Phase Change Materials: Are They Part of Our Energy Efficient Future?

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ABSTRACT

Phase change materials (PCMs) are used in commercial buildings to save energy by actively absorbing and releasing heat. PCMs help maintain comfortable building temperatures and may reduce energy consumption in California and western climate zones with enough variation in day and night time temperatures.

This paper investigates current PCM market trends and assesses their future potential application in commercial buildings. The goal is to determine their efficacy in peak demand reduction and energy savings. Discussions with PCM manufacturers provided a better understanding of the technical potential and current market availability of PCM products. Evaluation of PCM products for certain applications determined their energy-efficiency potential. Comparisons were drawn to determine mass equivalents between PCM and conventional thermal mass, such as stone, concrete, and brick. In addition, temperature and sensible cooling profiles were developed for a prototypical building based on energy simulations using EnergyPlus. Next, it was determined which climate zones were most appropriate for PCM installations. This was based on the day-to-night temperature variation required to regenerate a phase change.

PCM applications considered in this paper include micro-encapsulated PCM wall board, floor tiles, and ceiling panels; interior wall installation; attic installation between ceiling joists; and drop ceiling plenum installation. This paper discusses the technical potential for such applications in Southern California. PCM can potentially save 10-30% compared to existing cooling energy consumption. This correlates to a technical potential energy savings between 335 and 1,005 GWh/year.

Introduction

Phase change materials (PCMs) are materials that store and release latent heat. When used for building applications, the latent thermal storage capacity of PCMs can be used to offset cooling and heating loads in a building. Typically, PCMs store heat by undergoing a solid-liquid phase transformation.

With energy demands forecasted to rise over the coming decades, new energy saving technologies are essential to minimize the need for new power generation. The California Long Term Energy Efficiency Strategic Plan (CLTEESP) further stresses the advancement of energy-efficient products by outlining goals to reach zero-net energy for all new construction residential homes and reduce energy consumption in existing residential homes by 40% by 2020 compared to 2005 Title 24.[1] Additionally, CLTEESP has a goal for all new construction commercial buildings and 50% of existing commercial buildings to reach zero-net energy by 2030 compared to 2005 Title 24 (CLTEESP 2008). To support these goals, Southern California Edison's (SCE)

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[1] 2005 revision of Part 6 of Title 24 of the California Code of Regulations, the Energy Efficiency Standards for Residential and Nonresidential Buildings.

Emerging Technologies Program evaluates emerging energy-efficient technologies for adoption into utility incentive programs.

The objective of this paper is to assess the technical potential[2] of PCMs for reducing the cooling load in commercial buildings.

Background

Thermal energy storage in buildings comes in two forms: sensible heat storage (SHS) and latent heat storage (LHS). SHS systems charge and discharge energy, or heat, by using the heat capacity of the material and a corresponding change in temperature. Conversely, LHS systems charge and discharge energy by undergoing a phase change. LHS systems have a higher energy density and maintain near-constant temperature throughout the charging and discharging process.

PCMs have been studied for decades (Castellon et al. 2007). Various materials have been considered for building applications, such as paraffin wax, bio-based organic materials, and eutectic salts, to take advantage of the PCMs' latent heat capacities and high storage densities (Zalba et al. 2003). Unlike conventional thermal mass, such as concrete or adobe, PCMs store similar amounts of heat with significantly less mass. PCMs maintain a near-constant temperature within the conditioned space while undergoing a phase change. Melting temperatures typically range from 70 to 80°F in building cooling applications. This temperature range is varied based on application and designed to minimize the heating and cooling loads for the building while maintaining occupant comfort.

For a solid-liquid PCM product, once the temperature surrounding the PCM rises to the melting point, the PCM will absorb the heat as it melts and maintain a near-constant temperature until it has fully melted. Most of the energy in the PCM will be stored until the local temperature falls back to the melting point, at which time the PCM will discharge heat, maintaining the temperature of the space until it has fully solidified. Figure 1 depicts this process.

PCMs can be packaged in micro- or macro-encapsulated cells for application in interior wall construction (adjacent to insulation and wallboard), between attic joists, above ceiling panels in a drop ceiling, or integrated directly within wallboard, ceiling panels, and floor tiles.

