°F higher than the precooling setpoint during the peak hours. Sample home 2 is a one-story block home that has a single setpoint temperature of 75°F. However, the house is served by a Google Nest thermostat, which leverages the ECO mode to maintain 75°F when the home is occupied and raises the temperature to 80°F in unoccupied periods. Therefore, there was not a consistent schedule that could be followed for simulation. To address this, the authors instructed the homeowner to set their indoor temperature at 75°F during the day, which was considered for baseline calibration.

Baseline models

The architectural features of both sample buildings were used for energy modeling. Figure 8 shows the SketchUp model of Sample homes 1 and 2. Sample home 2 has an attached dining room area that can be seen on the right side of this building. Although this building is a block frame home, the dining room is a wood frame room with no insulation on the roof. Furthermore, this room has two large windows on the north and east sides that result in a higher temperature in comparison with other rooms.

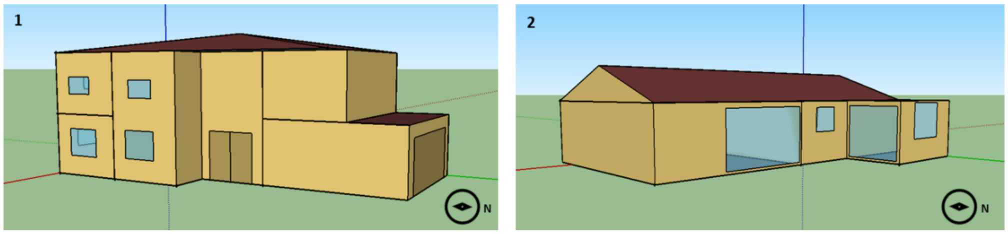
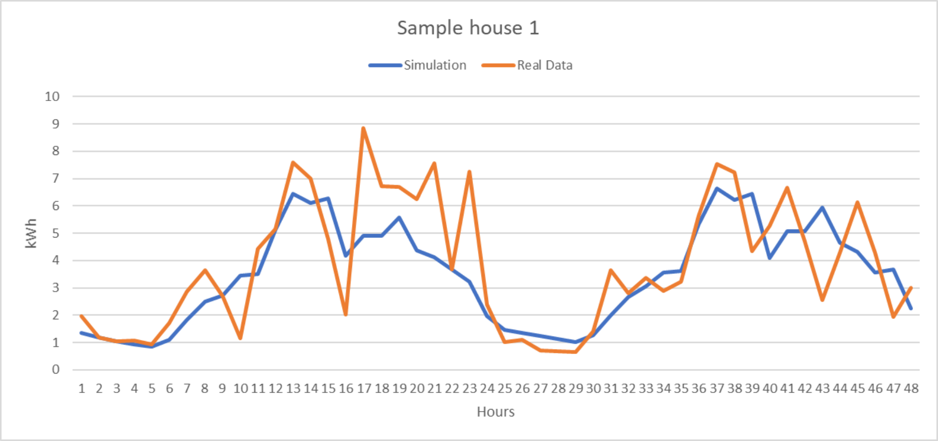


Figure 8. SketchUp Model for Sample Homes

Calibration the base models

As previously mentioned, the first two weeks in July 2019 were used for calibration. Due to different occupancy schedules and different electricity usage during the day, the variance between the models and actual consumption in some parts of the day was quite high. The following figures represent the calibration of both models for two days for each house. In general, these two days represent better alignment between the modeled and actual consumption than other days in the baseline period (Figure 9).

Both energy models were calibrated against the daily hourly energy use for two weeks. According to ASHRAE guideline 14-2002 (Aaron Garrett 2016), Normalized Mean Bias Error (NMBE) and Root Mean Square Error (RMSE) are the metrics used to calibrate and validate energy models.



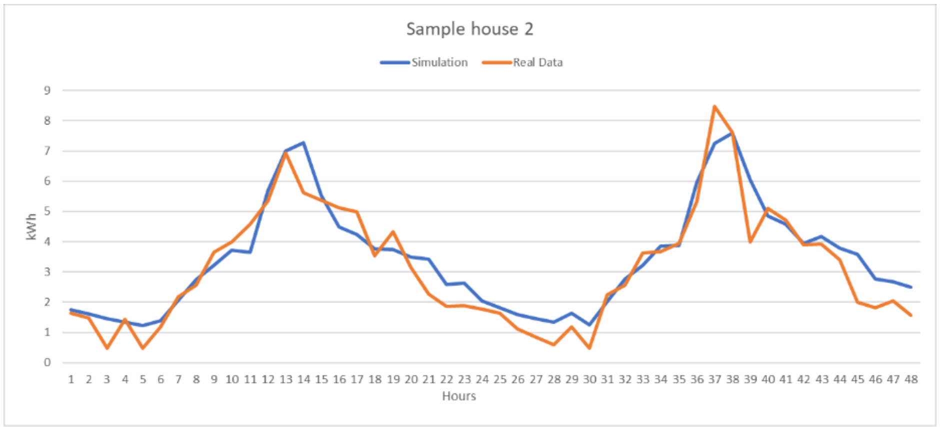


Figure 9. Electricity Consumption of the Calibrated Models for Two Days in July 2019

Table 6 lists the hourly energy calibration RMSE and NMBE in both models for two weeks in July 2019; the NMBE is below ASHRAE's suggested ±10% threshold (Germán Ramos Ruiz 2017).

Table 6. Hourly Calibration of the Sample Buildings for Two Weeks (July 1st until July 15th)

	RMSE (kWh)	**NMBE (%)**
Sample home 1	1.82	1.37
Sample home 2	1.78	-0.43

Experimental precooling strategies

Table 7 shows the precooling strategies implemented in the sample homes. In both strategies, the precooling period was 4 hours from 11 am until 3 pm.

Table 7. Precooling Setpoint Temperature Applied in Both Sample Homes

Precooling strategies				
	12am-11am	11am-3pm	3pm-6pm	6pm-12am
STR1	75◦F	70◦F	76◦F	75◦F
STR2	75◦F	72◦F	75◦F	75◦F

Sample home 1: wood frame

Analyzing the precooling strategies in the sample buildings showed a difference in energy consumption between the simulation and actual consumption data. Figure 10 and Figure 11 illustrate the energy consumption of the precooling strategies in sample home 1 for one week. As illustrated, the energy consumption drops or increases instantly in some days in the experiment, which can be the result of internal activities in the house that are not included in the simulation. The energy consumption from simulation results is 8 kWh more than the actual consumption data in the first precooling strategy. In the simulation, during precooling, the energy consumption increased and immediately dropped after 3 pm; results from the experiment show that the HVAC comes back on after 4 pm. Comparing these results illustrates that the thermal mass in the wood frame home cannot maintain the interior temperature in the home on very hot days without turning on the air conditioning.

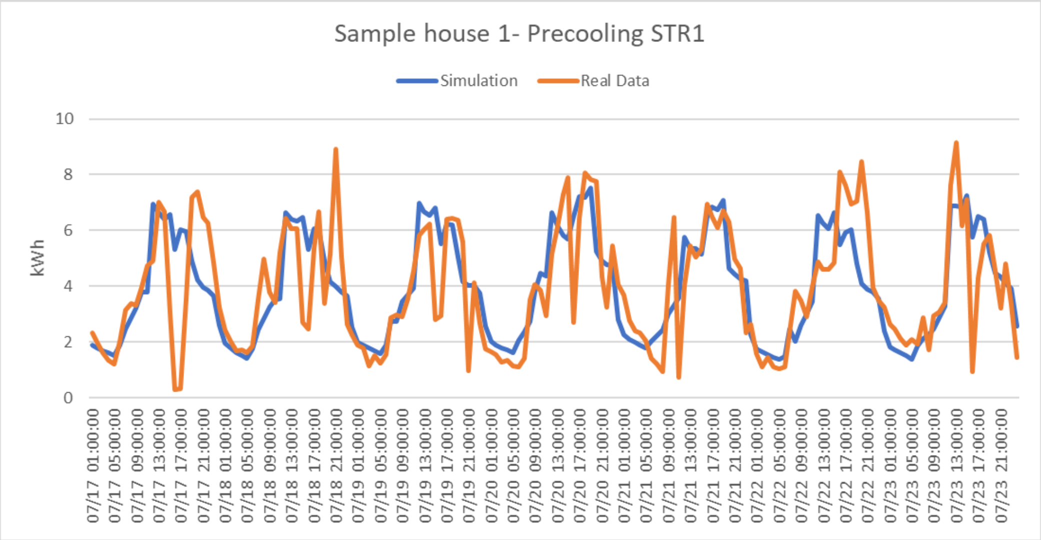


Figure 10. Electricity Consumption of Sample Home 1 in the First Precooling Strategy (STR1)

Unlike the first strategy, in the second strategy, the energy consumption of this house was 68kWh more than simulation results in one week. The energy consumption fluctuation in with 3◦F temperature difference (precooling STR2) is less than for the 6◦F temperature difference (precooling STR1). However, this strategy may not be very effective in the wood frame home, due to shifting the load from on-peak to off-peak hours.

As can be seen in Figures 9 and 10, the energy consumption of both experimental data and simulation had similar behavior some days (i.e., the 20th and 21st in the STR1 and the 25th and 27th in STR2). Therefore, the authors used those days as reference days to analyze the precooling strategies. The results indicate that the simulation model can be used for analyzing the precooling strategies in summer periods.

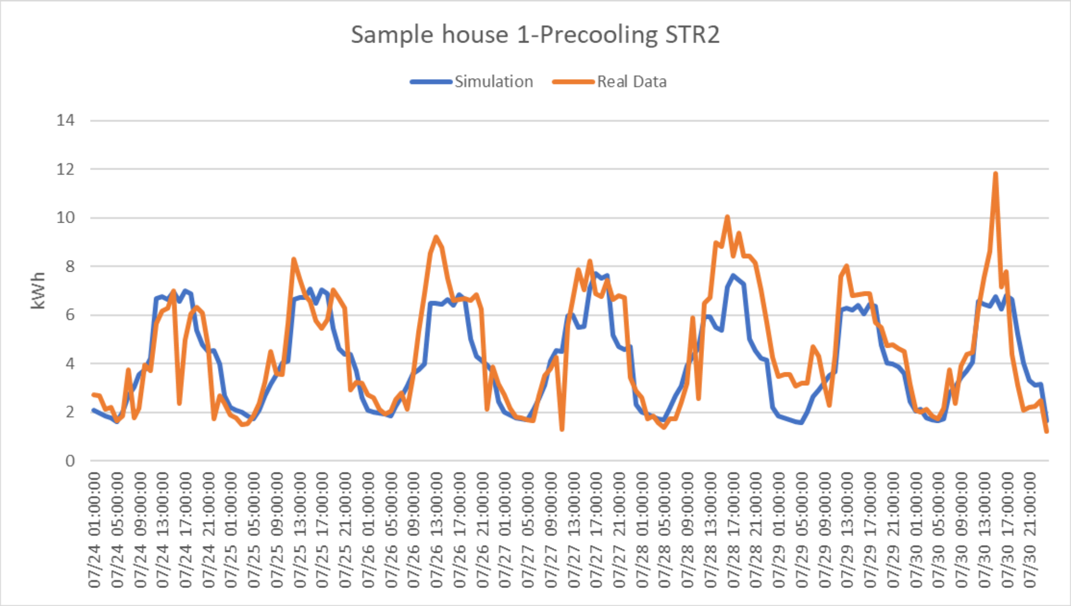


Figure 11. Electricity Consumption of Sample Home 1 in the Second Precooling Strategy (STR2)

Sample home 2- block frame

Figure 12 and Figure 13 compare the actual and simulated electricity consumption for precooling strategies 1 and 2, respectively. In sample home 2, the energy consumption increased in comparison to the baseline and due to the eco mode of the Nest thermostat and the poor insulation in the dining room, the precooling was not very effective. As seen in Figure 12, the actual electricity consumption is higher than the simulation for precooling STR1. After analyzing the precooling strategies in this house, the authors determined that the eco-mode from the Nest thermostat can result in more energy savings than precooling based on detecting and regulating the temperature in the home based on occupancy.

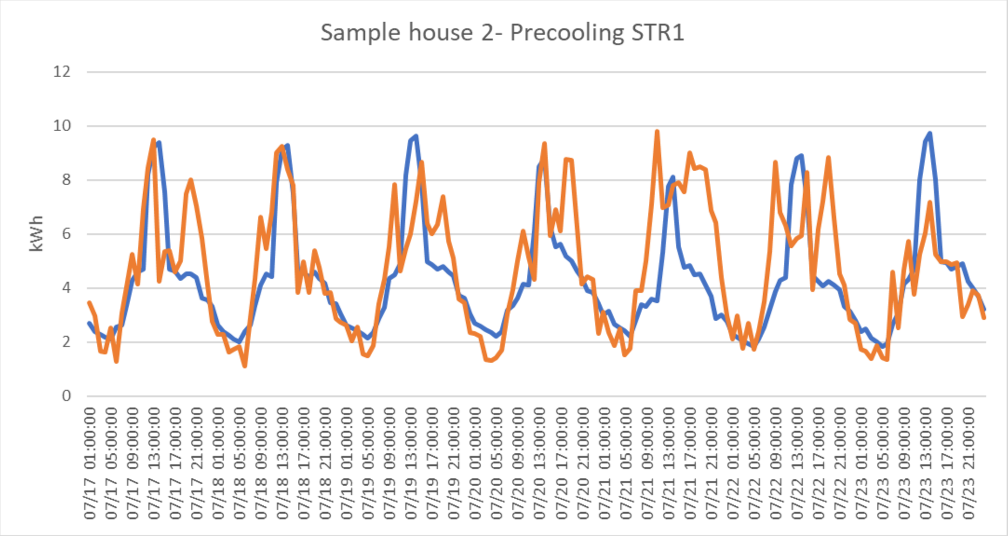


Figure 12. Electricity Consumption of Sample Home 2 in the First Precooling Strategy (STR1)

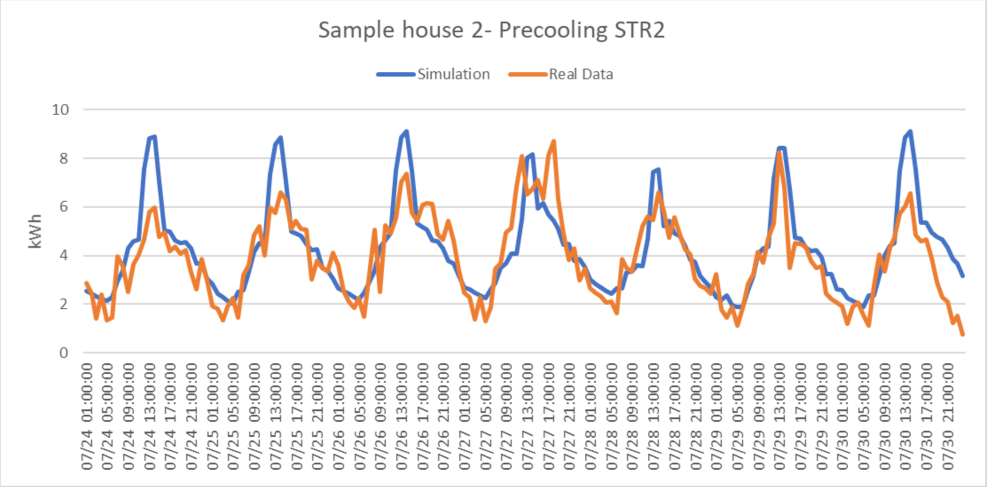


Figure 13. Electricity Consumption of Sample Home 2 in the Second Precooling Strategy (STR2)

Considering Figures 10-13, it is clear that the actual and simulated electricity consumption show agreement for some days considered. This similarity indicates that energy models for both homes can be used for further analysis and the models were used to simulate the energy consumption for the summer period as well as for PCM integration. Comparing precooling strategies shows that the energy consumption in the second precooling strategy is lower than the first strategy, which is due to lower temperature difference.

Simulation precooling strategies in the summer period

Sample home 1- wood frame

In order to compare the effect of different precooling strategies with the baseline, energy models for both homes were simulated from June 2019 until September 2019. Figure 14 represents the daily average energy consumption of the sample home 1 for baseline, STR1, and STR2 in July. As illustrated, the precooling period is from 11 am until 3 pm in both STR1 and STR2. Comparing the electricity consumption of all three scenarios shows that the baseline has higher energy consumption in the off-peak hours, which is due to the higher temperature difference between off-peak and on-peak hours; that is, the baseline is a more aggressive precooling strategy than either STR1 or STR2. On the other hand, during on-peak hours, the electricity consumption of baseline and STR1 is lower than STR2. This analysis indicates the total amount of cooling energy that can be stored in the thermal mass of the wood frame home directly depends on the length of the precooling and the precooling setpoint temperature. Results from baseline and STR1 show that the amount of energy stored in the thermal mass can reduce the load rapidly for one hour (3 pm until 4 pm) and after 4 pm the electricity consumption starts to increase to provide the desired temperature in the house. Moreover, the energy consumption of STR2 illustrates that precooling with 3◦F has no effect on reducing the load in peak hours. Due to the lower temperature difference is STR2, the electricity consumption decreased 0.3 kWh from 3 pm until 4 pm, which is negligible in comparison to 2.4 kWh in the baseline and 1.2 kWh in STR1, respectively.

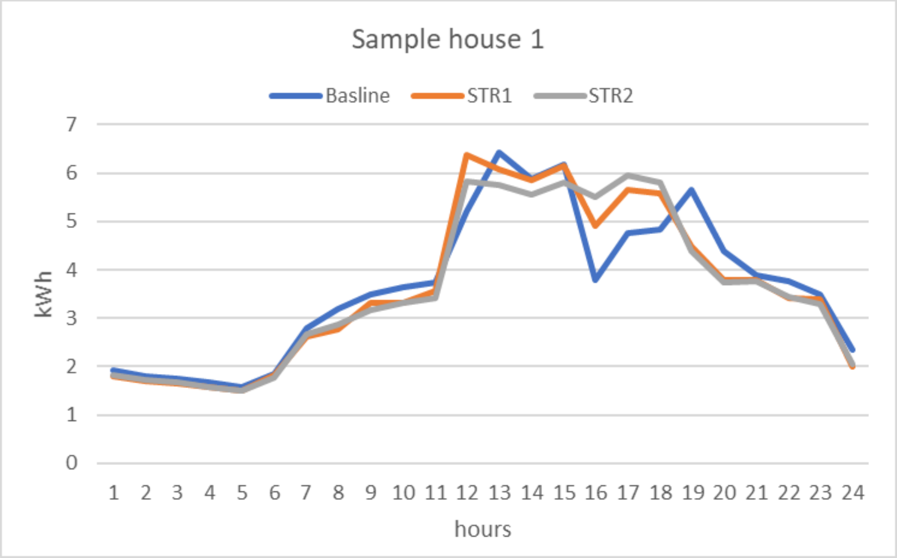


Figure 14. Daily Energy Consumption of Sample Home 1 for Baseline, STR1, and STR2 in July 2019

The following tables represent the energy consumption, cost and CO2 emissions in on peak and off-peak hours from June - September 2019 for the wood frame home. Sample home 1 was operating under three-hour precooling at 72◦F until 3 pm in the baseline, therefore, comparing both precooling strategies (STR1 and STR2) with the baseline shows that the total energy consumption is lower in both cases. However, the total electricity cost in the baseline is lower than STR1 as well as STR2. This is expected because the amount of electricity consumption in the peak hours is lowest for the baseline, compared to STR1 and STR2; this results in lower energy costs.

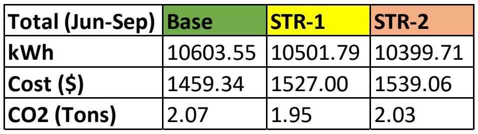
The following tables represent the energy consumption, cost and CO2 emissions in on peak and off-peak hours from June - September 2019 for the wood frame home. Sample home 1 was operating under three-hour precooling at 72◦F until 3 pm in the baseline, therefore, comparing both precooling strategies (STR1 and STR2) with the baseline shows that the total energy consumption is lower in both cases. However, the total electricity cost in the baseline is lower than STR1 as well as STR2. This is expected because the amount of electricity consumption in the peak hours is lowest for the baseline, compared to STR1 and STR2; this results in lower energy costs.

Table 8. On-Peak and Off-Peak Energy Consumption, Cost and CO2 Emission in the Summer Period

Simulation Results		**Jun-19**			**Jul-19**			**Aug-19**			**Sep-19**		
		Base	**STR-1**	**STR-2**	**Base**	**STR-1**	**STR-2**	**Base**	**STR-1**	**STR-2**	**Base**	**STR-1**	**STR-2**
kWh	**On Peak**	428.39	504.88	533.98	472.52	564.48	598.70	464.85	554.90	587.80	432.41	513.64	544.53
	Off Peak	1998.29	1898.73	1844.95	2454.96	2327.05	2264.64	2318.12	2201.91	2143.11	2034.00	1936.20	1882.00
	Total	2426.68	2403.61	2378.92	2927.48	2891.52	2863.35	2782.97	2756.81	2730.91	2466.41	2449.85	2426.53
Cost ($)	**On Peak**	124.02	146.16	154.59	162.74	194.41	206.19	160.10	191.11	202.44	125.18	148.70	157.64
	Off Peak	165.66	157.40	152.95	209.41	198.50	193.17	197.74	187.82	182.81	168.62	160.51	156.02
	Total	289.68	303.57	307.53	372.14	392.90	399.37	357.83	378.93	385.25	293.80	309.21	313.66
CO2 (Tons)	**On Peak**	0.08	0.10	0.10	0.09	0.11	0.12	0.09	0.11	0.11	0.08	0.10	0.11
	Off Peak	0.39	0.37	0.36	0.48	0.45	0.44	0.45	0.43	0.42	0.40	0.38	0.37
	Total	0.47	0.47	0.46	0.57	0.56	0.56	0.54	0.54	0.53	0.48	0.48	0.47

Comparing only the precooling strategies STR1 and STR2 illustrates that during the summer period, the STR1 is more effective in the wood frame home and results in lower energy consumption in the peak hours and more energy savings, compared to STR2. Furthermore, the amount of CO2 emissions produced in STR1 is lower than both the baseline and STR2 (Table 9). Studying the results indicates that the applying precooling STR1 in the wood frame home can result in 6% energy reduction in peak hours and 2.7% energy increase in off-peak hours, compared to STR2.

Table 9. Total Energy Consumption, Cost and CO2 Emission in Summer Period



Total (Jun-Sep)	**Base**	**STR-1**	**STR-2**
kWh	10603.55	10501.79	10399.71
Cost ($)	1459.34	1527.00	1539.06
CO2 (Tons)	2.07	1.95	2.03

Sample home 2- block frame

Simulating the precooling strategies from June - September 2019 shows that the total energy consumption of the block home increased 5% in STR1 and 4% in STR2 compared to the baseline. The energy consumption of STR1 increased during the precooling and the stored energy will be used during peak hours. As seen in Figure 15, the thermal mass of the home maintains the desired temperature until 7 pm, thus effectively storing cooling energy. This analysis illustrates that both precooling strategies are effective in the block home; however, the energy savings and load shifting are larger in STR1.

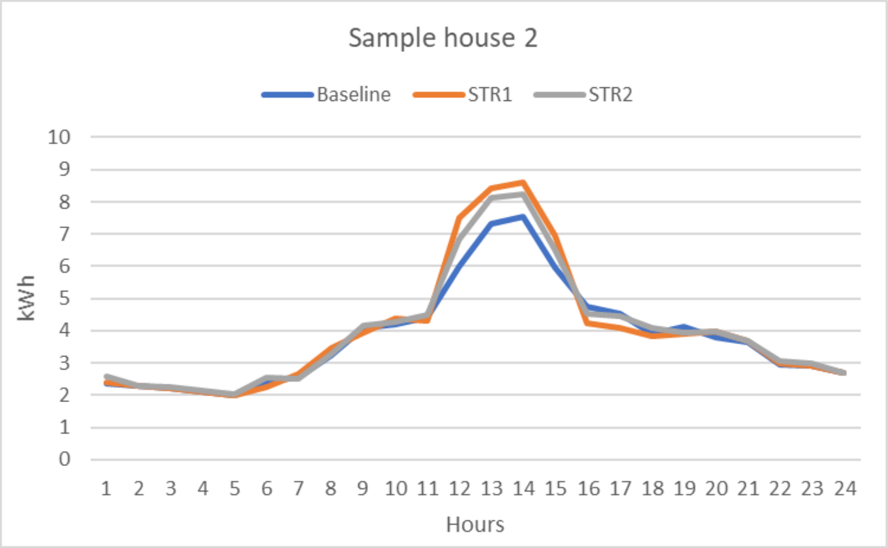


Figure 15. Daily Energy Consumption of Sample Home 2 for Baseline, STR1, and STR2 in July 2019

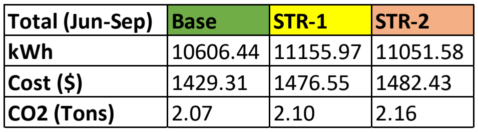
Table 10 illustrates that in sample home 2, the total energy consumption increased after applying precooling in summer periods. However, during the peak hours, the energy consumption is lowest with STR1, compared to the baseline as well as to STR2. Therefore, the authors recommend applying 6◦F precooling for four hours in block homes with similar construction as sample home 2.

Table 10. On-Peak and Off-Peak Energy Consumption, Cost and CO2 Emission in the Summer Period

Simulation Results		**Jun-19**			**Jul-19**			**Aug-19**			**Sep-19**		
		Base	STR-1	STR-2	Base	STR-1	STR-2	Base	STR-1	STR-2	Base	STR-1	STR-2
kWh	**On Peak**	394.96	364.40	390.85	472.39	437.99	469.30	447.61	411.40	442.31	404.64	370.47	399.19
	Off Peak	1971.44	2131.24	2075.77	2524.66	2721.80	2659.07	2339.35	2513.53	2460.08	2051.39	2205.14	2154.99
	Total	2366.40	2495.64	2466.62	2997.05	3159.79	3128.37	2786.96	2924.93	2902.39	2456.03	2575.61	2554.19
Cost ($)	**On Peak**	114.34	105.49	113.15	162.69	150.84	161.63	154.16	141.69	152.33	117.14	107.25	115.57
	Off Peak	163.43	176.68	172.08	215.35	232.17	226.82	199.55	214.40	209.84	170.06	182.81	178.65
	Total	277.77	282.17	285.23	378.04	383.01	388.45	353.70	356.09	362.18	287.20	290.06	294.22
CO2 (Tons)	**On Peak**	0.08	0.07	0.08	0.09	0.09	0.09	0.09	0.08	0.09	0.08	0.07	0.08
	Off Peak	0.38	0.42	0.40	0.49	0.53	0.52	0.46	0.49	0.48	0.40	0.43	0.42
	Total	0.46	0.49	0.48	0.58	0.62	0.61	0.54	0.57	0.57	0.48	0.50	0.50

Through applying precooling STR1, customers can capture up to 8% energy savings during peak hours and it only increase energy consumption 7% in off-peak hours compared to the baseline. Comparing precooling STR1 and STR2 shows that the CO2 emissions associated with STR2 are higher than STR1, although the total energy consumption (kWh) of STR2 is 1% lower than STR1 (Table 11).

Table 11. Total Energy Consumption, Cost and CO2 Emission in Summer Period



Total (Jun-Sep)	**Base**	**STR-1**	**STR-2**
kWh	10606.44	11155.97	11051.58
Cost ($)	1429.31	1476.55	1482.43
CO2 (Tons)	2.07	2.10	2.16

Simulating PCMs integration in the summer period

This section presents the effects of integrating PCMs into the sample homes. PCMs can be used as a thermal storage system to store energy during precooling hours. PCM location is one the major factors that can impact the savings potential. Energy savings will fluctuate based on the precooling duration and the location of the PCM. Results showed that one of the main impacts of the PCM installation in both buildings was the temperature profile in different zones of the buildings – if some parts of the home heat up too quickly, thereby triggering the air conditioning to turn back on, the PCM can help to maintain the cooler temperatures in these areas and delay the need for air conditioning until later in the peak period.

Sample home 1- wood frame

Figure 16 illustrates that PCM installation on the ceiling can decrease the energy consumption up to 1.6 kWh per day in the baseline case, 10◦F precooling (the highest temperature gradient studied). Therefore, the authors expected the PCM would have a wider temperature range to store energy and release it after 3pm. As seen in Figure 15, the savings potential increases after 5pm and reaches a maximum at 7 pm.

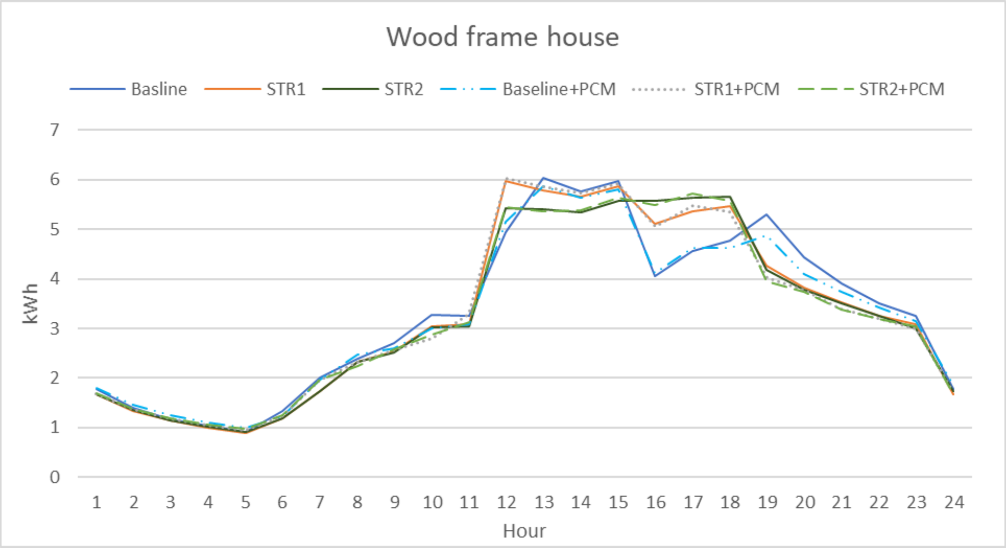


Figure 16. Daily Energy Consumption in Baseline and Precooling Scenarios with/without PCM Integration on the Ceiling

Figure 17 illustrates the daily energy consumption of the wood frame home with PCM integrated into the exterior walls. Comparing Figure 16 and Figure 17 shows that the highest energy savings are achieved when the PCM is integrated on the ceiling in the baseline case. However, the energy consumption increased in STR1 when PCM was located on the ceiling and in STR2 when PCM was integrated in the exterior wall. In addition, energy consumption decreased when PCM was integrated in the exterior wall in the baseline case and STR1, by 1.4 kWh/day and 1.2 kWh/day, respectively. Integrating PCM into the ceiling and the exterior walls can save up to $0.15/day and $0.14/day, respectively, in the baseline scenario.

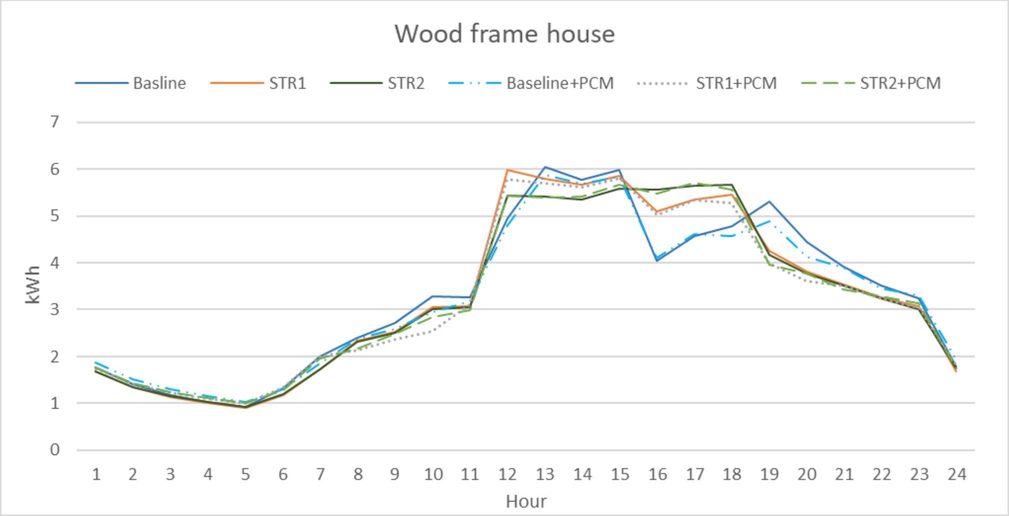


Figure 17. Daily Energy Consumption in Baseline and Precooling Scenarios with/without PCM Integration in the Exterior Wall

Sample home 2- block frame

The following figures (Figure 18 and Figure 19) show that PCM integration on the ceiling and in the exterior wall in the block frame home has negligible impact on daily load shifting and energy saving. Results indicate that that PCM integration has more effect in the baseline scenario on the ceiling (save up to 0.6 kWh/day, $0.1/day), and the impact of both precooling strategies will decrease the performance of the PCM. On the other hand, integration of the PCM in the exterior wall increase the energy saving up 0.2 kWh/day, which results is $0.04/day in the baseline. Comparing both precooling strategies with PCM integration shows higher energy saving is achieved when STR2 with 3◦F temperature difference is applied in the block house in both locations.

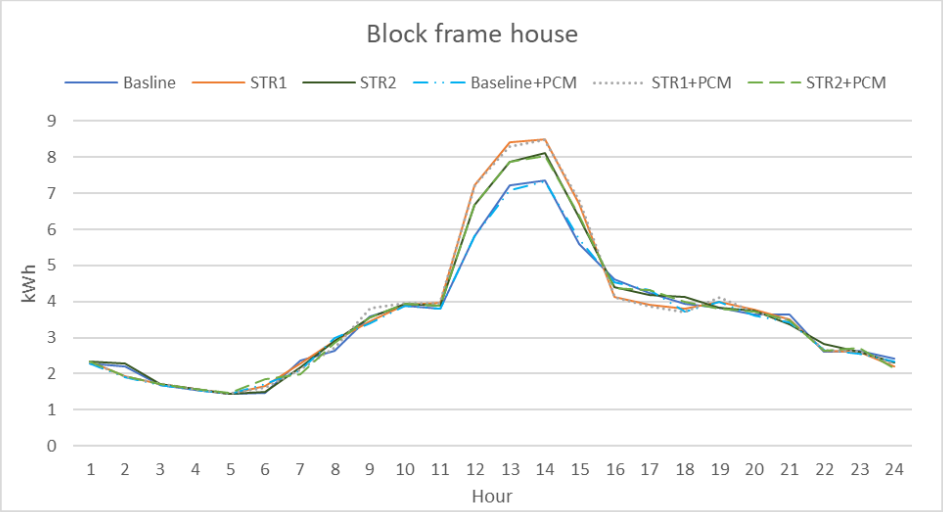


Figure 18. Daily Energy Consumption in Baseline and Precooling Scenarios with/without PCM Integration on the Ceiling

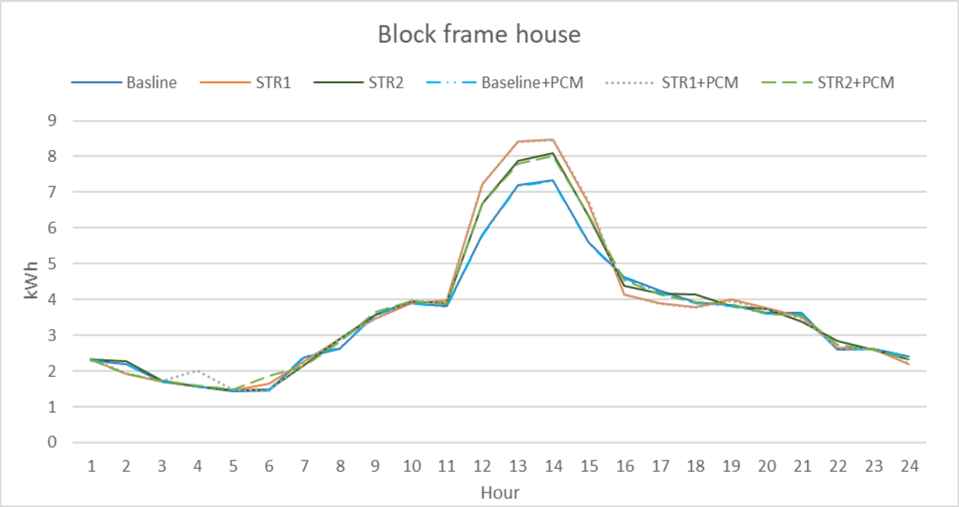


Figure 19. Daily Energy Consumption in Baseline and Precooling Scenarios with/without PCM Integration in the Exterior Wall

Analyzing the effect of PCM thickness in energy consumption

In this section, the authors compare the effect of PCM thickness in different locations in the homes, given the work of (Umberto Berardia 2017), who document that to see the impact of PCMs in EnergyPlus, the thickness should be magnified in order to build an EnergyPlus model that accurately reflects performance of PCMs installed in a building. Table 12 and Table 13 present the total energy savings with PCM integration from June until September with both 6mm thickness (i.e., reflecting the true thickness of a PCM sheet) and 5 cm of thickness, which was the thickness recommended in prior research (based on personal communication with professor Berardi at Ryerson University in Toronto, Ca). As shown, PCM integration on the ceiling is more effective than in the exterior wall for Home 1 and the reverse is true for Home 2. Moreover, by increasing the thickness of the PCM from 6mm to 5cm, the total energy savings will increase in most cases; importantly, the authors expect that the 5cm simulation results would be reflective of a 6mm installation in the field.

For Home 1, in the baseline case, installing 5cm of PCM, rather than 6mm of PCM in the ceiling results in additional energy savings. This result holds for the exterior wall as well, suggesting that the placement is less critical than the temperature gradient. Analyzing the energy savings in **STR1** shows that PCM integration on the ceiling will reduce the energy savings up to 9.3 kWh for Home 1 (Table 12). This means that with 6◦F temperature difference with precooling, less energy was stored in the PCM than in the 10◦F case, hence the savings were lower than the baseline case. In fact, for STR1, installing PCMs on the ceiling, either 6mm or 5cm thick, **cost energy**; that is, more energy was required to cool the home with PCM installed in the ceiling. The authors assume this is because the PCM simulation allows the PCM to freeze during the precooling, and then melt early in the peak period. After the PCM has melted, it transfers heat from the attic to the conditioned space, thereby increasing the energy required to maintain the set point temperature. On the other hand, in **STR2,** increasing the thickness of the PCM on the ceiling resulted in higher energy savings; this makes sense as with 3◦F precooling, there is not enough time for the PCM in the ceiling to freeze and melt, so the PCM essentially acts as an additional layer of insulation, rather than attracting heat throughout the peak hours, as was the case in STR1. In the case of exterior wall PCM installation, increasing the thickness improves the energy performance in the baseline case. However, in STR1 and STR2, there is an energy penalty associated with increasing the thickness of the PCM, likely due to the simulation algorithm's treatment of PCM freezing and melting with lower temperature gradients. Note that for STR2, the addition of PCMs in the exterior walls results in an energy increase, likely due to the PCM absorbing so much heat without ever becoming fully frozen. Thus, the air conditioner in the home must run more frequently to maintain the setpoint temperature in the home.

Table 12. Impact of PCM Thickness on Total Energy Savings for each Strategy, Relative to the Energy Performance without PCM Installed, for PCM Integrated into the Ceiling and into the Exterior Walls for Home 1 (wood)

With PCM from June until September				
Location	**Ceiling-6mm PCM**	**Ceiling-5cm PCM**	**EXT-Wall-6mm PCM**	**EXT-Wall-5cm PCM**
Baseline	227.28	338.70	204.73	337.43
Total Saving (kWh)				
Total Saving (%)	2.14	3.19	1.93	3.18
STR1	-7.04	-9.30	181.85	7.20
Total Saving (kWh)				
Total Saving (%)	-0.07	-0.09	1.73	0.07
STR2	17.90	65.64	-16.04	-16.03
Total Saving (kWh)				
Total Saving (%)	0.17	0.63	-0.15	-0.15

Table 13 represents the effect of increasing the thickness of the PCM on the energy savings for the summer period for Home 2. Increasing the thickness of the PCM will improve the total energy savings in both ceiling and exterior wall assemblies. In the block home, the performance of the PCM is more efficient when it is integrated in the exterior walls for all cases.

Table 13. Impact of PCM Thickness on Total Energy Savings for each Strategy, Relative to the Energy Performance without PCM Installed, for PCM Integrated into the Ceiling and into the Exterior Walls for Home 2 (block)

With PCM from June until September				
Location	**Ceiling-6mm PCM**	**Ceiling-5cm PCM**	**EXT-Wall-6mm PCM**	**EXT-Wall-5cm PCM**
Baseline	35.47	122.39	40.30	239.37
Total Saving (kWh)				
Total Saving (%)	0.33	1.15	0.38	2.26
STR1	14.16	62.52	22.78	174.92
Total Saving (kWh)				
Total Saving (%)	0.13	0.56	0.21	1.58
STR2	21.31	82.54	28.28	193.94
Total Saving (kWh)				
Total Saving (%)	0.19	0.75	0.26	1.76

Conclusion

This research aimed to analyze the impact on energy consumption of two different precooling strategies, as well as PCM integration, in single-family homes in Phoenix, AZ, a hot arid climate. The goal of this study was to illustrate the precooling strategy that increased load in off-peak hours and reduced the on-peak energy consumption and associated energy costs.

Based on the results of simulation and experimental data, the amount of cooling energy that can be stored in the thermal mass of homes depends on the construction, setpoint temperature of off-peak and on-peak hours, and the length of the precooling period, as well as the presence of “active” thermal energy storage, i.e., PCM. In this study, wood frame and block homes were precooled **without PCM** for four hours. The temperature difference in the first precooling strategy (STR1) was 6◦F and in the second precooling strategy (STR2) was 3◦F. Monitoring the energy performance in both homes showed that STR1 was more effective in both homes compared to STR2. However, the precooling strategies resulted in higher energy cost compare to the baselines, which can negatively impact consumers. From the utility point of view, however, precooling will support load leveling, as it increases the load in off-peak hours and supports balance between generation and consumption, particularly during off-peak hours. Results also showed reduced CO2 emissions from STR1 compared to STR2, which indicates that lower energy consumption in the peak hours is the determining factor in reducing CO2 emissions.

Integrating PCM and applying precooling strategies illustrated that three major factors play important roles in PCM behavior and energy savings in different building construction: 1) PCM location, 2) indoor temperature gradient, and 3) PCM thickness. Results showed that increasing thermal storage will not necessarily increase the energy savings potential, especially when PCM is applied in a wood frame building. Due to the phase change process in PCMs, the right thickness and melting point temperature should be considered for each dwelling type in order to achieve the desired goal. Furthermore, simulation results showed that PCMs did not have any impact on load shifting, i.e., the peak demand occurred at the same time regardless of whether or not PCMs were integrated into the home. However, PCMs allowed indoor temperatures in all zones to reach and maintain the desired set point temperature for the duration of the precooling period and increase slowly during the peak hours, thereby reducing cooling energy demand during the peak (i.e., load shedding).