Several issues have hampered PCM throughout the years. Early products embedded PCM directly into wallboard or cement causing stratification within the PCM. Newer products mitigate this by encapsulating the PCM (Demirbas 2006). In addition, potential fire-hazards exist in PCMs (Roth, Westphalen & Brodrick 2007). Fire retardants are often added to reduce fire hazards. However, this inhibits thermal performance (Feustel, Stetiu 1997).

In a 2009 study by Oak Ridge National Laboratory (ORNL), EnergyPlus was used to simulate application of PCM in a single-family ranch-style home based in Atlanta (Kosny et al. 2009). Results of the simulations showed about a 10% annual reduction in wall cooling and heating loads for the building with bio-based PCM-enhanced exterior walls. Additionally, a simulated PCM-enhanced attic floor with R-38 insulation showed a potential 14% reduction of annual loads generated by the attic, resulting in the equivalent to approximately R-58.

Moreover, Arizona State University experimentally measured a reduction of 30% in annual cooling energy for a 192 square-foot (sf) shed with bio-based PCM compared to a shed without PCM (Muruganantham 2010).

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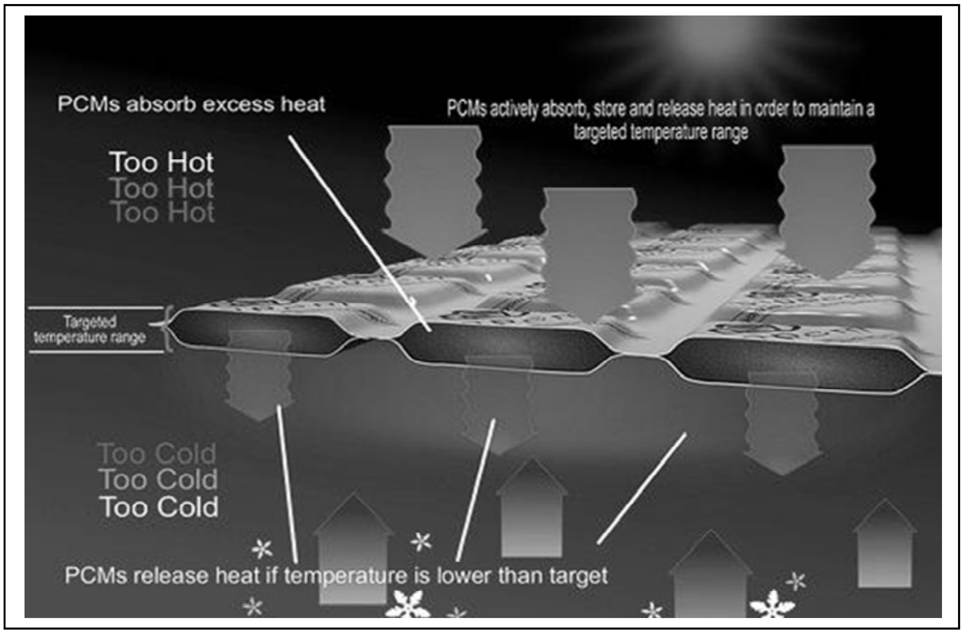
[2] Technical potential is defined as the amount of energy savings that would be possible if all technically applicable and feasible opportunities to improve energy efficiency were taken (CPUC 2011).

Figure 1. How PCM Works



Source: Phase Change Energy Solutions et al. 2012

Analysis

The technical potential was determined from literature research, EnergyPlus simulations, local climate data, and existing building stock information. This analysis focuses on Southern California Edison's (SCE's) service territory. Discussions with key industry stakeholders, including PCM manufacturers, were conducted to provide focus and insight to this study.

PCM Products and Applications

Despite decades of study, there is still uncertainty surrounding the practicality of PCM integration into building construction. There are several approaches for implementing PCMs in buildings. Table 1 lists potential PCMs and their applications analyzed in this paper.