CHAPTER 3

CASE STUDY: EVALUATING THE FEASIBILITY AND EFFICACY OF USING PHASE CHANGE MATERIALS IN SUPPORT OF LOAD SHIFTING IN A HOT ARID CLIMATE

Abstract

Residential and commercial buildings consume over 40% of the United States' total primary energy, and they account for nearly 40% of CO2 emissions. However, over the last 15 years, new technologies and strategies have merged to improve the thermal comfort in buildings while reducing their energy consumption. Applying latent heat storage (LHS), such as phase change materials (PCMs), is one such technology that can be effective in enhancing a building's thermal behavior. The purpose of using a PCM is to store energy in the freezing process and use the stored energy in the melting process, thereby reducing the need for mechanical cooling in the building.

This paper addresses the energy savings potential and construction feasibility of using a salt hydrate PCM in a commercial office building in Phoenix, Arizona (a hot-dry climate) and documents the process of selecting candidate buildings for PCM installation, as well as the selection of a particular PCM. The results of this paper provide useful information for utility providers and building owners that may be considering incentivizing or implementing PCMs in their commercial buildings, respectively. This paper also compares experimental work to EnergyPlus model results, focusing on the impact of the PCM on total energy cost, total energy consumption, and peak load

reduction. As such, this paper contributes to the building energy simulation body of knowledge, providing information about how measured PCM performance may differ from default options in EnergyPlus. The authors share lessons learned for effective PCM retrofit, and a process for selecting a good candidate building and PCM, thus expanding the PCM body of knowledge.

Introduction

The exponential growth of the world's population, coupled with the need to provide electricity and energy for this growing population, has led to an increased energy demand, a scarcity of primary conventional energy sources, and higher CO2 levels in the atmosphere. The United States consumes nearly a quarter of the world's energy, but accounts for only 5% of the world's population (Center for Sustainable Systems 2018). In the US, buildings consume about 40% of the total primary energy and more than 75% of the electricity load; moreover, they account for approximately 40% of national CO2 emissions (Administration 2018, Administration 2019, IEA 2019) It stands to reason, therefore, that reducing energy consumption in US buildings would make a measurable impact on global energy consumption patterns and CO2 emissions.

Existing commercial buildings are one of the main energy consumers in the United States, and offices are the highest consumer within that category, accounting for approximately 17% of energy use in commercial buildings nationwide (ACEEE 2018). Thermodynamic systems in buildings are complex systems that have a direct impact on occupants' comfort. The primary factor influencing the thermodynamic system in a building is the temperature differential between outdoor and indoor air. The energy required to maintain a temperature differential that provides a comfortable indoor air temperature is influenced by the building's envelope and the supply energy systems for heating and cooling (e.g., steam loop, chilled water loop). Building envelopes impact the internal and external loads, thermal resistance, and heat capacity of the building. Heating and cooling systems also have large impacts on energy consumption, and often account for about a third of overall building energy consumption (DOE 2010).

One method for curbing energy use in buildings is implementing energy efficiency measures (EEMs), such as improving the building envelope and implementing technologies into buildings that contain active thermal components. However, it is not always possible to increase the thermal mass of existing buildings; hence, it is not always possible to improve their thermal energy storage via thermal mass alone. Retrofitting buildings can improve their thermal energy storage, if the retrofit design strategies, materials, and equipment result in heating and cooling savings and improved building energy performance (Edwin Rodriguez-Ubinas 2013).

A building's thermal mass can serve as sensible heat storage (SHS); indeed, a building's thermal mass is one of the major parameters that can affect the total energy consumption of a building; the thermal mass also offers a potential for load shifting and peak demand reduction (R. Yin 2010). SHS in buildings with high thermal mass can be very efficient, but in retrofit and lightweight construction buildings with lower thermal mass, using SHS might not be feasible due to the volume of thermal mass (i.e., weight) needed. Therefore, applying latent heat storage (LHS) such as phase change material

(PCM) can be more effective to enhance these buildings' thermal behavior. PCMs have a high heat of fusion; during the phase change between solid and liquid at a constant temperature, a large amount of thermal energy can be stored in and released from these materials. Indeed, PCMs offer an opportunity for increasing thermal energy storage, saving energy, reducing cooling demand, improving thermal comfort, and load sifting (C.K. Halford 2007, Vineet VeerTyagi 2007, L.F. Cabeza 2011, N. Soares 2013, Servando Álvarez 2013, Farah Souayfane 2016).

This paper presents a case study of PCM installation in a commercial office building in the Phoenix, Arizona area. This case study can serve as a proof of concept for PCM strategies in commercial office buildings in hot arid climates. The purpose of this study is to demonstrate the HVAC control strategies and thermal energy storage (TES) systems that show most promise for reducing the energy demand. Such strategies aim for load shedding or load shifting to reduce the electricity bill for consumers while minimizing the voltage and frequency fluctuation in the grid at multiple time scales. In particular, this research explores the use of a PCM for TES in an existing office building. PCMs in the building envelope can serve as thermal energy storage that improve the thermal inertia of the building, at a relatively low cost and without any substantial weight increase.

Literature Review

PCMs can be divided into two main groups: organic material, such as paraffin and non-paraffin, and inorganic material such as salt hydrates and metals. The particular choice of PCM for a given application depends upon thermodynamic, kinetic, chemical and economic considerations. The most important properties of the PCM in the buildings' constructions include (Lavinia Socaciu 2014):

- matching the range of melting point temperatures to the desirable interval of working temperatures;
- high specific thermal capacity, heat of fusion;
- congruent melting of all PCM components (without congruent melting, the individual PCM components can undergo irreversible segregation);
- reliable and repeatable phase transformation during numerous melt-freeze cycles;
- minimum change in volume when transitioning from one phase in another;
- insignificant supercooling during the freezing process;
- good availability and low cost;
- non-corrosive to containment materials;
- non-toxic, non- flammable and non-explosive.

It cannot be overstated how critical it is to match the PCM to the building; generally speaking, designers and building owners should analyze building thermal performance, including heating and cooling energy, hot/cold calls from occupants, and function of HVAC equipment prior to selecting a building and a complementary PCM.

PCMs in commercial buildings

Studies analyze the performance of PCMs in different locations in the building envelope such as lateral walls, ceilings and roofs with simulation and modeling (Augustin Tardieu 2011, Frédéric Kuznik 2011, G.Evola 2014, Xing Jin 2014). In fact, most studies analyze integration of PCMs installed during building construction the construction of the buildings or they were experimental studies in sample rooms. Therefore, in the following section this paper reviews papers in more details about the PCM performance in commercial buildings and simulation methods used in the studies.

VeerTyagi and D.Buddhi (Vineet VeerTyagi 2007) compared the performance of PCMs at various locations in commercial building envelopes and ceilings. PCM application in the buildings can be active or passive for heating and cooling purposes. In the active system, the PCM is located in the thermal storage units (these store “heat” or “coolth”); these are thermally separated from the building’s insulation. In the passive system, the PCM is integrated into the building’s walls or other components of the building’s insulation. When using PCMs for space heating and cooling, designers must choose the “right PCM,” i.e., the PCM that has a desirable melting temperature, minimal supercooling during freezing, and chemical properties that excellent melt/freeze cyclability. The authors recommend using a PCM with a melting point between 22 –25°C for passive heating and cooling. VeerTyagi and D.Buddhi further document the critical role of proper placement and installation of PCMs for designed thermal performance to be realized.

Pomianowski et al. (2013) reviewed PCM usage in building applications and highlighted key factors for determine PCM choice. Climate condition should be taken into account when PCMs are integrated in the exterior envelope of the building (both transparent and opaque). It is preferable that PCMs be located close to the transparent building envelopes because of the higher exposure to direct solar radiation. It is recommended to combine PCM technologies with night cooling and natural ventilation. The thermal conductivity of the PCM should be determined as a function of the temperature to correctly determine the dynamic performance of the PCM and the energy saving potential.

Harland, MacKay et al. (Alice Harland 2010) described that PCMs are more suitable for commercial buildings than residential buildings due to the temperature different setpoint temperature and schedule. Moreover, Lei, Yang et al. (Jiawei Lei 2016) conducted numerical analysis on the efficacy of applying PCM in a commercial building in Singapore, with an indoor setpoint temperature of 25 °C. In their study, they used a 10 mm thick PCM layer, with melting point temperatures ranging from 22 °C to 32 °C. The PCM was integrated on the exterior and interior surface of walls in their cubic model. Based on their results, utilizing PCM with 28°C melting point on the exterior surface of the vertical concrete wall of the building resulted in significant cooling savings and 21%-32% reduction in building envelope heat gain throughout the whole year.

Sun, Wang et al. (Yongjun Sun 2012) compare the impact of precooling strategies in buildings without TES (passive building) to buildings with PCMs for TES. They found that using PCM as TES in the buildings will increase the heat capacity of the buildings for storing energy during high energy generation and use the surplus stored energy during peak hours. Sun, Wang et al. compared precooling strategies in two different types of buildings where the pre-cooling temperatures were 20 °C, 22.5 °C and 24 °C and the melting point of the chosen PCM in the building was 23°C. Results showed that in the passive building with demand limiting, the maximum peak demand reduction (17%) was reached at the lowest pre-cooling temperature (20 °C) with 9h pre-cooling. In the building with PCM and demand limiting, the peak demand could be reduced by 38%, 35% and 22%, for precooling to 20 °C for 4 hours, 22.5 °C for 4 hours, and 24 °C for 8 hours, respectively. Furthermore, results indicated that the energy consumption in the building with PCM with 3h precooling at 20°C was lower than 2.5h precooling, however, the peak demand reduction increased by 2.5%.

Various simulation tools have been used to simulate PCM performance in buildings and compare the experimental results to the simulation results. Saffari, Gracia et al. (Mohammad Saffari 2017) used three different simulation tools to analyze the potential energy demand reduction of passive cooling technologies. In their research, they studied PCM integration in building envelopes in different climates. Their results showed that in heating dominated climates, the melting point of the PCM plays an important role in reducing energy demand and the PCM melting point should be optimized to increase annual energy savings. To improve the PCM model in EnergyPlus software, Tabares-Velasco, Christensen et al. (Paulo Cesar Tabares-Velasco 2012) conducted studies in several climates to verify the results of EnergyPlus PCM simulations. In their analysis, they illustrated that PCM integration has a minor effect on reducing the peak load during cooling seasons in Phoenix. The PCM integrated into the building envelope reduced the peak cooling around 8% in the month of May and 4% in the month of July.

Pascha (Pascha 2019) conducted studies using PCMs for cooling in dry and arid climates, where there is a large diurnal swing (i.e., a large temperature difference between day and night). His results showed that PCMs are suitable for passive cooling strategies and with night- ventilation, PCMs will store energy during nighttime, and then release that energy during the day, offering an efficient means to reduce daytime cooling demand.

Gap in the literature

This literature review illustrates that while much has been done in the area of PCM integration into commercial and residential buildings, the role of active PCMs in commercial buildings in hot, arid climates has yet to be studied in detail. This work addresses that gap and explores the feasibility of using a PCM for peak load shifting in the Phoenix, Arizona metropolitan area. Moreover, this study compares PCM properties ascertained in laboratory tests, to those provided by manufacturers, to those assumed in EnergyPlus models, illustrating the discrepancies in the latter properties and those measured in the laboratory. Finally, this paper compares energy costs and peak demands measured in the case study building to those predicted in the EnergyPlus model, highlighting the importance of a clear decision-making process for both building and PCM selection.

Methodology

A PCM is designed to freeze during the off-peak (night) hours and absorb energy (in the form of heat) to cool the building during the daytime hours. This study compares experimental and EnergyPlus model results, focusing on the impact of the PCM on total energy cost and peak load reduction. This study comprises experimental work as well as EnergyPlus model results to determine the factors that can increase the efficacy of PCM integration.

Figure 20 represents a methodology and analysis approach in this case study, described here:

1. The author created the thermodynamic building model using the geometry documented in the building plans.
2. The author calibrated the model using the hourly electricity consumption, gathered from the building's energy information system. Various parameters, such as the lighting and equipment schedules of the building, were modified to ensure the EnergyPlus model "matches" building operations. That is, the authors calibrated the EnergyPlus model to reflect the building's actual energy consumption. The calibration was evaluated with root mean square error (RMSE) and the accuracy was analyzed according to American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Guideline 14 (Aaron Garrett 2016). The "Base Model" simulation was based on building performance prior to PCM installation, from August 2016 until July 2017.

3. The author integrated PCMs into the “Base Model”, adding PCM to the material layers in the roof and ceiling of the building.
    a) Colleagues of the author performed laboratory tests to determine relevant chemical properties of the PCM; their results were used in successive energy simulations.
4. The author simulated the building, with PCM, using the temperature setpoint schedule in the base model, where the building was set to 75 °F during occupied hours, and 83 °F during unoccupied hours.
5. The author simulated the building, with PCM, using a refined temperature setpoint strategy, termed “76 °F- 80 °F,” where the setpoint is 76 °F during occupied hours and 80°F during unoccupied hours.
6. To take better advantage of the PCM’s energy storage capacity, the author worked with the building facilities staff to develop a pre-cooling strategy that would support two phase changes, rather than one, per day. In this strategy, the HVAC system operated with setpoint temperatures of 72 °F and 77 °F and the temperature changed four times each day (Table 2).
7. The author calibrated the model a second time, this time leveraging energy information system for the building following PCM installation. This calibrated model was used to explore different pre-cooling scenarios and compare them.
8. The author compared experimental results to simulation results.

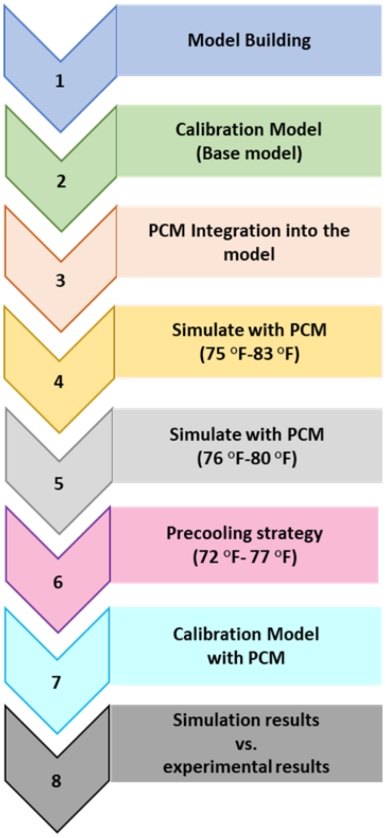


Figure 20. Analysis Approach in the Case Study- Office Building

Background

This paper evaluates the implementation of a salt hydrate PCM for peak-load shifting while improving a building's thermal behavior in a sample office building in Arizona. This section describes the building, the PCM installation, and the PCM itself.

Case study building characteristics

The sample office building is a one-story building, with four heat pump units, each of which has 15-ton capacity. The building comprises 4 thermal zones, each served by one HVAC unit. The total conditioned area of the building is 840.87 m^2 and the building does not have ceiling insulation. The building has multiple pitched roofs made of metal with several different heights and orientations, leading to varying levels of sun exposure as well as large differences in vertical space above the drop ceilings (Figure 21). North side of the building is on the left side of the Fig. 2 (30% of the total condition area), south side is on the right side of the Figure 21 (30% of the total condition area), lobby and conference room are in the center of the Figure 21 (40% of the total condition area). Table 14 represents the specification and parameter of the office building used in the EnergyPlus simulation.

Figure 21. Sample Office Building- West Facing

Table 14. Inputs to the EnergyPlus Model for the Sample Building

Input parameters	Sample office building
Total floor area	840.87 m^2 (9051 ft^2)
Floor height	7 m (22.92 ft)
Exterior wall U-value	0.78 (W/ m^2 -K)
Floor U-value	0.63 (W/ m^2 -K)
Roof U-value	16.12 (W/ m^2 -K)
Window U-value	4.83 (W/ m^2 -K)
HVAC coefficient of performance (COP)	3
Lighting power density	11 W/ m^2 (1.02 W/ ft^2)
Plug loads power density	6.8 W/ m^2 (0.63 W/ ft^2)
People	19.57 m^2/person (211 ft^2/person)
Construction Type	Metal frame, 1 story

PCM Installation

In summer 2017, the building owner installed PCM on the ceiling tiles of the building in the north and south side, lobby and conference room. The PCM, described in the next section, covered approximately 70% of the ceiling surface, as was advised by the PCM manufacturer. The goal of PCM installation, from the owner's perspective, was to reduce overall energy consumption in the building. The PCM manufacturer's goal was to reduce peak demand during hot summer months.

Unfortunately, due to the PCM leaks in the building, dissatisfaction of the building occupants, and an increase in electricity consumption, the PCMs were removed from the building in July 2018, effectively ending the study prior to the end of the summer peak loads.

PCM properties from lab measurement

The authors characterized the thermal properties of the PCM using two different methods, differential scanning calorimetry (DSC) measurements and temperature-history (T-History) measurements. The DSC measurements were used to characterize the melting behavior of the material. The freezing behavior of the material was characterized using the T-History method. The PCM material in this study is a salt hydrate and falls into the category of inorganic PCMs.

DSC measurements indicate that the PCM's latent heat, liquid state specific heat, and solid-state specific heat are 140 J/g, 2.05 J/g-K, and 1.4 J/g-K, respectively. Notably, these DSC measurements differ greatly from the data given by the PCM vendor, which indicated values of 200 J/g for latent heat and 3.14 J/g-K for specific heat (the vendor data sheet does not distinguish between the solid and liquid states for specific heat).

During DSC measurements, a small sample of ~30-40 mg was heated up at a constant temperature ramp rate of 0.9 °F per minute (0.5 °C per minute) and the heat flow rate needed to maintain this temperature ramp rate was recorded. Figure 22 shows a typical DSC curve. A negative heat indicates that heat is going into the sample as opposed to away from it. The valley in the data indicates the temperature range over which melting occurs (i.e., since melting is an endothermic process, a larger heat flux in needed to maintain the fixed temperature ramp rate during sample melting). The occurrences of three overlapping/neighboring valleys indicate multiple melting events and suggest that the sample is a heterogeneous mixture. Integrating over the area of this valley gives the latent heat of the PCM. This integration can also be graphed in a cumulative manner to illustrate the cumulative latent heat storage during melting as done in the blue curve of Figure 22b. Adding the sensible heat obtained from specific heat measurements to this latent heat yields the total heat stored during melting as shown in Figure 22b. Overall, Figure 22 shows that the melting process occurs over a very broad temperature range of ~61°F to 95 °F. This broad melting temperature range will impair thermal storage performance in the building because:

- The wide melting temperature range means that a large portion of the PCM’s latent heat is not utilized during regular building operation.

- The 77 °F melting temperature indicated in the PCM's vendor data sheet insufficiently describes the PCM's melting for thermal energy storage purposes. A much more appropriate descriptor would be the temperature range over which the majority of the latent heat occurs.
- For example, the building in this study typically operates between 75°F and 83°F. This temperature range is narrower than the PCM melting range. Only ~63% of the PCM latent heat is accessed in this 75-83°F temperature range.

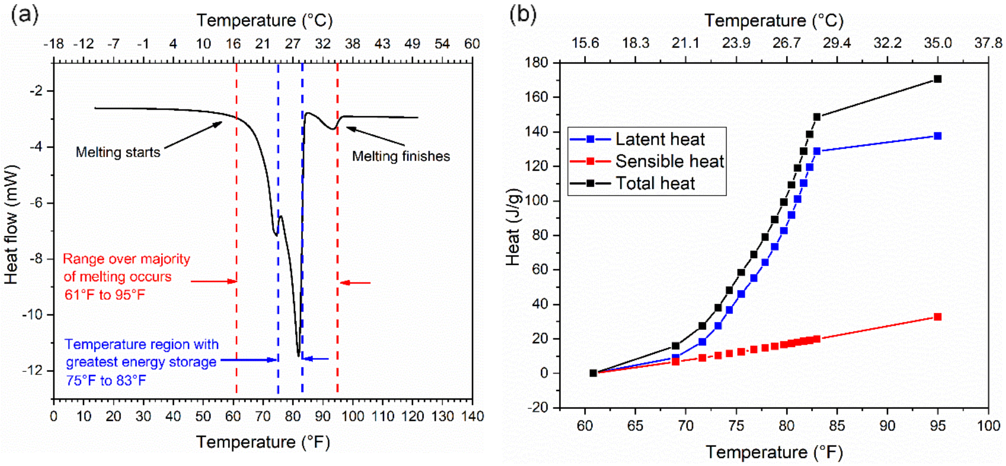


Figure 22. (a) Differential Scanning Calorimetry Measurements on the PCM Indicates that Melting Occurs over a Broad Temperature Range of ~61 to 95 °F. (b) The Accumulation of Latent Heat (Blue Curve) during the Melting Process as Obtained by Integrating the Differential Scanning Calorimetry Data Trace. Adding the Sensible Heat (Red Curve) Obtained from Specific Heat Measurements to this Latent Heat Yields the Total Heat (Black Curve) Stored during Melting.

Figure 23 shows a typical T-history measurement on the PCM and illustrates that supercooling occurs during PCM freezing. Supercooling is the phenomenon where a material can continue to maintain its liquid state despite being below its freezing temperature. Since supercooling can delay or even prevent phase change from occurring, it is detrimental to PCM performance in thermal storage applications. While not all materials exhibit supercooling behavior, a common method to minimize this phenomenon for materials that do supercool is to add nucleating agents that promote freezing. Evidentially, either an insufficient number of nucleating agents and/or a better nucleating agent is needed for this PCM.

During our T-history measurements, a melted PCM sample was placed in a temperature-controlled chamber and the PCM temperature was continuously monitored during freezing. The samples during these measurements consisted of the contents of a full-size PCM packet (~28 g) that was melted and placed in a test tube. The PCM temperature was monitored using a thermocouple placed in the center of the PCM volume. Fig. 4 shows a typical T-History data set for the PCM. The occurrence of supercooling is evident in this data trace. Rather than the temperature decreasing in a monotonic fashion, a sharp increase in temperature occurs at approximately 1000 s (16.7 min). At this point in time the temperature increases from 66 °F to 80 °F. This 80 °F is the onset melting temperature of the PCM and a supercooling of 14 °F is observed (80 °F - 66 °F). Over the course of measurements on eight different PCM packets, supercooling is observed that ranged from 14 °F – 24 °F (7.8 °C – 13.4 °C) with an average of 18 °F (10 °C). This supercooling has important impacts to the function of PCM in a building application:

- Supercooling impacts fully melted samples and can delay or even prevent freezing. This then delays or even prevents phase change thermal storage from occurring.

- Freezing of a supercooled material is a stochastic event whose statistical likelihood increases with increased time duration and/or increased temperature differential below the freezing temperature. Consequently, a PCM packet will eventually freeze given a cold enough temperature and/or enough elapsed time. Since the building has thousands of PCM packets, this would manifest as a continually increasing fraction (that may or may not reach 100%) of PCM packets in the building becoming frozen during cold periods.

Although the broad melting temperature of the PCM (Figure 23) is generally a negative characteristic, it does mitigate the negative results of supercooling to some extent. This is because supercooling only effects fully melted materials. Since this PCM doesn't fully until ~95 °F, it is reasonable to believe that full melting (and therefore supercooling) would be an uncommon event on a day-to-day basis.

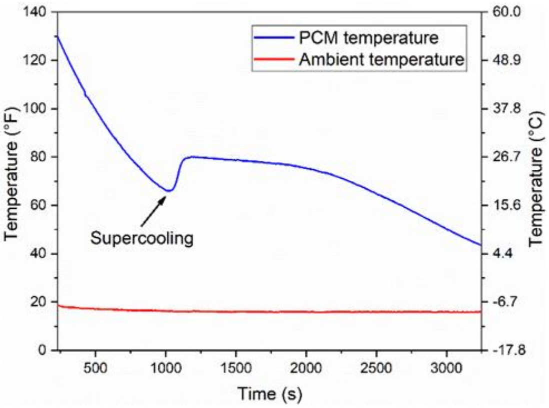


Figure 23. The Freezing Process of a PCM Packet is Observed during Temperature-History Measurements. Supercooling was Observed in all Temperature-History Measurements of the PCM. In this Particular Measurement, a Supercooling of ~14 °F is Observed at ~ 1000 s. Over a Total of 8 Runs, Supercooling was Observed that Ranged from 14 °F – 24 °F with an Average of 18 °F.

Results and Discussion

This section will explain different strategies implemented for the simulation and will discuss the results for each strategy. In this paper, different temperature setpoint cases are studied that include PCM integration into the building with different HVAC schedules and pre-cooling strategy.

Table 15 illustrates the setpoint temperature schedules for the different cases comprising this study and lists temperature setpoints for the base case (case #1) and the modified HVAC schedules, without precooling (case #2, case #3 and case #4). Case #5 studies the building with PCM installation when pre-cooling was implemented in the building.

The first case is the base model of the building, including an 8ºF temperature difference for occupied versus unoccupied hours. This schedule was used to generate and calibrate the base model (i.e., the model that simulates the building prior to PCM installation). In the second case, the temperature difference is smaller than the base model (4 ºF). The 3rd and 4th cases add PCMs to cases #1 and #2, with 8 ºF and 4 ºF temperature differences, respectively. Comparing cases #3 and #4 allows the authors to determine the effectiveness of the charging and discharging phases in each temperature setpoint scenarios.

Case #5 illustrates the precooling strategy implemented in the building. This strategy was designed to support PCM charging and discharging twice in a day, rather than once each day. The precooling strategy was implemented for two weeks, beginning in the end of June 2018.

Table 15. Strategies According to HVAC Cooling Setpoint Temperature for Occupied and Unoccupied Schedule

Case #	**Description**	**Weekdays**			**Weekends**
		12am-7am	**7am-17pm**	**17pm-12am**	**24 Hours**
1	Baseline operation of the building (Base model)	83 °F	75 °F	83 °F	83 °F
2	Baseline operation with modified HVAC sched	80 °F	76 °F	80 °F	80 °F
3	Base model with PCM installation	83 °F	75 °F	83 °F	83 °F
4	PCM installation with modified HVAC sched	80 °F	76 °F	80 °F	80 °F
5	PCM + precooling	**Weekdays+ Weekends**			
		5am-12pm	**12pm-16pm**	**16pm- 19pm**	**19pm-5am**
		77 °F	72 °F	77 °F	72 °F

Given the goals of the project, the authors present results for electricity consumption of the building with and without the PCM (kWh), the average demand of the building (kW), and any load shifting and cost savings ($) due to PCM installation.

Baseline model

The architectural features of the office building were input using Google Sketchup and the energy modeling was completed in OpenStudio and EnergyPlus (Figure 24).

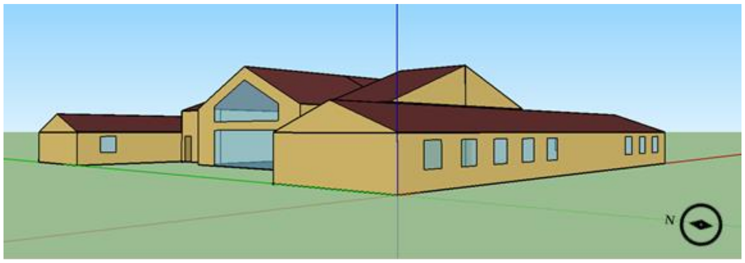


Figure 24. Sketchup Model of the Office Building in Arizona

Validation of "Base Model"

The calibration of the "Base Model" was based on building energy data from the 12 months prior to PCM installation (i.e., August 2016- July 2017). The baseline model did not include any PCM. The authors calibrated the model to match the measured energy consumption by adjusting the equipment and lighting schedules for weekdays and weekends.

Figure 25 compares the modeled electricity to the building's measured electricity consumption. The main purpose of PCM installation was to save energy during the summer, the period with the highest cooling energy consumption for the building. Therefore, this model was calibrated based on the hourly electricity consumption of the building in the months of June and July. The RMSE of the model for one year is 4.84 kWh (August 2016-July 2017).

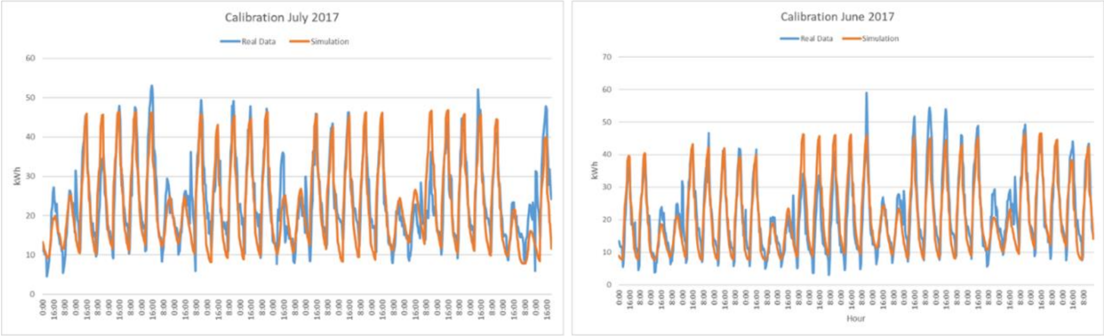


Figure 25. Electricity Consumption of the Calibrated Model for June and July 2017

Based on ASHRAE Guideline 14 (Aaron Garrett 2016), the authors also calculated the CVRMSE (Coefficient of Variation of the Root Mean Square Error) for the monthly calibration; it was 9%, below ASHRAE's suggested 15% threshold (Figure 26) (Germán Ramos Ruiz 2017). Thus, the authors consider the baseline model calibrated and suitable for simulation of building modifications, including installation of PCMs.

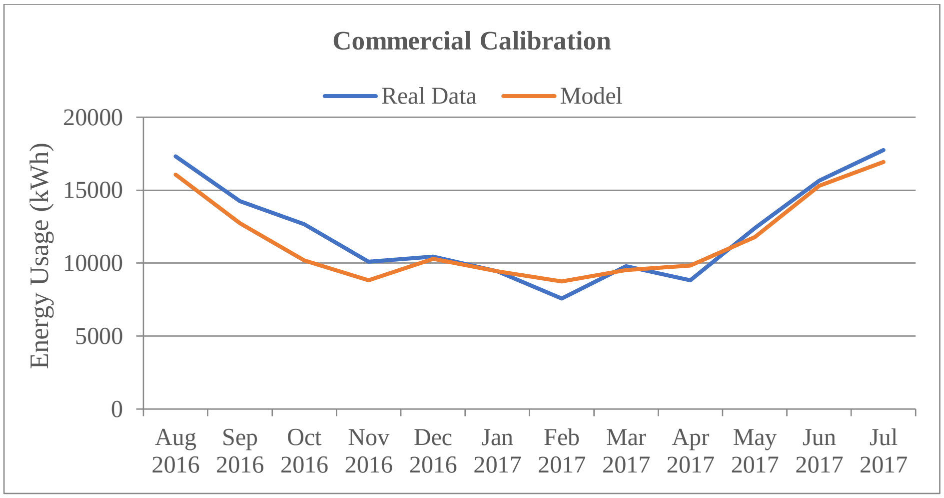


Figure 26. Commercial Calibration Based on ASHRAE Guideline 14

PCM integration into the "Base Model"

Based on the available data from material measurements, PCMs, with the measured properties, were added to the ceiling of the "Base Model". The EnergyPlus simulation algorithm assumes the PCM as another layer added to the ceiling.

EnergyPlus can only simulate PCM with the Conduction Finite Difference (CondFD) solution algorithm. According to the National Renewable Energy Laboratory (NREL) (Paulo Cesar Tabares-Velasco 2012) , EnergyPlus uses this algorithm to discretize the walls, roof and ceilings into several nodes. CondFD uses implicit finite difference scheme coupled with an enthalpy-temperature function to numerically solve the appropriate heat transfer equation. This algorithm considers the PCM as a homogenous material and calculates the heat transfer with uniform node spacing. Laboratory tests of the PCM used for this study confirm that the material does not act in a homogeneous manner; this a limitation of the PCM simulation.

According to the manufacturer's datasheet, the melting point of the PCM is 77 ºF, and the PCM should store energy in the freezing process (lower than 77 ºF, charging phase) and should release the stored energy in the melting process (at temperatures higher than 77 ºF, in the discharging phase). However, DCS measurements revealed a much wider temperature band for the melting phase. The manufacture datasheet did not provide an accurate depiction of the heat transfer curve, therefore, in order to use the PCM properties in the simulation, the following heat transfer curve has been generated from

DSC measurement. Figure 27 displays the PCM behavior from DCS measurements, which were used as PCM properties for EnergyPlus modeling.

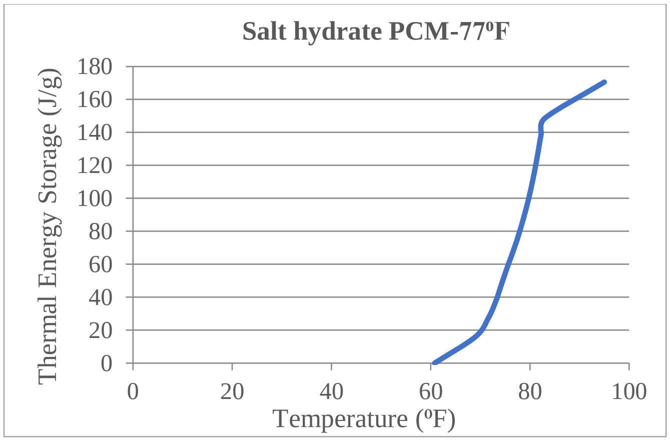


Figure 27. Thermal Energy Storage of the Salt Hydrate PCM from DSC Measurement

Calibration of the model with PCM

In order to calibrate the model that includes PCM, the schedule of the building was changed to match the actual energy consumption. Therefore, the calibrated model with PCM has a different schedule from the calibrated base model.

The authors calibrated the model with the PCM for April and May 2018, due to the constant schedule of the building during that time (76 ºF -80 ºF). Figure 28 and Figure 29 compare the energy consumption of the calibrated PCM model and the actual building with the PCM in one week in April 2018 and May 2018. The root mean square error of the PCM calibration model is 5.6 kWh from April 2018 until May 2018.

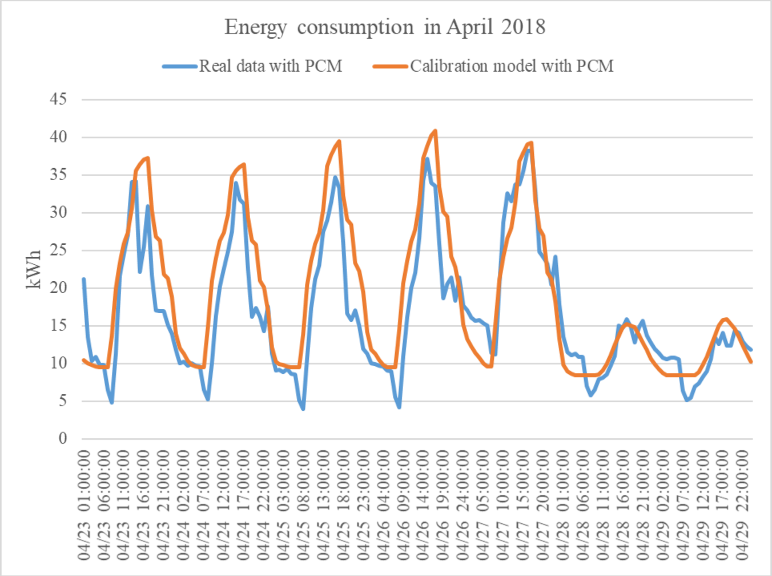


Figure 28. Energy Consumption of the Calibrated Model and Real Data with PCM in April 2018

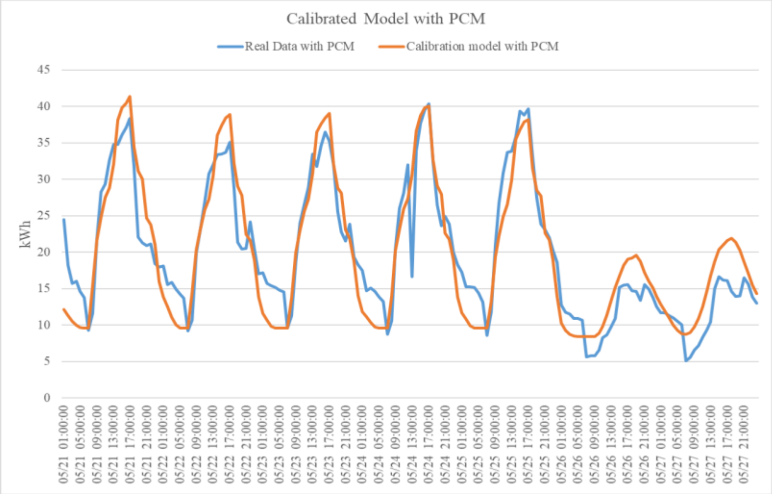


Figure 29. Energy Consumption of the Calibrated Model and Real Data with PCM in May 2018

Energy consumption of the building- comparison of different scenarios

The following figure (Figure 30) represents the energy consumption of the office building from June 2017 (prior the PCM installation) until August 2018 (PCM removal).

In this diagram, different operating cases, e.g., with PCM and without PCM, are shown. The energy consumption of the building is highest during the pre-cooling period. This consumption increase is due to the lower setpoint temperature of the HVAC systems.

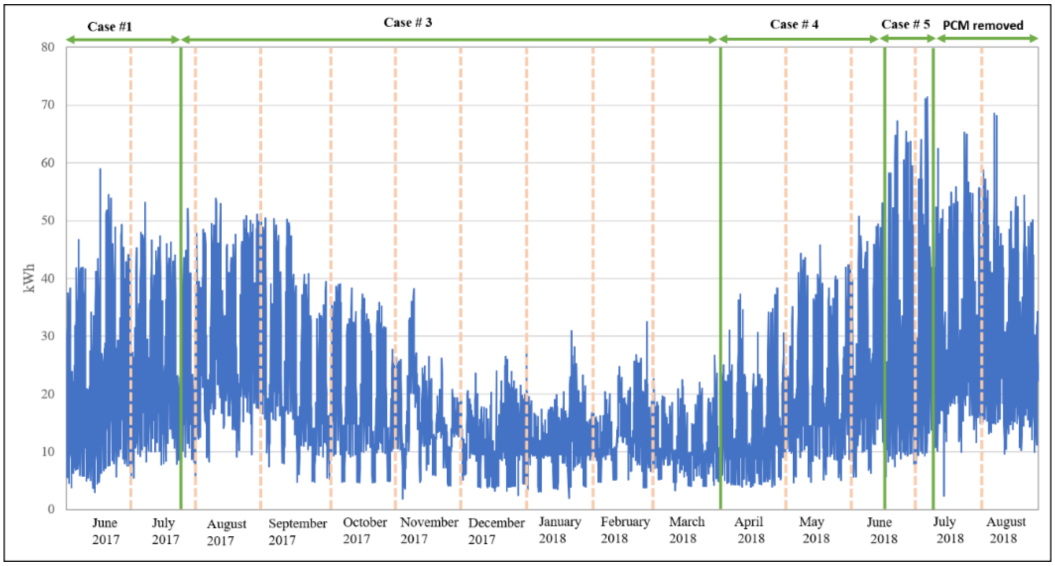


Figure 30. Energy Consumption of the Office Building from June 2017 until August 2018

Figure 31 represents the energy consumption of the building with the PCM from April till June 2018. In this period, the HVAC system in the building was operating between 76 ^{o}F for occupied and 80 ^{o}F for unoccupied schedule (Table 1). The energy consumption from the real data was higher than the simulation data, which was due to internal activities in the building. Also, the heat transfer algorithm in EnergyPlus simulation calculates a uniform convection between the PCM layer and the air, and this can lead to lower energy consumption than reality.

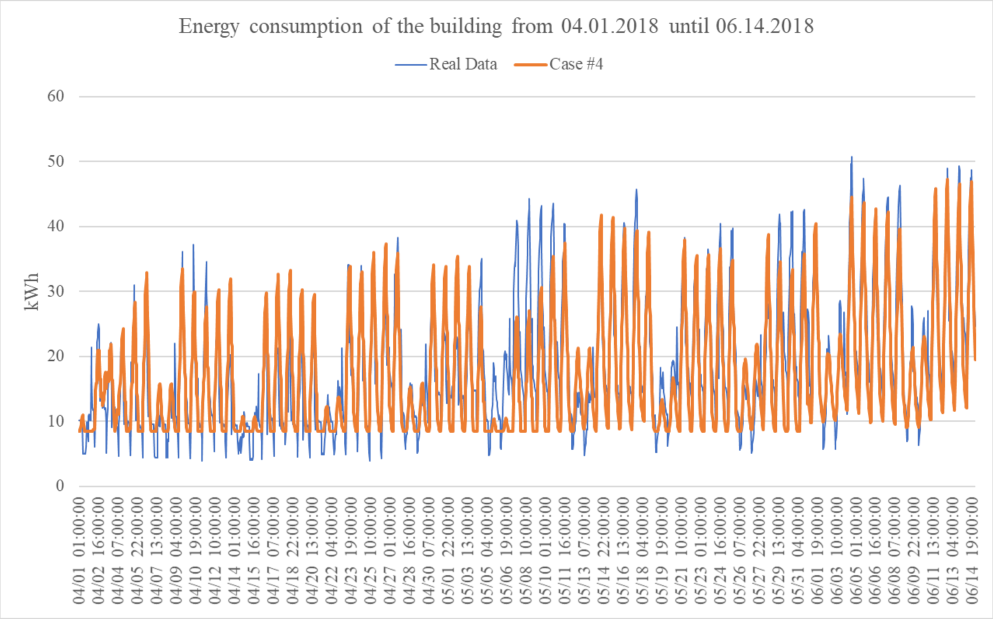


Figure 31. Energy Consumption of the Building from 04.01.2018 until 06.14.2018

In order to compare the effects of different temperature setpoint strategies and PCM installations, the electricity consumption for case #1, case #2 and case #4 have been plotted in Figure 32 alongside the actual data. The difference between the energy consumption of Case #1 and Case # 2 is due to a higher temperature set point in case #1 during unoccupied hours. There is no PCM in both cases. After installing a PCM (Case #4), the PCM’s effect was minimal, in terms of impact on energy consumption and time of day when the peak demand occurred (load shifting). Comparing actual data with simulation data illustrates that higher energy consumption when the PCM was installed in the building is not due to the PCM; rather, it is due to the updated setpoint temperature for the HVAC units. This result illustrates that this setpoint temperature was not the ideal for the building once PCM was installed, as this temperature scenario prevented the PCM from charging or discharging properly.