Table 1. List of Phase Change Materials and Applications

PCM Product	Application
Micro-encapsulated Paraffin Wax	Wallboard
	Ceiling Tile
	Floor Panel
	Interior Wall Construction
Bio-based (Organic) Materials	Interior Wall Construction
	Attic/Drop Ceiling Plenum Floor
Eutectic Salt Mixtures	Interior Wall Construction
	Attic/Drop Ceiling Plenum Floor

Sources: Phase Change Energy Solutions 2011, Jaworski, Abeid. 2004, The thermal properties of a select number of PCMs are displayed in Table 2. These properties are based on manufacturer's published documentation, when possible.

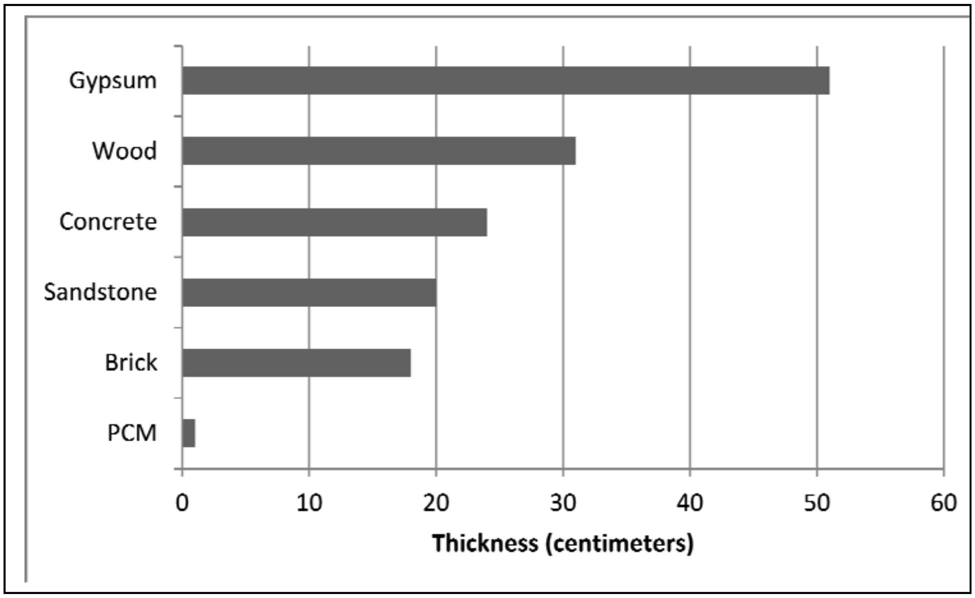
Table 2. Properties of Select PCM Products

PCM Product	Melting Temperature Range (°F)	Heat of Fusion (Btu/lb)
Micro-encapsulated Paraffin Wax[1, 2]	73	75
Bio-based (Organic) Materials[3]	73-79	71-86
Eutectic Salt Mixtures[4]	77-80	55-81

Sources: 1. Thermal Core 2012, 2. Demirbas 2006, 3. Phase Change Energy Solutions 2011 4. Zalba et al. 2003

Figure 2 shows the required thickness for conventional materials used in building construction to match the equivalent heat capacity of a one-centimeter-thick PCM with a heat of fusion of approximately 70 Btu/lb (Konstandtinidou 2010).

Figure 2. PCM Thickness Compared to Conventional Thermal Mass



Source: (Konstantinidou 2010)

The high energy storage density of PCMs allows for the incorporation of thermal mass into wood framing and other lightweight buildings without compromising the original design. Certain PCM applications, such as placement of PCM on the plenum floor of a drop ceiling, can be implemented without major renovation.

Strategies should be implemented to fully optimize PCM's impact. Strategies to enhance PCM's impact include using the HVAC system to regenerate PCM, running the cooling system off-peak, and economizing during cooler nighttime temperatures. More complex active strategies may involve integrating PCM directly with the HVAC system, such as placing PCM in ductwork, or developing control systems to continually charge and discharge the PCM.

Currently, PCM use in Southern California is limited to a few pilot installations. Local climate, building type (design, construction, orientation, etc.), PCM properties, HVAC system, and customer economics must be considered when installing PCM products in a commercial space. It is anticipated that the initial markets prime for PCM installations are those with diurnal swing characteristics that will aid in passively charging and recharging the materials.