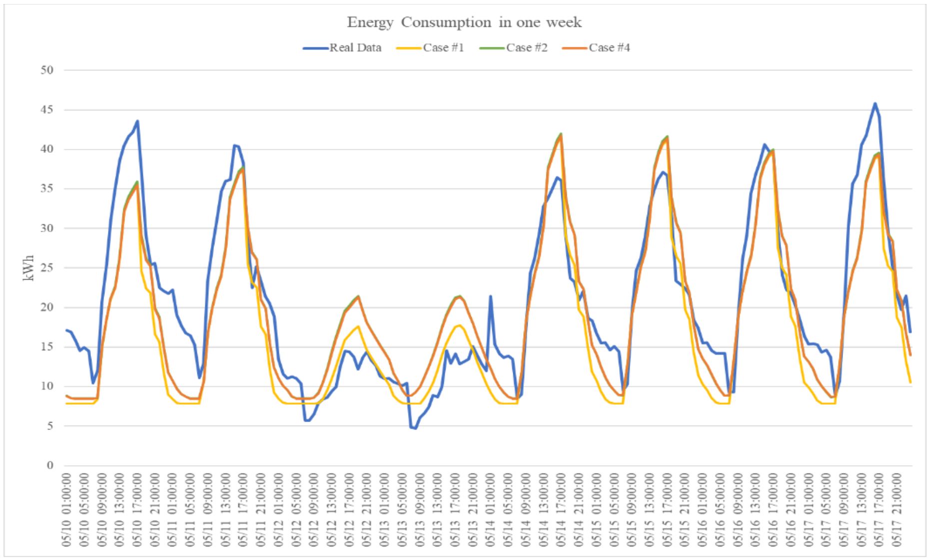


Figure 32. Energy Consumption of the Building in a Week of May 2018

Based on the constant HVAC setpoint temperature for the office building in April and May 2018, the authors compared modeled and actual data in these months. Table 16 lists the electricity consumption of each scenario and compares it to the base model. The modified HVAC setpoint temperature increased electricity consumption by 8.5% in April and 9.8% in May. Comparing electricity consumption of the building with and without PCM, Case#2 and Case#4, respectively, shows that PCM installation only decreases the energy consumption by about 1%.

Table 16. Electricity Consumption and Energy Saving of Different Scenarios in April and May 2018

	Electricity Consumption kWh			
Scenarios	**April**	**Saving %**	**May**	**Saving %**
Case #1 (Base Model)	9967.34	-	11800.61	-
Case #2	10820.19	-8.56	12960.23	-9.83
Case #4	10721.16	-7.56	12892.45	-9.25
Real Data	9872.97	0.95	14986.44	-27

In June 2018, the pre-cooling strategy (Case #5) was tested in the building to examine the PCM’s behavior during charging and discharging and to observe any load shifting during the day. The HVAC systems were operating between 72 ºF and 77 ºF to try to both freeze and melt the PCM twice daily.

A site visit during the pre-cooling period revealed that almost 50% of the PCM sheets in the south wing of the building were melted at 11:00 AM and the PCM sheets in the north wing were almost completely frozen. This discrepancy led the authors to further study this matter. After speaking to the maintenance team for the building, the authors discovered that the HVAC unit serving the south wing of the building was broken, leading to higher temperatures in the south wing of the building, and consequently, the PCM had melted.

Figure 33 shows the energy consumption in the pre-cooling phase. The energy consumption of the actual data was lower than the simulation data during this period. It should be noted that the actual data are the total energy consumption of three functioning HVAC units in the building and the results of the simulation (case #5) are the energy consumption of four HVAC units.

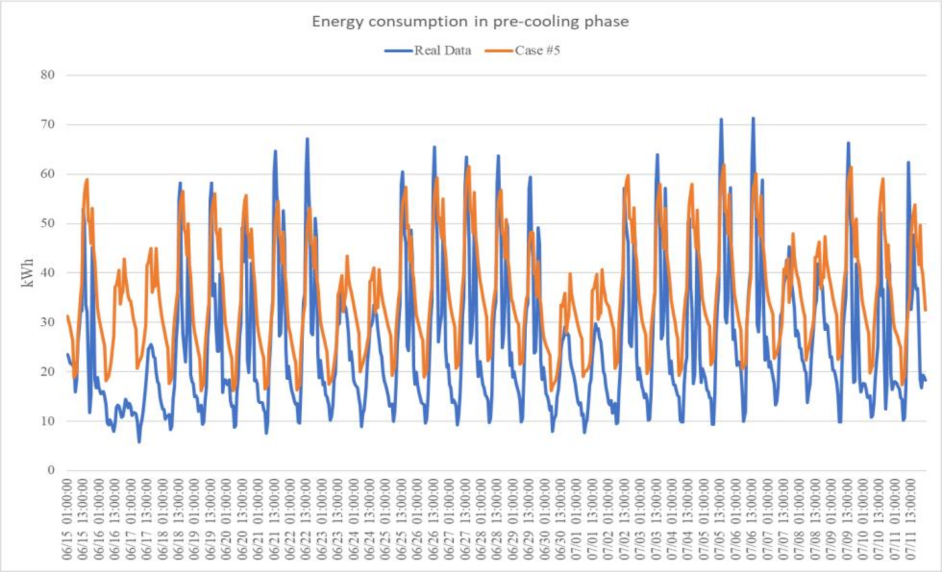


Figure 33. Energy Consumption of the Building during the Pre-cooling Strategy

Analyzing data from temperature loggers installed in the building showed some fluctuation in indoor temperature of the building. The indoor temperature from the data logger did not match the setpoint temperature of the HVAC systems. For example, the setpoint temperature in the pre-cooling phase had been set to 72 ºF or 77 ºF, depending on time of day. However, the temperature logger showed that the actual temperature often varied considerably from the setpoint temperature (Figure 34).

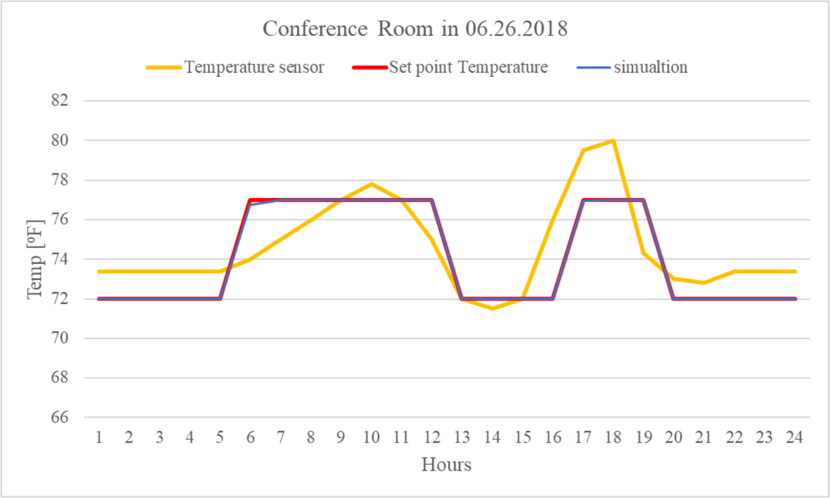


Figure 34. Temperature Profile of the Conference Room in the Pre-cooling Phase

Energy demand of the building

Weekdays

Figure 35 shows the average demand of the building in June 2018 when the setpoint temperature of the building was 76 ºF- 80 ºF. The peak difference between the actual data and base model (case #1) is 3.10 kW. However, there is only 0.3 kW between the peak demand of case #1 and case #3.

$\Delta\text{Peak}_{(\text{Real data, case \#1})} = 3.10$ kW (15 min delay)

$\Delta\text{Peak}_{(\text{case \#1, case \#3})} = 0.3$ kW (no time difference)

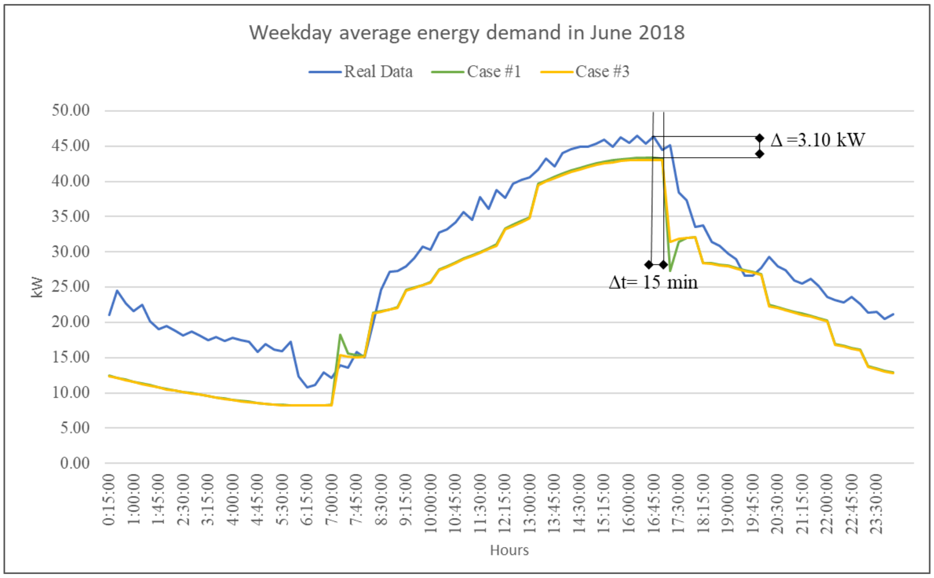


Figure 35. Average Energy Demand of a Weekday in June 2018 before Pre-cooling

Figure 36 represents the average energy demand between actual data, case #2 and case #4. In this diagram, all the setpoint temperatures are the same (76 ºF- 80 ºF). Therefore, through this diagram three cases can be clearly discussed:

1 Simulation model with setpoint temperature 76 ºF- 80 ºF without any PCM

2 Simulation model with setpoint temperature 76 ºF- 80 ºF with any PCM

3 Real data with setpoint temperature 76 ºF- 80 ºF with PCM

The peak demand difference between these cases are:

$\Delta \text{Peak}_{(\text{Real data, case \#2})} = 2.22$ kW (30 min delay)

$\Delta \text{Peak}_{(\text{case \#2, case \#4})} = 0.23$ kW (no time difference)

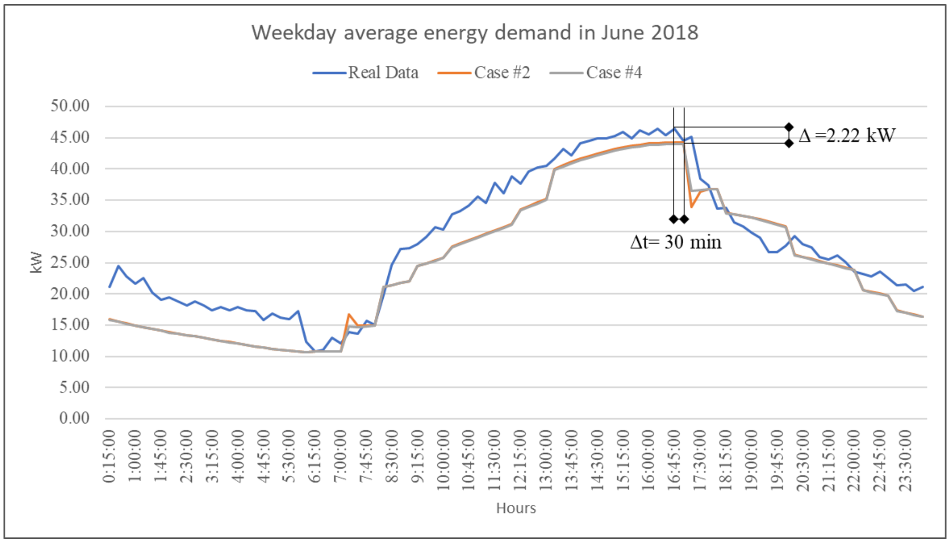


Figure 36. Average Energy Demand of a Weekday in June 2018 before Pre-cooling

Table 17 illustrates the maximum and minimum average value of the energy demand of different scenarios in a weekday.

Table 17. Minimum and Maximum Average Energy Demand in a Weekday in June 2018

	Real Data	**Case #1**	**Case #2**	**Case #3**	**Case #4**
Max kW	46.45	43.35	44.22	43.05	43.99
Min Kw	10.80	8.22	10.63	8.18	10.64

Weekends

Figure 37 and Figure 38 represent the average energy demand in a weekend of the building. Integrating PCM in the building had no effect on load shifting and had a minor effect of energy demand.

$\Delta\text{Peak}_{(\text{Real data, case \#1})}$ = 8.88 kW (30 min delay)

$\Delta\text{Peak}_{(\text{case \#1, case \#3})}$ = 0.22 kW (no time difference)

$\Delta\text{Peak}_{(\text{Real data, case \#2})}$ = 5.05 kW (30 min delay)

$\Delta\text{Peak}_{(\text{case \#2, case \#4})} = 0.16$ kW (no time difference)

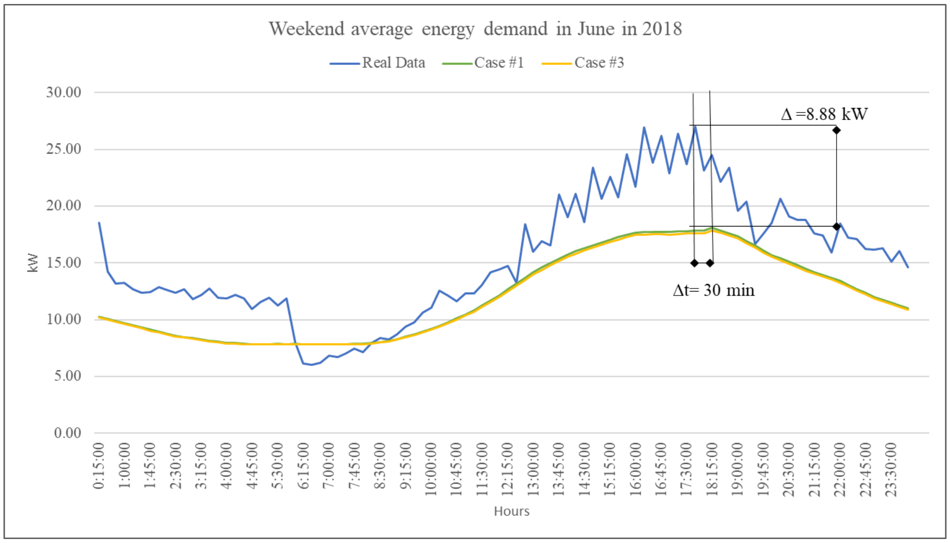


Figure 37. Average Energy Demand of a Weekend in June 2018 before Pre-cooling

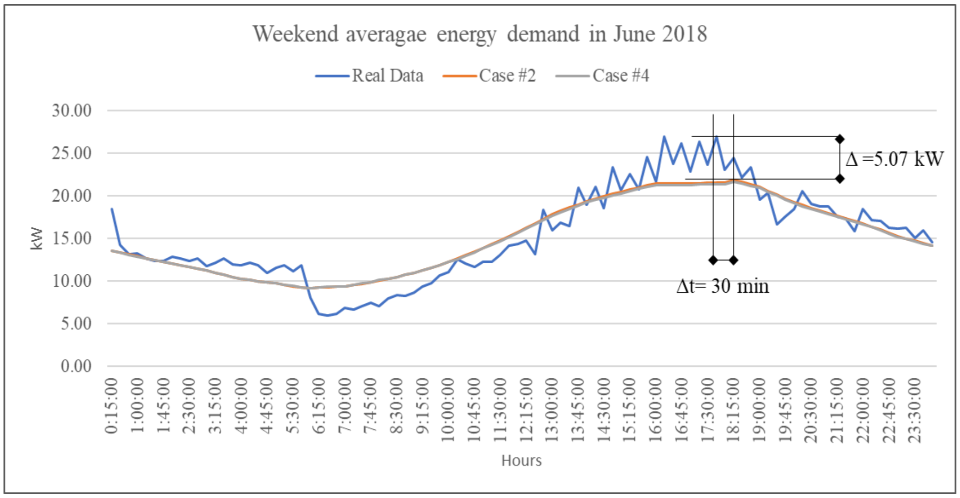


Figure 38. Average Energy Demand of a Weekend in June 2018 before Pre-cooling

Table 18 illustrates the maximum and minimum average value of the energy demand of different scenarios in a weekend.

Table 18. Minimum and Maximum Average Energy Demand in a Weekend in June 2018

	Real Data	**Case #1**	**Case #2**	**Case #3**	**Case #4**
Max kW	26.97	18.09	21.89	17.87	21.73
Min kW	6.01	7.84	9.15	7.81	9.17

Cost analysis

Figure 39 illustrates the building's price plan; the Time-of-Use Price Plan (TOU) is an optional price plan where electricity is priced at three different levels depending on the time of day — on-peak ($0.153/kWh), shoulder ($0.1039/kWh) and off-peak ($0.0537/kwh) pricing periods (SRP 2018).

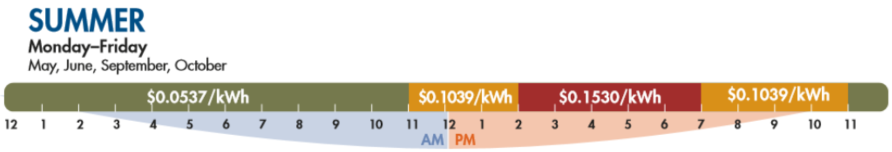


Figure 39. SRP's Time of Use Price Plan E-32 (SRP 2018)

The following table (Table 19) displays the energy price for each of the scenarios based on the average energy demand per day. The total price includes the price of off-peak hours, shoulder, on-peak period, on peak demand charge for maximum average demand and monthly service charge.

$$Total\ (\$) = (P_{peak\ demand\ charge} * E_{max,avg}) + (P_{Monthly\ service\ charge}) + P_{off\ peak} + P_{shoulder} + P_{on\ peak}$$

For the office building presented in this paper, the values for the above equation are:

$P_{\text{peak demand charge}}$ =$4.32

$E_{\text{max,avg}}$= maximum average demand in an hour

$P_{\text{Monthly service charge}}$= $22.08

Comparing the costs of cases #1 and #3, and cases #2 and #4, shows that PCM installation saves $0.25/day and $0.19 /day, respectively.

Table 19. Total Price of the Different Scenarios Based on SRP E-32 Price Plan in June 2018

	Off Pick $/day	**Shoulder $/day**	**on Peak $/day**	**Total $/day**
REAL Data	11.69	20.09	27.78	66.06
Case #1	8.24	17.16	24.37	55.71
Case #2	9.65	19.09	26.48	61.41
Case #3	8.17	17.05	24.35	55.46
Case #4	9.61	19.01	26.44	61.22

Conclusion

This paper presented data from a PCM installation in a commercial office building in a hot, arid climate. The paper presents laboratory data for the salt hydrate PCM installed in the case study building. Moreover, the paper compares simulated to actual energy performance for different temperature setpoint strategies. Results from this study illustrate that PCM behavior, particularly the temperatures at which the material will change phase, vary widely. In turn, this can lead to inconsistent energy performance.

This study also illuminated the need for rigorous pre-study of buildings prior to PCM installation. The case study building ultimately removed the PCM due to unsatisfactory performance. In particular, building owners should review energy consumption for at least 24 months prior to PCM installation to ensure that the building is a good candidate for PCMs. Specifically, the building’s energy performance should be predictable over the two years prior to PCM installation, and indoor temperature profiles should match set point temperatures. Similarly, building owners should review PCM performance data and select a melting point temperature that is well within their normal operating temperatures; this will support PCM installation that supports load shifting, which may in turn support energy cost savings.

Acknowledgement

This research is funded by Salt River Project (SRP). Their support is gratefully acknowledged. All views expressed in the paper are those of the authors and do not necessarily reflect the viewpoint of SRP.

CHAPTER 4

USING BIO PCM AS SENSIBLE HEAT STORAGE IN A HOT ARID CLIMATE: CASE STUDY

This chapter was accepted as a conference paper and will be published in the ASHRAE Transactions in July 2020. It appears exactly as published with the exception of text and figure formatting. The citation for this article is: Neda Askari Tari, M.N., Kristen Parrish, Using Bio PCM as Sensible Heat Storage in a Hot Arid Climate: A Case Study, in 2020 ASHRAE Annual Conference. 2020, ASHRAE Transactions Austin, TX.

Abstract

Using sensible heat storage (SHS) in buildings with high thermal mass can support energy efficiency; in retrofits, as well as in buildings with lower thermal mass, using SHS might not be feasible due to the lack of thermal mass required to maintain comfort in a volume of air (i.e., in a room within a building). Therefore, applying Latent Heat Thermal Storage (LHTS), such as Phase Change Materials (PCM), can be more effective to enhance these buildings' thermal behavior. PCMs have a high heat of fusion; during the phase change between solid and liquid, a large amount of thermal energy can be stored and released in these materials. This paper presents a detailed analysis of PCM behavior seen in sample retail buildings located in Arizona, a hot-dry climate. This paper presents the impact of air circulation in the plenum space, on PCM efficacy and energy performance. This paper comprises experimental work as well as EnergyPlus model

results to determine the factors that can increase the efficacy of PCM integration. In particular, results indicate that air circulation in the plenum promotes convection heat transfer between the air and the PCM sheets, resulting in reduced energy consumption. Finally, the paper evaluates cost saving potential for consumers, as well as the potential for peak load reduction for utility providers.

Introduction

Global energy demand is increasing due to global human population growth that causes not only the depletion of primary conventional energy sources but also higher CO2 levels in the atmosphere. According to the U.S. Energy Information Administration (EIA), in 2016, the U.S. accounted for 17% of the world's total primary energy consumption with only 4.4% share of the world’s population (EIA 2019). The residential and commercial building sector is the single largest consumer of the U.S. total primary energy, using 40% of the total primary energy leading to approximately 40% of the national CO2 emissions (Administration 2019, Energy 2019). Hence, energy consumption reduction in U.S. residential and commercial buildings would make a considerable impact on national energy consumption patterns and CO2 emissions. Existing retail buildings are one of the main energy end-users within the commercial sector in the U.S. with the second-highest amount of energy consumption (Joelle Davis 2000, OECD 2013).

Thermodynamic systems in buildings are complex systems that affect occupants’ comfort directly. The primary factor influencing the thermodynamic system in a building is the temperature differential between outdoor and indoor air. The required energy to maintain the comfort temperature is influenced by the building's envelope and the supply energy for heating, ventilation, and air conditioning (HVAC) systems (e.g., steam loop, chilled water loop). Building envelopes impact the internal loads, thermal resistance, and heat capacity of the building. Besides, HVAC systems consume a significant proportion of total energy in buildings (i.e. approximately 40%) (Energy 2013).

One method of reducing the energy consumption in buildings is to utilize Demand Side Management (DSM) strategies such as Energy Efficiency Measures (EEMs) (e.g., (Alvarode Gracia 2015). Improving the building envelope's thermal properties, and implementing technologies into buildings with active thermal components, increases energy performance and energy savings potential. However, improving the thermal mass of existing buildings is more challenging than new construction. In order to enhance energy performance when retrofitting existing buildings, a proper combination of retrofit design strategies, materials, and equipment should be applied (Edwin Rodriguez-Ubinas 2013).

Various DSM strategies such as building thermal mass (BTM) along with thermal energy storage systems (TES) have a large impact on the total energy consumption of buildings; they also offer potential applications for load shifting and peak demand reduction (Yongjun Sun 2013). TES systems are classified into Sensible Heat Storage (SHS), latent heat thermal storage (LHTS), and thermochemical reversible endothermic/exothermic reaction process (D. Zhou 2012). The heat is stored or released accompanied by the temperature change of the storage media in SHS, while heat of fusion/solidification during phase change processes is stored or released in LHTS. SHS in buildings with high thermal mass can be very efficient, but it is not a feasible method in retrofit and lightweight construction due to the volume of thermal mass (i.e., weight) required. Therefore, applying LHTS such as phase change material (PCM) can be more influential to enhance these buildings' thermal behavior. PCMs are compounds that liquefy and solidify at a specific point where the phase of substance changes. The substance captures excess heat through the building envelopes and releases it when the room temperature goes up and down respectively (in cooling mode). This process makes buildings more stable and energy-efficient by reducing temperature fluctuations.

This paper presents a case study of two retail buildings located in Arizona, each with PCMs sheets installed on the ceiling tiles. The purpose of this study is to compare the performance of the PCMs and the reduction of the energy consumption in buildings with and without air circulation in the plenum space.

PCM applications in buildings

PCMs' raw material can be divided into three main groups: (1) organic compounds, such as paraffin and fatty acids; (2) inorganic compounds such as salt hydrates and metallics; and (3) eutectics including a mixture of two organics, two inorganics or one organic and one inorganic material (D. Zhou 2012). In order to select a PCM for a specific application, the thermodynamic, kinetic, chemical and economic properties of the candidate PCMs, as well as the thermal properties of the building where the PCM will be installed, should be considered (Socaciu 2014).

Pomianowski et al. (Michal Pomianowski 2013) studied PCM application in buildings by focusing on the identification of proper methods to determine the thermal properties of PCMs along with their savings potential. The savings potential should be evaluated with respect to the relevant time span of PCM performance and climatic condition, especially when PCMs are integrated into the exterior envelope of a building. Aranda-Usón et al. (Alfonso Aranda-Usón 2012) performed a life cycle assessment (LCA) of PCMs to find out whether the correlated energy savings were significant enough to balance the environmental impact associated with manufacturing, installation, and disposal of PCMs. Waqas and Ud Din (Adeel Waqas 2013) offered PCM applications as an alternate HVAC system for buildings that provide environmentally friendly cooling and heating energy, due to the high thermal storage capacity of PCMs.

Koschenz and Lehmann (Markus Koschenz 2004) discussed TES systems in lightweight and retrofitted structures, where ceiling panels were introduced as the most appropriate location for installing TES systems. The microencapsulated PCM was embedded into the gypsum and poured into a steel tray, which was controllable by integrating water capillary tube system into the composite. In order to design such a thermally activated ceiling panel, the authors combined numerical modeling with TRNSYS software.

Using an EnergyPlus simulation single-zone model, Soares et al. performed a parametric study with the aim of exploring the validity of a single PCM-wallboard and found the impact of PCM-wallboard on the reduction of both cooling demand and peak-loads was on the order of 5% (Nelson Soares 2017).

Methodology

Case study methodology

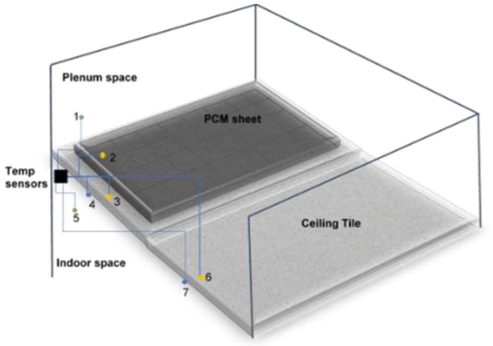
This research aims to explore the impact of Bio-PCM applications in existing retail buildings with different air circulation schemes in the plenum space. The authors have developed a methodology that highlights key factors in choosing PCMs as an EEM in buildings. Furthermore, this methodology uses both experimental and simulation modeling and compares the results, focusing on the impact of the PCM on the total energy cost reduction.

Energy audit and EEM saving potential. After analyzing and evaluating the historical data of two retail buildings, results showed that both buildings did not have a steady temperature setpoint schedule, nor an occupancy schedule prior to PCM installation. Therefore, developing and calibrating a base model without PCM was not possible. Also, having various setpoint temperatures in buildings proved difficult in making energy savings decisions and recommendations for PCMs. According to the Advanced Energy Retrofit Guide (AERG's) (PNNL 2011), analyzing the savings potential of the building should be compared to the baseline. However, in this case study, there were variable factors impacting the energy performance and energy consumption of both buildings. After integrating the PCMs into the buildings, the setpoint temperature schedule was set to remain under occupied and unoccupied mode, which gave the opportunity to evaluate the retail buildings under steady situation and to calibrate the baseline with PCMs integration.

It is proposed that for future projects with similar circumstances (i.e., unsteady schedules) or factors that can cause an imbalance to the system, building owners should consider a testing period before integrating PCMs. The testing period can be defined as a timeframe where factors such as indoor temperature, thermostat setpoint schedules during occupied and unoccupied periods, and light and equipment schedules are monitored and maintained steady prior to PCMs integration. By installing indoor temperature sensors, one has the opportunity to monitor the indoor temperature and compare the data with HVAC setpoint temperatures, as well as the data from the building management system (BMS). Validating data from both sensors and BMS data can prove that the building is operating as expected, and that the base model (or the model without EEMs) can be utilized for calibration. Nevertheless, if the results of the data comparison are not similar, then site visit analysis should be repeated in order to locate the source of disparity in the data streams. During the testing period, the effect of implementing the PCMs into the base model can be simulated and studied. The energy storage performance of the PCMs is directly related to the indoor temperature. Therefore, the setpoint temperature schedule of the building should be consistent; this facilitates selection of PCMs with an appropriate melting point. If the building operates with different setpoint temperatures, PCMs will be inefficient and, in some cases, will result in uncomfortable thermal conditions (temperature irregularities throughout the zones of the building).

EEM integration (PCMs) into the building. In this case study, BioPCM sheets with a 73.4 °F melting point were integrated on the ceiling tiles of both buildings. There had been no testing period prior to PCM integration. However, in order to monitor the

PCM behavior and collect data for the simulation and energy model, the research team installed two sets of seven temperature sensors, which can be seen in Figure 40. One set of the temperature sensors is used only for backup in order to validate the collected data from the first set of sensors.



# Sensors	Location
1	Above PCM Air Temp
2	Above PCM Surf Temp
3	Above Tile Surf Temp (W PCM)
4	Below Tile Surf Temp (W PCM)
5	Below Tile Air Temp (Indoor Air Temp)
6	Above Tile Surf Temp (W/O PCM)
7	Below Tile Surf Temp (W/O PCM)

Figure 40. Schema of the Ceiling Tiles with/without PCM Sheet with Temperature Sensors Locations

After analyzing the data presented, as well as the variable factors, it indicated that the energy performance, building's structure and location, ceiling material and thickness, as well as the mechanical and electrical systems of both buildings, should have been observed more carefully and with greater detail. In order to eliminate the unsteady and complex characteristics of the buildings, the cold and hot zones should have been inspected prior to the PCM installation.

Experimental Study

Buildings characteristics

Building A is a metal frame, one-story building containing seven heat pump units. The conditioned area of this building is 455.85 m^2 (4906.73 ft^2), and is comprised of seven thermal zones, each served by one HVAC unit without return air duct in the plenum space. Building B is a one-story, metal frame building, with two air-cooled packages and two heat pump units. The building has four thermal zones, each served by one HVAC unit. The total conditioned area of this building is 467.90 m^2 (5036.43 ft^2). The architectural features of these buildings were rendered using Google Sketchup and the energy modeling was completed in OpenStudio and EnergyPlus (Figure 41).

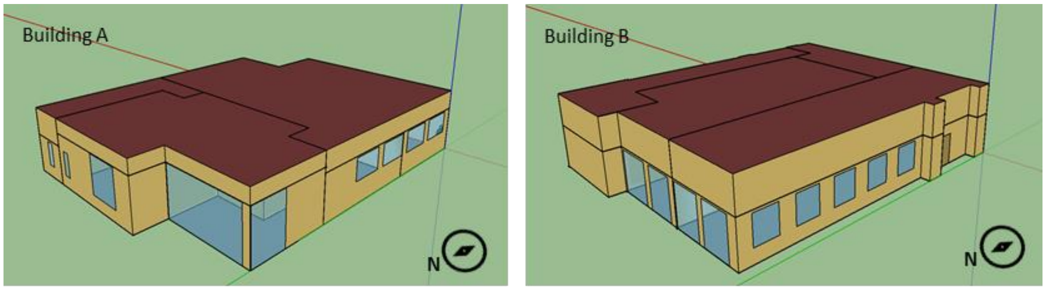


Figure 41. Sketchup Model of Building A and Building B in Arizona

The occupancy schedule along with the heating and cooling setpoint temperatures of both buildings are shown in Table 20. The temperature gradient in these buildings can vary up to 2 °F. However, BMS data showed that the zones in each of the buildings operated with different setpoint temperatures in different periods. BMS data was used for calibration and simulation in both models.

Table 20. Schedule and Setpoint Temperature of the Retail Buildings

	Occupied Monday- Friday	**Occupied Saturday**	**Unoccupied Sundays-Holidays**
Working hours	8:30-18:00	8:30-14:00	-
Heating setpoint temp	70 °F (21.11°C)	70 °F (21.11°C)	62 °F (16.67°C)
Cooling setpoint temp	74 °F (23.33°C)	74 °F (23.33°C)	83 °F (28.33°C)

BioPCM properties

The location of the PCM sheets is one of the leading factors having a direct impact on energy consumption. Likewise, PCMs sheets should be installed with care, and based on the manufacturer’s recommendations to minimize or eliminate penetrations. This will mitigate the risk of leaks after PCM installation has been performed.

Table 21 displays the BioPCM physical and chemical properties, which were used as PCM properties for EnergyPlus modeling (Solutions 2019). In this case study, authors used the CondFD model in the EnergyPlus software for phase change material simulations, which uses enthalpy-temperature information for the heating mode (Figure 42). Due to a lack of information from the manufacturer neither the hysteresis curve of the PCMs nor the subcooling curve during the discharge were used in the CondFD model. According to the U.S. Department of Energy, using the PCM temperature/enthalpy single curve in the EnergyPlus software may not generate the exact result compared with the PCM’s actual behavior during the melting and freezing phase (Welter 2017). Therefore, it is recommended to use “material property phase change hysteresis” in the EnergyPlus model.

Table 21. BioPCM Physical and Chemical Properties

	SI-Unit	**Imperial units**
Melting point	23 °C	73.4 °F
Latent Heat	210-250 J/g	90- 110 BTU/lb
Energy Storage Capacity	400- 1250 kJ/m²	35- 110 BTU/sqft
specific Heat	2.2 - 4.5 J/gK	0.6- 1.1 BTU/lb °F
Thermal Conductivity	0.15-2.5 W/mK	0.09-1.45 BTU/ft hr °F
Relative density	0.85- 1.4 g/mL	53- 87 lb/ ft3

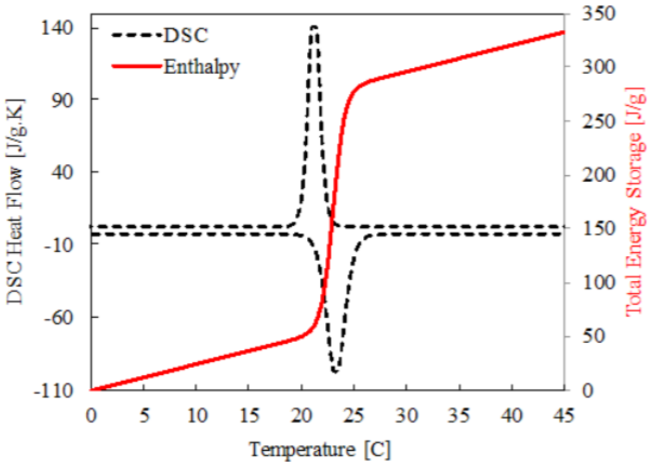


Figure 42. Thermal Energy Storage and Heat Flow of the BioPCM (Solutions 2019)

Results and Discussion

Calibration of models based on ASHRAE guideline 14

The calibration of the “Base Model” for both buildings was based on the hourly electricity consumption and building energy data with the PCM installation in 2018-2019 (Figure 43). In order to calibrate both models as close to reality as possible, BMS data was used as input data for the simulation. Both baseline models were calibrated for one year based on American Society of Heating, Refrigerating and Air-Conditioning

Engineers (ASHRAE) Guideline 14 (Aaron Garrett 2016) with 7.1% and 12.8% CVRMSE (Coefficient of Variation of the Root Mean Square Error) for building A and building B respectively. According to ASHRAE Guideline 14, the CVRMSE are below ASHRAE's suggested 15% threshold (Germán Ramos Ruiz 2017). Analyzing real data shows the average energy consumption of building B to be approximately 34% more than building A. This difference in energy consumption may be due to the lower Energy Efficiency Ratio (EER) of the HVAC units, or variability in internal loads between the buildings that were unclear to authors. Building A is located in an urban area; building B is located in a rural area. The ambient temperature in rural areas can decrease by 5° during the night, in comparison to an urban area. This decrease in temperature can improve the PCM's behavior in storing energy during the night and releasing it during the day.

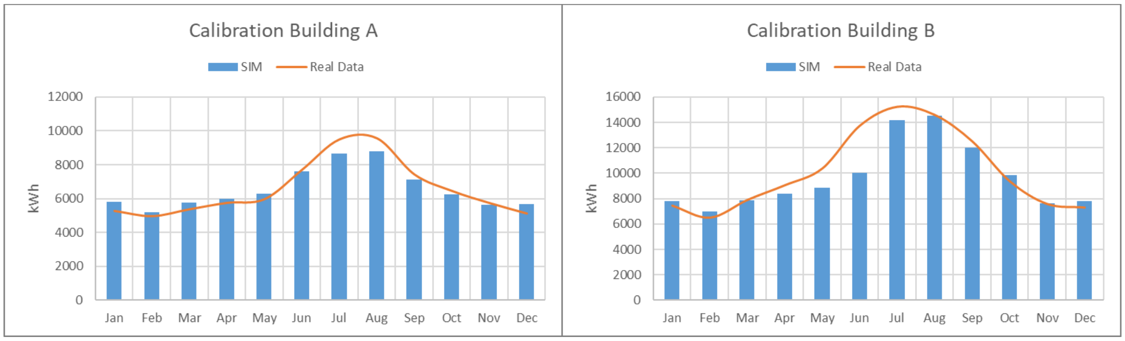


Figure 43. Monthly Electricity Consumption of the Calibrated Model for Buildings A and B

Indoor temperature analysis

Figure 44 represents the setpoint temperature from the BMS, average indoor temperature from simulation, and the data from temperature sensors in building A and B over a 72-hour period in May 2019. Figure 44 illustrates that the behavior of indoor temperature from simulation is dependent on the ambient temperature during the night when the setpoint temperature in the building is scheduled to be 83 °F. After monitoring the data from the temperature sensors and comparing them to the BMS data, results showed variable setpoint temperatures in building A. This indicated that the setpoint temperature was changed manually, although the setpoint temperature was scheduled to be steady throughout the year.

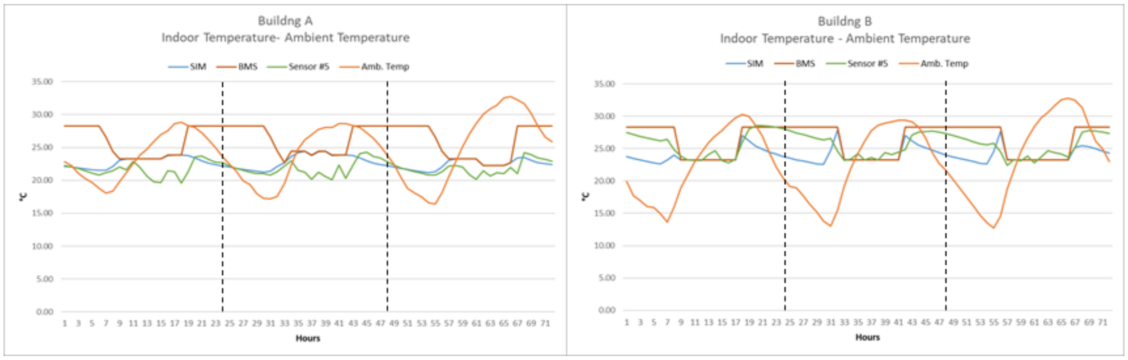


Figure 44. Temperate Profile of Building A and Building B during a Three-day Period in May 2019

Further investigation of building A showed that BMS data was not reading the correct temperature, as thermostats were placed in different zones throughout the building. Figure 44 shows the average indoor temperature from sensor #5 is lower than simulation data during peak hours in building A. This temperature difference was due to the location of this particular sensor, which was placed near the diffuser. Thus, the sensor was reading the discharge air temperature, rather than the indoor temperature of building A. Likewise, the data from sensor #5 showed a similar temperature profile from sensor #1 in building B, which authors attributed to sensor #1 being located very close to the ceiling tiles present there.

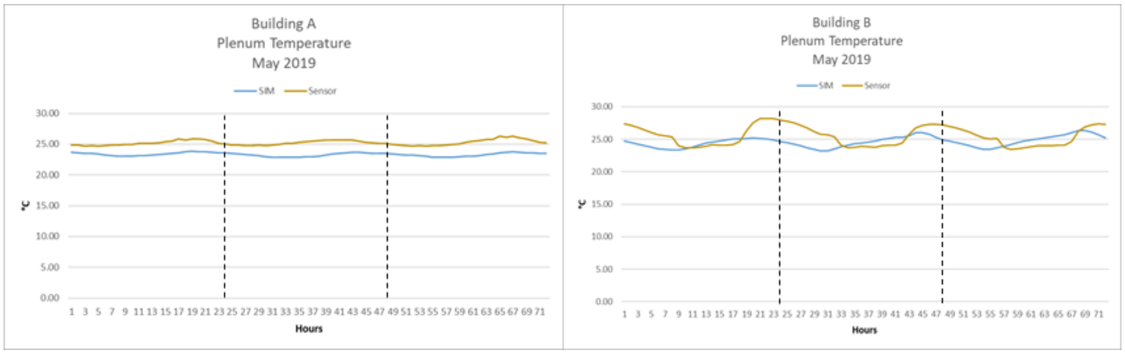


Figure 45. Plenum Temperature of Building A and Building B over a Three-day Period in May 2019

Moreover, data from sensor #1 (air temperature above the ceiling) in both buildings indicated that the location of these sensors was located close to the PCM sheets. However, this sensor should have been installed in the middle of the plenum space to read the average temperature above the PCMs. After reviewing and analyzing the data, the authors recommend that indoor temperature sensors be installed in more suitable locations throughout the building for more accurate measurement. Comparing the plenum temperature of the simulation to the data collected from sensor #1 illustrates more air fluctuation in the building using a return air duct (building B), which can improve the freezing and melting interval of PCMs (Figure 45).

Energy consumption of the buildings

Figure 46 represents the monthly energy consumption of building A and building B, with and without PCM integration. The return air duct in the plenum can improve energy savings (building B) up to 3% and it increases the efficiency of the PCMs overall. In fact, PCM installation decreased the energy consumption by a mere 1.5 % in building A. Figure 9 also shows that PCMs are more productive and efficient during the "shoulder seasons" (January through April and October through December). Therefore, if the goal of PCM installation is to reduce energy consumption during summer periods, then PCM integration may not be effective in hot-arid climates. In some cases, PCM installation may actually result in higher energy consumption during peak hours.

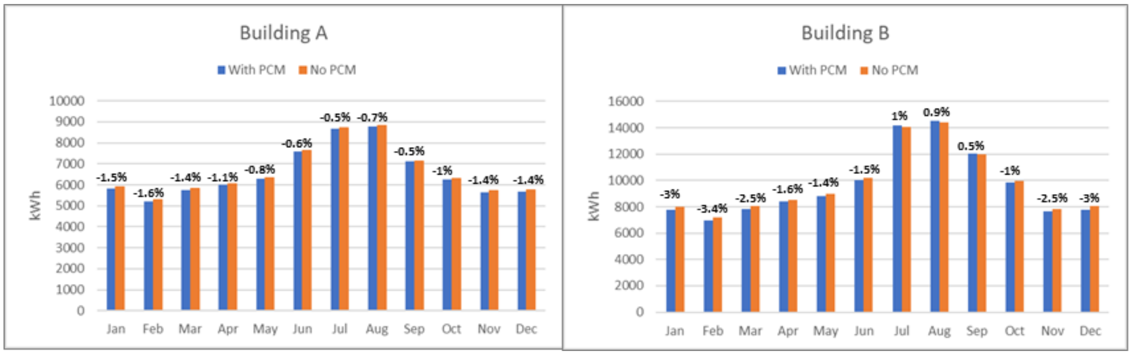


Figure 46. Energy Consumption of Building A and Building B with and without PCM

Cost analysis

Both buildings A and B use the tiered electricity pricing plan provided by Arizona Public Service (APS). E32-S price plan is available for non-residential buildings with a monthly load ranging from 21 kW to 100kW (APS 2019). APS presents its users with three different charges; a basic service charge, a demand charge for the average demand (kW), and an energy charge for total energy consumption (kWh).