Energy Simulations

Simulation models are useful tools due to the many variables and input parameters required to estimate energy consumption and demand for buildings with PCM products. EnergyPlus was used as the simulation tool for this study because of its ability to simulate PCMs (Pederson 2007). Other simulation engines, such as DOE-2, do not have built-in algorithms to model PCM. This makes modeling of latent thermal storage difficult.

A 1,250 sf commercial office building was simulated in California's climate zone (CZ) 13. This location was chosen due to its hot summer days with nights cool enough to assist in recharging the PCM. There are 16 such CZs in California as identified by the California Energy Commission (CEC 2011). The simulated building had brick and steel framing and a 30% window-to-wall ratio. The control strategy was designed such that the HVAC system would cool the space to 68°F and then allow the temperature to rise to 75°F prior to cooling again. The PCM simulated was micro-encapsulated paraffin wax embedded in wallboard with a melting temperature of 73°F.

Figure 3 shows the outside dry-bulb, exterior surface and inside surface temperature profiles for a one-week span for the building without PCM. The first two peaks are weekend days.

Figure 3. Temperature Profiles of Building in CZ 13 without PCM

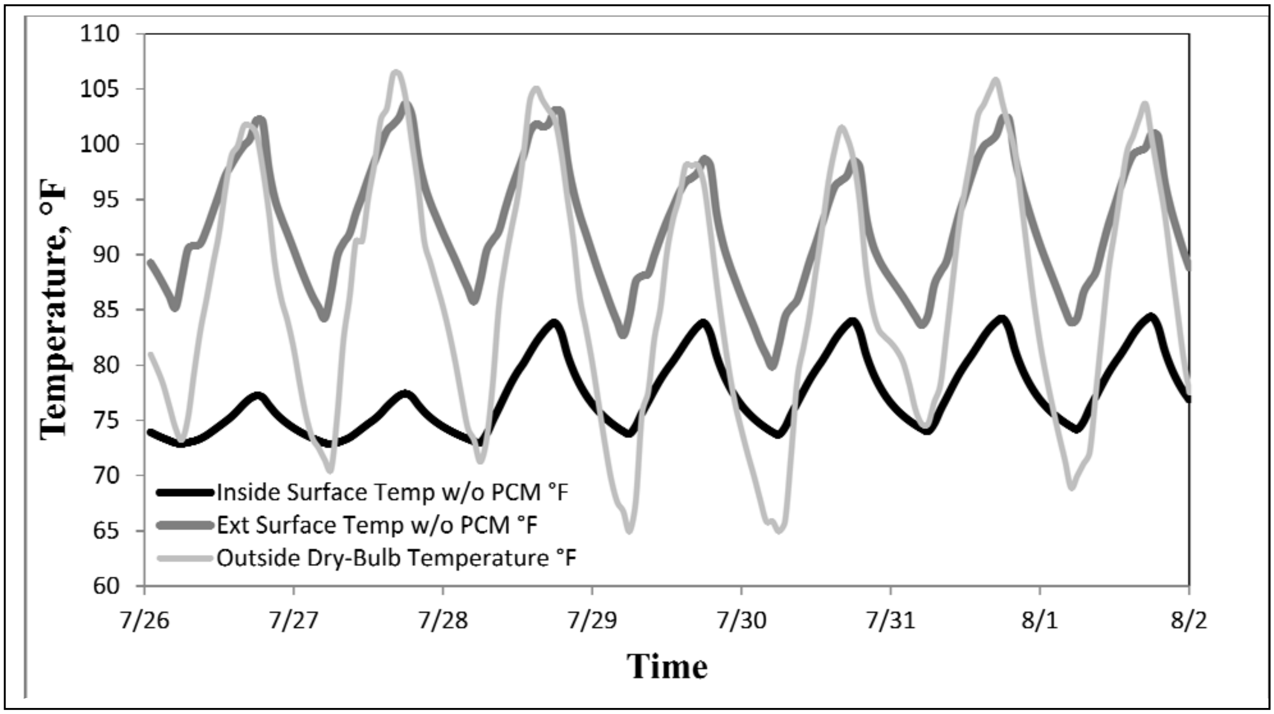


Figure 4 shows the inside surface temperature profile comparison for the same building with and without PCM. There is a noticeable decrease in temperature swing in the PCM curve compared to no PCM. The PCM looks to be fully discharged (melted) at 77°F as evident by the increase in temperature gradient above 77°F. The PCM never fully recharges since temperatures drop below the melting point for a significant amount of time, which the limits PCM’s capacity.