In detail, the energy charge incurred in the summer months for the first 200 kWh/kW is $0.096/kWh and all additional usage is billed at $0.054/kWh. During the winter months, the user is charged for the first 200 kWh/kW at $0.08/kWh and all additional usage is billed at $0.04/kWh. The demand charge for the first 100kW is $8.49/kW. This study compares the cost savings using the APS rate schedule for both building A and B. After calculating and analyzing the energy demand (kW) and hourly energy consumption (kWh), it was noted that the peak demand in building A was reduced in upwards of 39% when PCM was integrated into the building. This reduction in energy demand resulted in a cost savings of $932.83 a year.

The reduction in energy consumption for building B was higher than that of building A; indeed, the PCM integration in building B reduced the peak demand up to 12%. This resulted in savings of $522 per year. This comparison illustrates that if the PCM integration does not affect the peak demand of a building, then the time of use plan will support greater cost savings than the tiered price plan. This approach not only increases the overall savings potential for utility providers, it will also give consumers the opportunity to save money during peak hours.

Conclusion

This paper presents data from a BioPCM installation in two retail buildings located in a hot and arid climate. The buildings sit in different areas of Arizona and were built using different construction materials and mechanical systems. After performing a detailed analysis of the results, one can see the need for a rigorous pre-study of the building’s characteristics, as well as a serious review of its energy consumption prior to PCM installation. Furthermore, PCM performance data should also be considered with respect to thermal comfort and the building’s operating temperatures. This study evaluates the impact of PCMs in buildings with and without an active plenum and demonstrates that integrating PCM sheets above the ceiling tiles in the building with a return air duct in the plenum space (an active plenum) increases energy savings up to 3%. However, the PCM integration reduced the peak demand in building A, which in turn supports energy cost savings. This study also indicates that PCMs do not have a significant impact on energy savings and reducing energy consumption in the summer period.

CHAPTER 5

A NOVEL PROCESS FOR SELECTING A PCM FOR A BUILDING ENERGY RETROFIT

Abstract

Retrofitting existing buildings shows promise for reducing energy consumption and greenhouse gas emissions. However, selecting the appropriate retrofit strategy(ies) requires careful planning, detailed information about a building's current condition, and evaluation of multiple retrofit options. One such retrofit strategy, using phase change materials (PCMs) as a relatively inexpensive means of increasing the thermal mass of an existing building, continues to be of interest to building owners, operators, and utilities alike. Despite the seeming ease of installation, a few primary factors need be considered before applying PCMs in existing buildings. This paper presents a novel process for selecting PCMs for building energy retrofits, comprising an evaluation of both the candidate building as well as the PCM. This process includes goal setting for the energy retrofit as well as the PCM installation, evaluation of an existing building to ensure that it is a good candidate for PCM integration, and finally analyzing the energy savings potential of PCM integration as a retrofit strategy. This process was developed based on results of multiple commercial building PCM installations as well as simulation results from residential buildings. The author presents how application of this process would have changed the choices made by stakeholders involved in the cases studied, thereby avoiding the undesirable results on these projects.

Introduction

Buildings account for more than one-third of the total energy use worldwide (Mehrdad Rabani 2017). The buildings industry in the United States consumes approximately 40% of the total U.S. energy consumption, and existing buildings are one of the main sources of carbon dioxide (CO2) emissions (Administration 2018). In 2016, Space heating and cooling in buildings accounted for approximately 30% of the total CO2 emissions in commercial buildings and 38% of the CO2 emissions in residential buildings (Leung 2018). Therefore, retrofitting buildings, and reducing the space heating and cooling demand in particular, is one effective means of supporting reduction in energy demand and carbon emissions.

Retrofitting existing buildings to reduce their energy consumption while simultaneously increasing their useful life requires planning. Building retrofit strategies can influence one or more of the three primary energy end uses: 1) the lighting system, 2) the HVAC systems, and 3) the plug loads (D. Kolokotsa 2009). Several workflows and processes in the architecture-engineering-construction industry aim to help building owners and operators identify the savings potential in buildings and collect information to support choosing Energy Efficiency Measures (EEMs) that will most effectively reduce energy, energy costs, or both in existing buildings (e.g., (Kristen Parrish 2013, Sawyer 2014, A.V. Androutsopoulos 2017)).

Research that focuses on improving the building envelope in commercial and residential buildings has become more common. Similarly, increasing the Thermal

Energy Storage (TES) in buildings has become a popular strategy to reduce energy demand and peak load, given its relatively low cost (R. Yin 2010). Integrating Phase Change Materials (PCMs) as latent heat thermal energy storage (LHTES), in particular, has gained popularity in the last decade, given the ability of PCMs to improve the thermal comfort, shift load and possibly reduce energy consumption (Vineet VeerTyagi 2007, Frédéric Kuznik 2011, L.F. Cabeza 2011, G. Evola 2013, Jisoo Jeon 2013). The purpose of integrating PCMs into buildings is to increase the thermal efficiency of the building with relatively low weight; indeed PCMs are cost-effective and have high specific heat and high density (Fabrizio Ascione 2014, Xing Jin 2014). During the freezing of a PCM, it can store energy that will be reduced during the melting phase (Lavinia Socaciu 2014).

Halford and Boehm developed a model to study the impact of PCMs on load shifting in the cooling season (C.K. Halford 2007). Evola et al. (G.Evola 2014) conducted a case study in which they evaluated the thermal comfort of a building in the summer after applying PCMs micro-encapsulated in thin drywall; they used EnergyPlus for their simulation. Berardi and Sousian (Umberto Berardi 2018) compared PCM integrations in high-rise residential buildings in two different locations in Canada and illustrated the effectiveness of PCMs in the shoulder seasons. Harland, MacKay et al. (Alice Harland 2010) describe that PCMs are most suitable for retrofitting commercial buildings (compared to residential buildings) due to the temperature and occupancy schedules in commercial buildings.

In addition to exploring the efficacy of PCM integration via case study and experiment (i.e., actual installations of PCMs), research also documents simulation results for PCM integration, using different PCM parameters and different software programs. Bourdakis et al. (Eleftherios Bourdakis 2017) studied the thermal comfort and also energy use impacts of integrating PCM panels on the ceiling of an office building via simulation. Saffari, Gracia et al. (Mohammad Saffari 2017) conducted a systematic literature review of PCM integration into buildings as a passive cooling strategy. This review documented that simulation of PCMs was often completed with EnergyPlus, TRNSYS, and ESP-r, with EnergyPlus being most common. Ferster et al. (Bronson Ferster 2017) used EnergyPlus to simulate PCM integration in South Texas and measure the energy savings . Soares, Costa, et al. (N. Soares 2013) explored how and where PCMs are applied in passive LHTES systems and investigate how these construction solutions are correlated to building's energy performance, using EnergyPlus, ESP-r, and TRNSYS software tools. In most case studies where EnergyPlus were used, the Conduction Finite Difference (CondFD) solution algorithm used a single temperature/enthalpy curve. However, the latest research shows that in order to model the PCMs performance such that the model behavior more closely relates to actual behavior, EnergyPlus requires two hysteresis curves, one that describes the PCM's melting phase, and another that describes its solidification phase (Welter 2017, Anna Zastawna-Rumin 2020). In addition, Berardi and Manco (Umberto Berardia 2017) studied the performance of PCMs in EnergyPlus; based on their results, they discovered that increasing the thickness of the PCMs in the simulation software improved the behavior of the PCMs in the model such that the simulation results better match the experimental results. However, they did not document a specific factor by which to increase the thickness in order to improve the simulation results.

Gap in the literature

Literature documents how PCMs integration into buildings impacts thermal comfort and load shifting; however, there is a lack of experimental results that examine the impact of PCM integration into *existing buildings* for energy savings purposes during cooling seasons. Furthermore, there is a gap in the energy retrofit planning literature, where the most commonly-cited process for selecting energy efficiency measures (Figure 47) does not consider PCMs as potential EEMs for existing buildings (PNNL 2011). Similarly, most PCM literature that presents experimental results does not discuss how the PCM installation team selected a building to install the PCM, nor does it discuss how a PCM was selected. This paper addresses this gap, and marries the energy retrofit planning and PCM bodies of knowledge to develop a novel process for selecting PCMs for building energy retrofits.

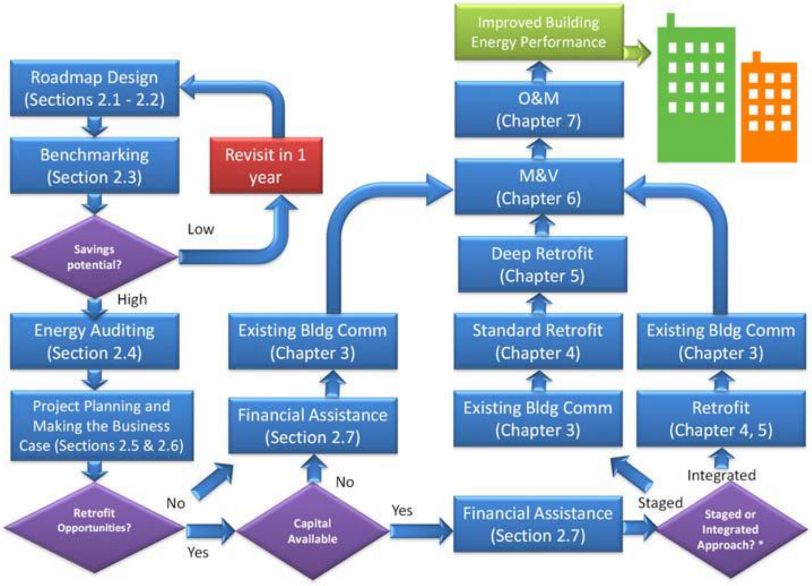


Figure 47. AERGs Planning Flow Chart for Existing Building (PNNL 2011)

This paper presents a novel process for including a PCM as an energy retrofit strategy in existing buildings. This process was developed based on literature review, case studies, and simulation results, and discusses how such a process can help building owners and operators determine: (1) whether or not a PCM is a good candidate for the building they plan to retrofit, and (b) how to select the appropriate PCM for that building.

Methodology

The author develops a novel process that supports selection of a building that is ideal for a PCM retrofit. To do so, the author first reviewed literature about PCM selection and building energy retrofits (described in the previous section). However, this literature review did not yield information about how to match PCMs to existing buildings considering an energy retrofit. Thus, the author took a multiple case study approach (Yin 2008) and compared six units of analysis (see

Table 22). This case study analysis illuminated lessons learned in each case study, and ultimately these lessons learned served as the basis for our proposed process.

Table 22. Comparison of Units of Analysis Across Case Studies

		Building information				**PCM information**	
Analysis	**Case study building**	**building cooling setpoint temperature (occupied-unoccupied)**	**Building construction / Insulation present**	**Plenum space**	**Energy consumption historical data availability**	**PCM melting point**	**PCM location/ Coverage (%)**
Experimental and simulation	Office	75°F-83°F (23.9°C -28.8°C)	Metal frame/No	no return duct	Dating back to 2011	77°F (25°C)	pitch roof and ceiling tiles ~70%
	Retail A	74°F-8°F (23.3°C -28.8°C)	Metal frame/ Yes	no return duct	Energy bills and smart meter data from 2016 - present	73.4°F (23°C)	ceiling tiles ~75%
	Retail B	74°F-83°F (23.3°C -28.8°C)	Metal frame/ Yes	active plenum, with return duct	Energy bills and smart meter data from 2016 - present	73.4°F (23°C)	ceiling tiles ~80%
Simulation	Residential A	75°F-82°F (23.9°C -27.8°C)	Wood frame/ Yes	no return duct	Energy bills and smart meter data from 2016 - present	73.4°F (23°C)	ceiling/ external wall ~95%
	Residential B	75°F-80°F (23.9°C -26.7°C)	Block frame/ Yes	no return duct	Energy bills and smart meter data from 8/2018 - present	73.4°F (23°C)	ceiling/ external wall ~95%

Case Studies

Office building

In the first project, salt hydrate PCMs with 77 °F melting point were integrated on the ceilings of a metal frame office building. The PCM was selected based on utility provider preference; the melting point temperature was based on the PCM manufacturer’s recommendation. This building had multiple pitched roofs with several different heights and four zones, each of which was served with a 15-ton capacity heat pump and the total conditioned area of this building was 840.86 m2 (9,051 ft2) (Figure 48). This building included multiple open office spaces, each with different heights, which resulted in unsteady air circulation and air flow.

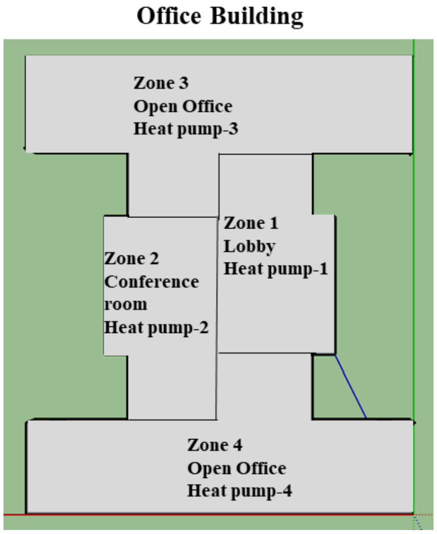


Figure 48. Thermal Zones of an Office Building

Early on in this project, it became clear that the PCMs were not supporting energy savings; moreover, they were leaking into the office and conference room spaces. Despite these challenges, this case study provided useful lessons learned:

- **Study the physics of the building,** specifically the insulation and building envelope prior to selecting the building for PCM installation. If the PCM will be installed on the ceiling of a building with a pitched roof, the airflow in the attic should be considered.
- **Collect historical energy consumption data for building for at least 2 years prior to PCM installation** in order to understand the energy demand profile and troubleshoot issues prior to installing the PCM. Historical data from this building, not considered prior to PCM installation, showed variable energy consumption through summer; not only did this illustrate unpredictable behavior in terms of

HVAC consumption, despite the constant temperature setpoint schedule, it also made calibration of the simulation difficult.

- **Choose a PCM with suitable melting point and conductivity** with respect to building's indoor temperature profile.
- **Install PCM sheets such that penetrations to the sheets can be minimized or eliminated.** This will mitigate the risk of leaks after PCM installation.
- **Select the appropriate location to install the PCM sheets**. Weak airflow above ceiling tiles results in low heat convection between PCM sheets and the air. Also, the thickness and conductivity of the ceiling tiles play an important role in the heat transfer between the indoor temperature and PCM sheets.
- **Install temperature sensors in different areas of the building to measure the indoor temperature and compare it to the outdoor temperature and the HVAC setpoint temperature**. This data collection helps illuminate any differences between indoor temperature and setpoint temperature of the HVAC systems. Also, installing temperature sensors on the PCMs sheets will provide data about PCM performance.

Retail buildings

Following the office building experience, for the second project, the physics of each of the retail buildings was analyzed prior to PCM installation. The retail building owner considered building physics for three buildings, A, B, and C, and decided not to install PCMs in Building C because Building C did not have a return air duct in the plenum space, while Building B did. The owner selected buildings A and B for PCM integration to compare the PCM behavior with respect to the building structure and air circulation system. The selected PCMs in both buildings were Bio PCM with 73.4 °F melting point. Figure 49 represents the process of choosing the buildings in this project.

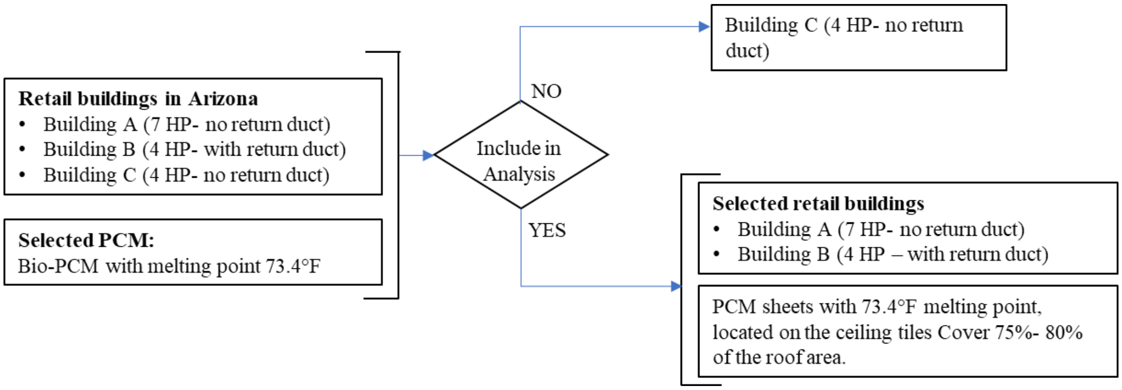


Figure 49. Flow Diagram of Choosing PCM in Retail Buildings

Building characteristic: building A and building B

Both buildings A and B were metal frame one-story buildings. The conditioned area of building A was 456 m2 (4907 ft2); it had seven thermal zones, each served by its own HVAC unit, without return air duct in the plenum space. The HVAC units in building B were two air-cooled packages and two heat pump units, which supplied four thermal zones with a total conditioned area of 468 m2 (5036 ft2) (Figure 50, Table 23). In both buildings, temperature sensors were installed to monitor the indoor temperature, plenum temperature, ceiling tile temperature and PCM temperature prior to analysis. The historical data, for two years prior to PCM installation, were studied for both of these buildings. Through an energy audit, the author discovered that both buildings were operating with variable indoor temperatures in different zones. Therefore, the energy consumption profiles of the buildings were different from one year to another. However, alongside integrating PCMs into the buildings, all the setpoint temperatures were fixed and scheduled to maintain the 74 °F-occupied and 83 °F-unoccupied schedule.

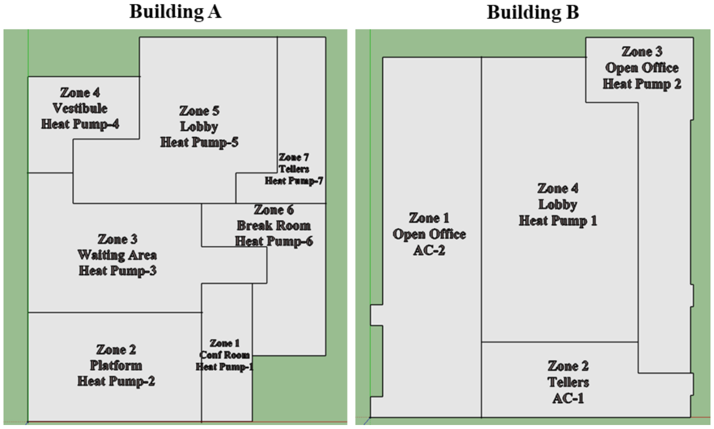


Figure 50. Thermal Zones of Building A and Building B

Table 23. Retail Buildings A and B HVAC Zones

Building A						
Zone	Zone Name	Area (ft2)	Height	HVAC System	CFM	Total Cooling (MBH)
1	Conference Room	327.15	10' 2"	Split HP-1	800	18.3
2	Platform	883.39	10' 2"	Split HP-2	1600	38.2
3	Waiting Area	1059.4	10' 2"	Split HP-3	1960	48.2
4	Vestibule	396.22	11' 4"	Split HP-4	1960	48.2
5	Lobby	1208.14	11' 4"	Split HP-5	1960	48.2
6	Breakroom Restrooms	599.07	10' 2"	Split HP-6	800	18.3
7	Drive-Up/Tellers	433.38	8' 6"	Split HP-7	1200	28

Building B						
Zone	Zone Name	Area (ft2)	Height	HVAC System	CFM	Total Cooling (MBH)
1	Open Office	1590.33	9' 6"	Air-cooled Package AC-2 Unit	2000	101
2	Tellers	628.28	9' 6"	Air-cooled Package AC-1 Unit	2500	76.5
3	Open Office	942.33	9' 6"	Package Outdoor Rooftop HP	1750	48
4	Lobby	1875.5	9' 6"	Package Outdoor Rooftop HP	1750	48

These installations, more successful than the office installation, yielded the following lessons learned:

- **Air circulation is critical for PCM performance.** The air circulation will have a considerable impact on PCM performance, so being aware of air circulation in the ceiling (in this case) is critical for predicting PCM performance
- **Energy Audits should be completed prior to PCM installation** to ensure that the as-built conditions are as expected from drawings or facility models.

- **Indoor temperature sensors should be installed prior to PCM installation** to ensure that PCMs will be cooled and warmed enough to change phase (i.e., store and release energy).

Residential buildings

In order to address building energy retrofits more holistically, residential buildings were analyzed in addition to commercial buildings. In particular, wood frame and concrete block single family homes were modeled, as these dwelling types represent about 70% of the housing stock in the climate zone studied (Zone 2B). The block frame single family home was one story, served with a Google Nest thermostat and a single HVAC unit; the wood frame single family home was two stories, served with a programmable thermostat and a single HVAC unit. Based on the previous case studies, the Bio-PCM with 73.4 °F melting point was selected for the simulation in both houses.

This case yielded the following lessons learned that informed the novel process:

- **The thickness of the PCM in a simulation should be at least 1 cm** to ensure that the simulation effectively freezes and thaws the PCM, regardless of the actual thickness of PCM installed.