Figure 4. Temperature Profile Comparison with and without PCM

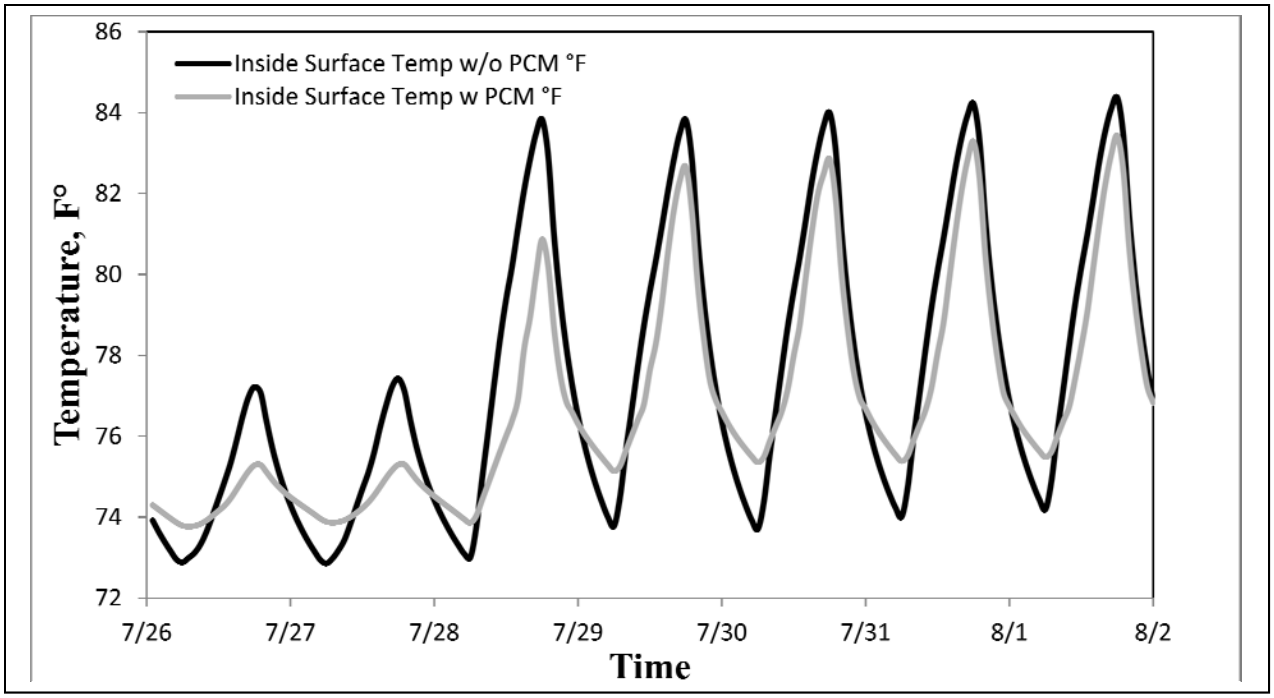
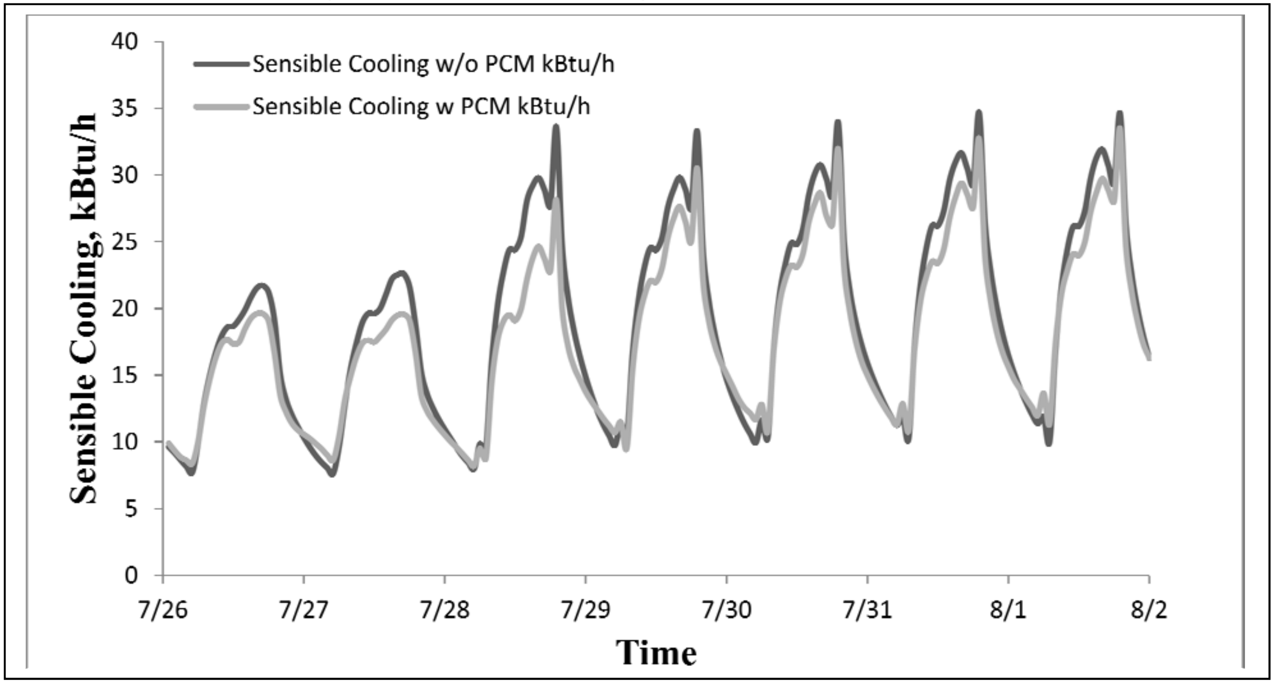


Figure 5 shows the sensible cooling profiles with and without PCM. The sensible cooling load in the building with PCM is approximately 10% less than the building without.

Figure 5. Sensible Cooling Profile with and without PCM



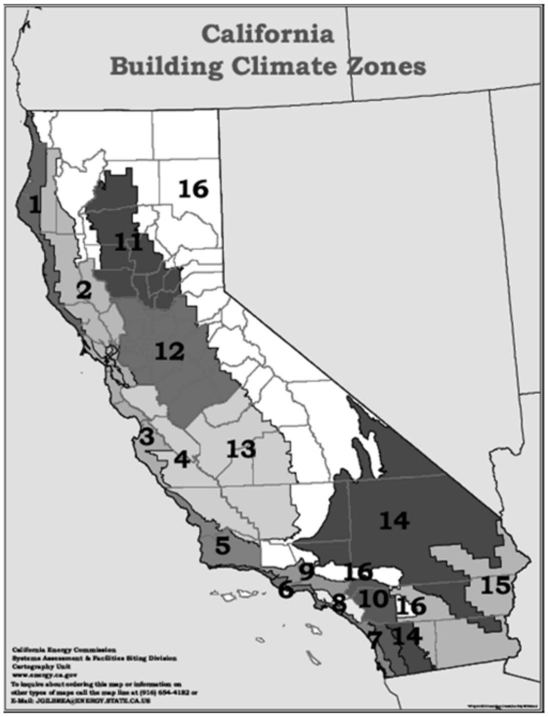
The results of these simulations show there is potential for PCM to save energy and demand in a commercial building. However, annual simulations should be explored to verify the savings potential. It is expected the local climate can play a significant role in determining the effectiveness of PCM for a given application.

More simulations are needed to better understand the effects of varying parameters. A parametric simulation study can help identify the climate, building type, PCM properties, and HVAC system to theoretically optimize performance. However, such a study must also include laboratory or field validation. Development of a systematic approach (as opposed to a custom simulation-based approach or contractor's best guess) would be constructive in selecting the PCM best suitable for each application.