Results

This section presents the proposed process for planning an energy retrofit that includes a PCM. This process provides requirements for selecting buildings as well as for selecting PCMs; it assesses their compatibility in six steps in order to realize the savings potential of PCMs. Figure 51 presents the proposed process, and the following subsections discuss each of the steps in detail.

Set Goals

The first step in implementing an energy retrofit with PCMs is to define the purpose of the energy retrofit (i.e., (US DOE 2011)) as well as the purpose of the PCM integration specifically. Generally speaking, PCMs can be applied in buildings for energy savings and reducing electricity costs and/or peak load shifting. In either case, building decision-makers should consider the thermal comfort of the building occupants, as well as the energy cost savings that PCM integration may support.

Select building

As with any building energy retrofit, a key element of the process is ensuring that the building selected for retrofit is a good candidate. This can be particularly important for PCM integration, as the PCM will amplify thermal behavior, which may turn out to be counterproductive. As such, reviewing building information and collecting historical energy data is a critical step in determining whether the chosen building is suitable for PCM implementation. In particular, decision-makers should consider:

- Building type (commercial, residential or industrial)
- Building construction parameters, including structural system material (e.g., wood frame, block frame, metal frame), insulation materials and location.

- Building location. The geographical information system (GIS) provides information about the building’s location and weather information. Weather and climate conditions impact PCM performance; climate extremes often pose challenges for the PCMs unless buildings are well insulated.
- After collecting general information about the selected building, the energy consumption data (kWh/month) should be analyzed for a minimum of two years if possible, using an ASHRAE LEVEL I audit. The more data about the building’s behavior and energy consumption, the more confidently building owners and operators can be in a PCM’s performance.
    - **ASHRAE Level I:** This is a simple analysis, including reviewing the monthly energy consumption of the building. The following parameters should be collected for a time period, and these data should be analyzed individually. The aim of this analysis is to observe the stability of the building’s schedule and performance.
        - Occupancy schedule; this provides information about occupied and unoccupied hours during the day, which allows the team to define a time frame to analyze the melting and freezing period of the PCMs in order to maintain the thermal comfort for the inhabitants.
        - Lighting and equipment schedule; this gives information about the numbers and types of various pieces of equipment and lighting in the building, along with their operating hours. This information

will help the team identify how much energy is consumed (kWh/m2) for heating and cooling systems.

- Building HVAC system; complete information about the mechanical system, including the number of heat pumps, chillers, fans, boilers (gas or electric), compressors, and other equipment, along with their efficiency ratio. This information will help the team to identify any changes or any anomalous energy consumption in the two years prior to retrofit.
- Number and location of HVAC zones in the building; this information helps the team to prioritize the location(s) for PCM installation. If the zones have different temperature schedules, that should inform PCM selection.
- HVAC setpoint temperature; this information dictates the appropriate PCM melting point temperature. The indoor setpoint temperature of different zones in the building during occupied and unoccupied hours should be analyzed and considered, in order to identify the storage potential of the PCM.
- Cold/hot spots in the building; detecting cold and hot spots in the building help to avoid PCM leaks or subfreezing. In some buildings, the indoor temperature of some areas will not reach the setpoint temperature, due to shading, proximity of supply ducts, or

other reasons. In this case, the PCMs will never melt, so PCMs should not be installed near these areas.

After reviewing the aforementioned data, building owners and operators can determine if the selected building is suitable for PCM integration or not. If the energy analysis shows that the building has energy savings potential with PCM installation, i.e., consistent heating and cooling demand over the past two summer and winter seasons, respectively, the energy audit can begin, as shown in Figure 51. However, if this data review suggests that the building will not achieve savings (either in terms of overall energy or peak load, as described in “Set Goals”, i.e., historical energy consumption data is erratic, another building should be selected. Poor insulation, erratic energy consumption behavior in the summer or winter period, and outdoor temperature extremes are parameters that decrease the efficacy of the PCMs, especially when they are used for load shifting.

Energy Audit

In order to analyze the energy savings potential of the selected building in more detail, an ASHRAE level II audit should be completed. This analysis leads to PCM selection for specific goals.

ASHRAE Level II: In this step, the energy consumption can be analyzed in more detail, of particular interest is analyzing the building energy consumption by end use; this helps to define the effect of the PCMs on reducing the HVAC energy consumption.

- Seek out submeter data for the building. This may be available from the utility provider if the building is equipped with a smart meter. If not, sensors can be installed to assist in collecting energy consumption data for each end-use. A second option is to break down the energy consumption by manually collecting the inventory of the plug loads and lighting systems (exterior and interior) in each zone.
    - The list of all type, number, and wattage of equipment such as computers, printers, toaster, coffeemakers, etc. should be collected.
    - The list of all types of lamps such as fluorescent, LED, Emergency light with battery, etc. included in the utility bill should also be collected as well as the number of fixtures and their wattage.
    - The total energy consumption from the equipment and lighting should be calculated based on their density (kWh/m^2). Thus, the energy consumption of the HVAC system will be determined by subtraction from the total energy consumption of the building.
- Install sensors as required to conduct measurement and verification of the baseline conditions within the facility. Of particular interest for PCM retrofits would be indoor temperature sensors that document the ambient temperature of each zone.

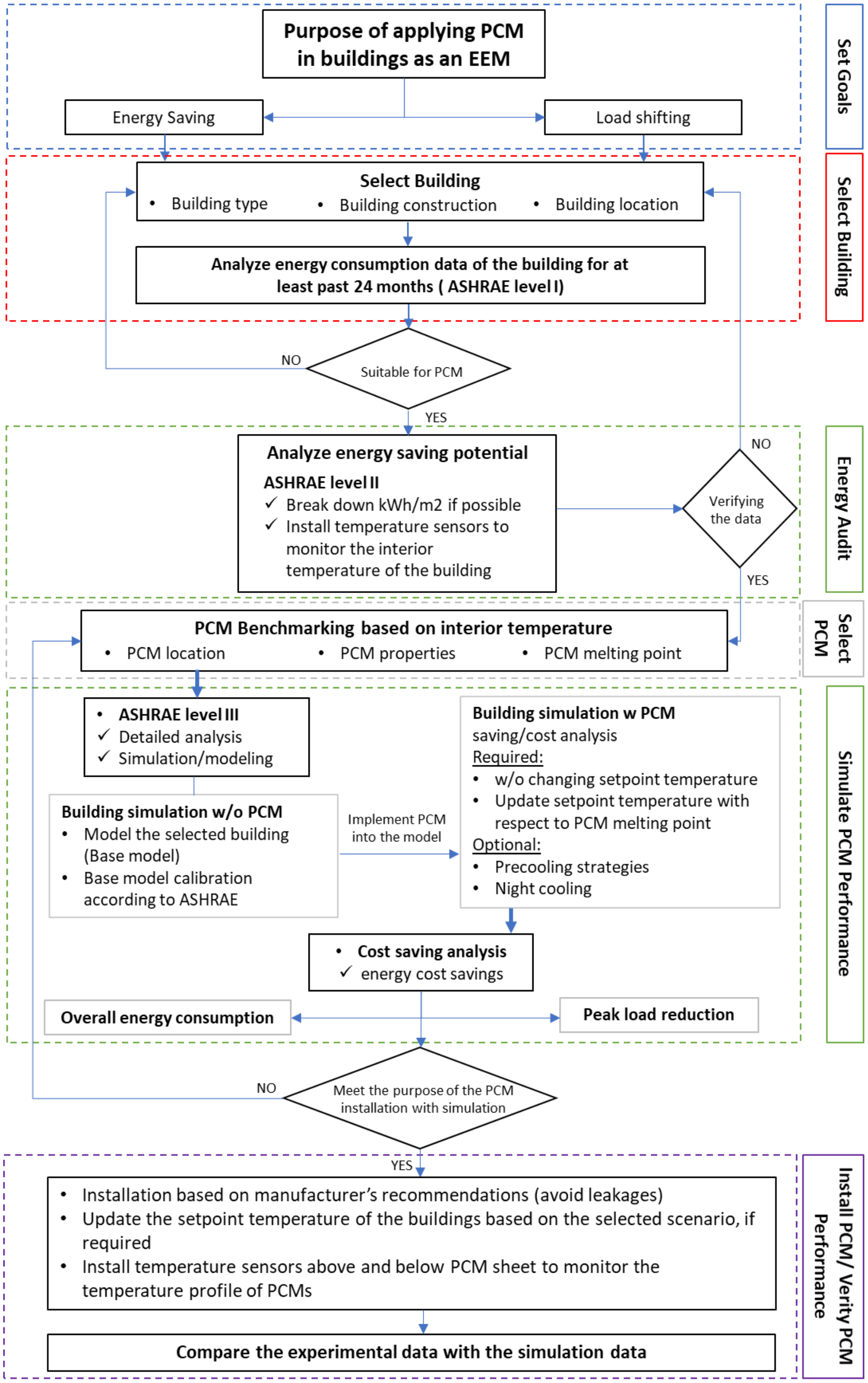


Figure 51. Proposed Process for Integration PCMs into the Existing Buildings

Select PCM

After evaluating the energy audit data, compare the temperature profile data to PCM data. This supports selecting a PCM that can freeze and melt each day, based on the curves provided by the manufacturer and their compatibility with the temperature profile in the PCM’s planned location. The important factors in selecting the PCMs are the PCM’s location in the building, the physical and chemical properties of the PCM, and the melting point of the PCM.

Simulation of PCM performance

Predicting the impact of PCM integration into the buildings requires more detailed analysis and developing energy models. The more detailed energy audit can be completed through ASHRAE Level III; in this audit, the thermodynamic building model can be created using the geometry documented in the building plans.

First, conduct a building simulation without PCM. The energy model should be created without PCMs. This model will be calibrated as a “Base Model;” it is evaluated with Root Mean Square Error (RMSE) and the accuracy should be analyzed according to the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Guideline 14. The calibration of the sample building can be based on the hourly comparison of electricity consumption (kWh) for at least two weeks, but it could be up to a year, depending on the goal of the PCM integration. If the objective is to shift peak demand in a particular season, data from that season should be used for calibrating the base model. Conversely, if the goal is overall energy savings, then a full year of data should be used for calibration.

Secondly, complete a building simulation that includes PCM. PCMs should be integrated into the calibrated base model, through the addition of PCM to the material layers in the building. Through simulation, different operating scenarios can be considered. It is recommended to simulate the building with PCMs without changing the setpoint temperature. However, after analyzing the data, the model can be changed if the setpoint temperature of the building needs to be updated to better leverage the PCMs, i.e., implementing precooling or night cooling. Ensure that thermal comfort of building occupants is maintained for each setpoint strategy. Simulation results will provide the energy savings potential. Using the simulated consumption along with the rate plan, the cost analysis can be conducted. This analysis provides information about the cost-effectiveness of the different operational strategies, i.e., precooling or night cooling. Finally, this simulation supports verification of goals. If the simulation illustrates total energy consumption reduction and/or peak load reduction, then it seems prudent to install PCMs. If not, another PCM should be selected or different strategies should be analyzed and simulated. These scenarios can be related to different setpoint temperatures in the building or changing schedule of the HVAC system with respect to the PCM’s melting point and comfort level of the occupants.

Install PCM and Verify PCM performance

To avoid PCM leaks, the PCM sheets should be installed based on the manufacturer's recommendations. The setpoint temperature of the building should be updated to reflect the schedule included in the "Simulation w/ PCM" model. After PCM installation into the building, in addition to the indoor temperature sensors, temperature sensors should be installed on the PCM sheet, in order to monitor the temperature profile of the PCM. These data will provide results to ensure that the PCM is melting and freezing as expected during the day. Finally, experimental results should be compared with simulation results, to verify PCM performance.

Discussion

Revisiting Case Studies

Reviewing Figure 51 for the Office Case study, it is clear that if the project team had considered historical energy data, they would have found that energy performance was anomalous in August of 2016 and 2017; hence, they would not proceed with PCM installation. In the event that PCM installation happened despite anomalous performance, the building setpoint temperatures would need to be updated to make best use of the PCM (i.e., "Updated Temperature Setpoint" in the "Install/Verify PCM Performance" box in Figure 51). Similarly, reviewing Figure 51 for the retail cases illustrates that a PCM would be selected and installed. However, if energy performance results were not as expected, despite ensuring alignment between modeled and actual operations, this would indicate a systemic error in the way PCMs are modeled and behave in the EnergyPlus environment. Indeed, studies with similar approaches (Umberto Berardia 2017, Umberto Berardi 2018) suggest that EnergyPlus does not match experimental PCM data unless the thickness of PCM in the model is increased to match the experimental performance. Further, Askari (Tari 2020) describes the actual melting process for PCMs, which occurs over a wider temperature range than is modeled in EnergyPlus. Finally, for the residential buildings, Figure 51 would suggest that PCMs will not be effective in the block home, as the ASHRAE Level I audit would reveal the home's erratic energy consumption during the summer peak period (due to Eco mode operation on the Nest). Conversely, in the wood frame home, following Figure 51 would result in a realization during the "Simulation with PCM" that PCMs in the ceiling would be largely ineffective in the home, suggesting that the homeowner should **not** proceed with installation in the ceiling.

EnergyPlus and PCM

In order to model and simulate PCMs in the EnergyPlus software, two hysteresis curves, one for melting and another for freezing, should be considered in the simulation (Anna Zastawna-Rumin 2020). However, most PCM datasheets from manufacturers provide only one temperature/enthalpy curve, which is used for monitoring the PCMs performance in real cases. Applying only one curve for both the melting and the freezing processes in the simulation will not generate accurate results in comparison with reality, as the heat transfer algorithm in EnergyPlus cannot define the phase change when the PCM is modeled with its actual thickness. As a result, if the PCM is modeled with its actual thickness and a single temperature/enthalpy curve, it will appear inefficient in the simulation results. As simulation and verification of PCM performance were presented in the proposed process, it is recommended to use two hysteresis curves in the EnergyPlus simulation to achieve precise results with minimum error.

Limitations

One limitation of this paper is that it is based on a small sample of five case studies. In order to validate this process, the author recommends collecting data from at least 30 buildings employing this process and tracking their energy performance. Their energy performance results would be compared to the results of PCM installations that did not implement this process. If the energy savings results are statistically-significantly different, that would be an indicator that this proposed process is effective. Alternatively, a panel of experts could review the process and a Delphi study could be conducted to validate the process.

Conclusion

In recent years, the interest in increasing a building’s thermal mass by integrating PCMs has emerged as a low-cost retrofit option. Many studies analyzed building energy consumption assuming that PCMs are integrated into the building envelope, typically in the walls; these studies generally involved micro-encapsulated PCMs and a moderate climate. Clearly, these results would be most applicable to new construction. Even when literature documented the efficacy of PCMs in a hot arid climate, they rarely considered

PCMs as a building energy retrofit strategy, either for load shifting or overall energy savings, and these studies did not discuss how buildings or PCMs were selected, let alone how these two decisions were inter-related. The process presented in this paper addresses these gaps and makes explicit how building owners and operators can determine buildings that would be good candidates for energy retrofits that involve PCM installation, as well as how to select the appropriate PCM to meet the energy retrofit goal(s).

This paper presented how the proposed process would change the decisions made in the different case studies that used PCMs as an EEM for building energy retrofits. In all these studies, PCM sheets were integrated on the ceiling tiles of the buildings located in Arizona, a hot-arid climate. Different scenarios were tested and results from the experimental analysis were compared to simulation results. Through each of the projects, the research team discovered different parameters and factors that impact PCM efficacy. Therefore, this process focuses on matching buildings and PCMs, a process that is not yet documented in literature. In particular, the author provides recommendations for selecting buildings that are good candidates for PCM integration first, and then how to choose the PCMs based on their chemical proprieties, melting point and the location where the PCM would be installed in the existing building in the event of a retrofit.

Collecting more information about the building’s annual energy consumption, thermal behavior and energy demand in the cooling/heating seasons contributes to precise decision making in choosing PCMs as EEM. Likewise, the goal of integrating PCMs into the existing buildings should be defined carefully. During the PCM solidification process, energy is consumed at greater levels during certain times of the day. Therefore, when setting a goal for energy consumption reduction, climate conditions and PCM thermal behavior should be considered. While PCMs may have a relatively low impact on reducing energy consumption in hot-arid climates, they can be effective in load shifting and improving the thermal comfort of the inhabitants.

CHAPTER 6

SUMMARY

This research aims to analyze the impact on peak demand of PCM integration into commercial and residential buildings in a hot arid climate. Studying the results of each of the case studies revealed primary factors that need to be addressed prior to PCM selection and installation.

Conclusions

Chapter 2 studied PCM integration into two single-family homes, one block and another wood-frame. This chapter addressed RQ1 and discussed the impact on load shifting of PCM integration into residential buildings. Results illustrated that PCM location and indoor temperature have a direct influence on PCM performance and achieving load shifting. This study showed that PCM integration resulted in reduced energy demand and load shedding, rather than load shifting. Furthermore, this chapter illustrated that integrating PCMs with proper thickness as energy retrofit measure is more effective on the ceiling in wood-frame homes. Results showed that PCMs can reduce energy consumption when they are integrated into the exterior walls in the block frame home; however, this strategy is not cost-effective for retrofitting an existing building. This EEM measure can be considered in new construction of block homes.

Chapter 3 analyzed the results of case study research in an office building with PCMs. This case study addressed RQ2 and discussed the impact on load shifting of PCM integration into commercial buildings. This study examined the PCM melting and solidification process and compared experimental results with EnergyPlus simulation results in different scenarios. Evaluating the results demonstrated that the effect of PCM installation was insignificant, in terms of reducing energy consumption and shifting load. In this case study, due to the discomfort of the occupants and PCM leaks in the offices and conference room, PCMs were removed. Building construction and insulation, HVAC setpoint temperature and historical energy consumption data were understood as key characteristics to consider prior to PCM installation. Assessing all these factors guide the engineers and researchers to choose the proper PCMs, in the event that the building is a good candidate for PCM integration. Furthermore, this chapter discussed the lessons learned that should be considered prior to PCM installation in any existing building.

Chapter 4 discussed the impact of PCM integration into two retail buildings with and without return air ducts (different plenum type), which addressed both RQ2 and RQ3. Based on the author’s previous experience, the building physics and construction, historical energy consumption, operating temperatures, and occupancy schedules were carefully analyzed before PCM installation, which resulted in better outcomes. In both buildings, BioPCM was installed and in order to monitor the indoor temperature and PCM performance, different sensors were installed. Collecting all these data gave the author better information about PCM behavior and their impact on load shifting or load shedding with respect to plenum types. The results of these case studies illustrated that integrating PCMs into a building without an active plenum (i.e., Building A) resulted in a greater reduction (39%) in the peak demand (kW), which led to greater cost savings (~$933/year). Conversely, the building with an active plenum (Building B) saved 5%

more energy (kWh) than Building A. However, due to the tiered price plan used in both of the buildings, the cost savings in Building A were higher than in Building B.

Finally, after reviewing the results of all the previous studies, the author developed a novel process to choose a building that would be a good candidate for PCM integration as well as the appropriate PCMs for that building. The proposed process aims to increase the compatibility of buildings with the selected PCMs and vice versa. Chapter 5 addressed RQ4 and RQ5 and presents factors critical for selecting PCMs, as well as for selecting buildings that would benefit from PCM integration in an energy retrofit. This proposed process would benefit from a validation effort, either through a comparison of energy performance of projects that do and do not implement the process, or a Delphi study. This chapter also addressed a gap in energy retrofit literature (lack of PCMs as energy efficiency measures) and a gap in PCM literature (i.e., using PCMs for energy retrofits). Furthermore, this chapter presented the gap between simulation software results and actual energy data, indicating that EnergyPlus software does not provide accurate results unless two hysteresis curves, one for melting and another for solidification.

Overall, this dissertation illustrates that retrofitting existing residential and commercial buildings in a hot arid climate via integrating PCMs will have a minor impact on load shifting and, in some cases, will increase energy consumption in the summer. However, the impact of PCM integration on energy demand reduction (load shedding) supports reduced energy consumption in the shoulder seasons. There are limitations in integrating PCMs into existing buildings that should be taken into consideration. The following factors were the important limitations that the research team confronted during the case studies:

- Low heat transfer between PCM sheets and ceiling
- Air gaps between the PCM sheets and the ceiling tiles
- Poor or no insulation on building roofs
- Lack of information and guidelines from manufacturers about PCM installation

Future Work

This research focused on PCM efficacy for energy retrofits in existing buildings. Much of the research explored how PCMs supported load shifting during the summer period in the Phoenix, Arizona metropolitan area. The results showed that in general, PCM integration into buildings has negligible impact on load shifting. The reduction of energy consumption can be up to 3% in a year; most of the energy savings occur in the shoulder seasons. In fact, the PCM’s effect on energy consumption may result in increasing energy consumption in the summer period. Likewise, integrating PCMs into existing buildings requires detailed information about the building and the PCMs, which can influence the early decision-making process.

The author highlights opportunities for future projects using PCMs:

- Utilize the proposed process (Figure 51, chapter 5) and refine it as required. Future projects can match buildings and PCMs based on the information about the building construction and historical energy consumption. After verifying the compatibility of the building, the proper PCM can be selected and installed. This process will save time and money for all of the collaborators in the project.

- Explicitly analyze the effect of PCM integration in experimental studies in shoulder seasons, rather than in the summer in a hot arid climate.
- Broaden the set of goals for PCM integration; include thermal comfort and load shedding as goals
- Better leverage PCM performance, explicitly using the wide temperature band for the melting/freezing phase.
- Focus on improving simulation analysis and software development, which will enhance the PCM energy modeling and will support more accurate data-driven decision making.
- Analyze PCM integration in different types of buildings, different locations in the buildings and in other climatological conditions.
- Charge the PCMs with a fluid other than air.

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