Weather Analysis

We examined temperature data for the California CZs within SCE's (CZs 6, 8, 9, 10, 13, 14, 15, and 16) to determine which regions are more conducive to PCMs. Figure 6 provides a map of the 16 CZs.

Figure 6. California Climate Zone 9 Weather Data



Source: CEC 2011

The assumed melting temperature of PCM was 80°F.[3] Figures 7 to 10 show temperature data for a typical year in CZ 6, 9, 10, and 13.[4] The data are presented as three-dimensional contour plots viewed from above with each hour of the day (x-axis) and month (y-axis) having a corresponding temperature value (plot area).

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[3] PCMs can be "tuned" to a wide-range of melting temperatures. The optimal melting temperature depends on the application, but will generally be between 70 to 80°F in order to maintain human comfort.

[4] California Energy Commission provides these data for use in Title 24 Building Energy Efficiency Standards.

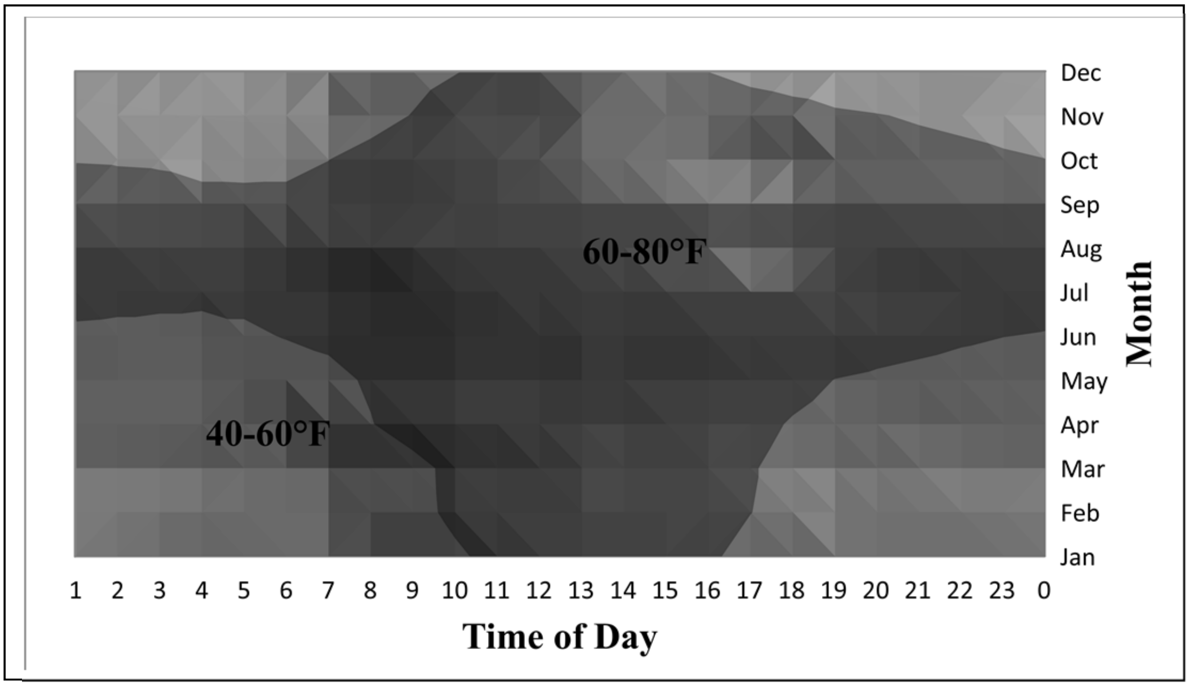
Figure 7 shows CZ 6 temperature data, which is a mild coastal climate. Typical temperatures for CZ 6 do not rise above 80°F for any point of the year. PCM in this region will likely be underutilized, unless the melting temperature is tuned to a lower temperature. PCM may be useful in buildings with high internal load, such as fast food restaurants and commercial office buildings with high occupancy and large plug loads. Use of PCM products in mild climates could reduce or eliminate the need for an air-conditioning system. A ventilation system will likely still be required to address occupant indoor air quality concerns and to supply cooler outside air for PCM regeneration.

Figure 8 shows CZ 9 temperature data, which has both coastal and interior weather influences. As a result, CZ 9 is has a diurnal swing that is seemingly beneficial for PCM applications. During summer months, typical temperatures peak in the high 80s and drop to the high 50s or low 60s. This diurnal swing will allow for night ventilation strategies to be used to regenerate PCM products.

Figure 9 shows CZ 10 temperature data, which encompasses interior valleys of Southern California. This region has warmer summers and cooler winters than CZ 9. During summer months, average temperatures peak in the high 80s and low 90s and drop to high 50s at night. This diurnal swing is expectedly larger than CZ 9, and offers greater potential for PCM applications. Air-conditioners have increased operating hours in this region, therefore the potential energy savings are greater.

Figure 10 shows CZ 13 temperature data for California's Central Valley. Temperatures are above 80°F for much longer periods in the summer months. The result is increased air-conditioner operating hours and a need for higher capacity HVAC systems. PCM has the potential to reduce the capacity, but HVAC control strategies (i.e. night ventilation, off-peak cooling) are needed to allow for sufficient regeneration of PCM.

Figure 7. California Climate Zone 6 Weather Data



Source: CEC 2011

Figure 8. California Climate Zone 9 Weather Data

Source: CEC 2011

Figure 9. California Climate Zone 10 Weather Data

Source: CEC 2011

Figure 10. California Climate Zone 13 Weather Data

Source: CEC 2011

Market Segments

PCMs can be incorporated into a variety of commercial building types. The California Commercial End-Use Survey (CEUS 2006) was used to estimate the total market for PCM in Southern California. Table 3 provides the total estimated floor stock in SCE's service territory by building type.

Table 3. Building Floor Stock in SCE Service Territory by Building Type

Building Type	**Floor Stock (kft^2)**	**Cooling Electricity Usage (GWh/yr)**
Small Office (< 30,000 ft^2)	157,884	460
Large Office (≥ 30,000 ft^2)	227,225	899
Restaurant	61,623	483
Retail	309,601	863
Food Store	63,820	229
School	176,999	279
College	64,809	138
Refrigerated Warehouse	30,031	15
Unrefrigerated Warehouse	353,765	122
Health	106,471	454
Lodging	112,405	196
Miscellaneous	477,725	659
TOTAL	**2,142,359**	**4,939**

Source: (CEUS 2006)

The commercial market sector has several buildings types suitable for PCM integration: small and large office buildings, restaurants, retail stores, food stores, schools, and colleges. The result is a potential market size of 1.06 billion sf of total floor stock in SCE service territory corresponding in 3,351 GWh/yr of cooling-related energy consumption**Error! Bookmark not defined.** (CEUS 2006). If properly applied, PCM can save 10-30% from existing cooling energy consumption (Kosny et al 2009, Muruganantham et al 2010). The result is a total technical potential energy savings between 335 and 1,005 GWh/year. Full market saturation is unrealistic; however, fractions thereof still represent significant potential.

The remaining buildings types face additional integration challenges that make the likelihood of their success minimal. For example, hospitals (health) have strict ventilation requirements that will inhibit the ability to optimize the charging/discharging process, unrefrigerated warehouses are often unconditioned, and lodging buildings provide control to occupants making control strategies difficult to implement. Refrigerated warehouses and miscellaneous are also excluded from consideration.

Conclusion

PCMs have potential in reducing cooling loads in commercial buildings. The exact savings is still not well known due to the many variables and parameters that must be considered. The success of PCM is dependent upon the identification of what combinations of climate, building type, PCM product type, PCM quantity (latent storage capacity), HVAC system, and regeneration control strategy have the ability to deliver energy savings and economic benefit to the consumer.

PCMs have a projected technical potential of 335 to 1,005 GWh/yr cooling-related energy reduction in commercial buildings. To begin to realize these savings, a systematic approach is desired to allow consumers to easily identify the optimal PCM application. PCM technologies can qualify for utility incentives if future parametric studies validate the energy savings and demand reduction potential outlined in this paper.

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