# US Map Visualization of Optimal Properties of Phase Change Materials for Building Efficiency

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ABSTRACT: Incorporating phase change materials (PCM) in construction materials can reduce the heating and cooling loads of buildings significantly. During the past ten years, many studies have estimated potential reductions of energy consumption of buildings between 10 and 30 percent. This wide range is due to the large number of parameters that affect energy consumption and make the process of selecting the type and amount of PCM challenging. In fact, extensive engineering studies are generally necessary to determine the practicality of PCM in any specific case. As a result, architects and engineers are reluctant to use PCM because of the lack of design guidelines. The International Energy Conservation Code (IECC) and the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) identified eight climate zones in the United States, each determined on the basis of annual degree heating and degree cooling days. Climate zones are further divided into moist, dry and coastal regions leading to 15 specific climates. Phase change materials are defined by their melting temperature, energy storage capacity, i.e., enthalpy, and cost, among other parameters. For a given building in a given climate, there exist an optimal melting temperature and enthalpy that minimize the energy consumption and the payback period. In this research, the optimal properties of PCM are determined for all 15 climates and results are visualized in the form of maps of the United States. Additional topics discussed in this paper are the sensitivity of the optimal properties of PCM and the effect of the average cost of energy on the selection of PCM. Fifteen different maps of the United States were created, from which the most relevant are presented in this paper. The energy consumption is determined numerically using the Department of Energy software EnergyPlus, which calculates the energy consumption for heating and cooling a building under any climate and operation schedule. The software is run on a computer cluster for a wide range of properties from which the optimal values are extracted.

KEYWORDS: Phase change materials, energy, visualization maps, design guidelines, payback period.

## INTRODUCTION

Energy efficiency is a dominant theme in today's global lexicon. It is becoming increasingly clear that our finite energy resources cannot meet our needs of the future. Currently the global energy consumption rests at a staggering 513.2 Quadrillion British Thermal Units (Quads) and is projected to increase to 769.8 Quads by the year 2035 (Conti et al 2011). Among the industrialized nations the United States is one of the leading energy consumers with approximately 1/5$^{th}$ of the global annual energy consumption, of which the built environment accounts for approximately 40% (Buildings Energy Databook 2010). It is therefore incumbent on engineers, scientists and designers to explore sustainable ways to curb the energy consumption within the building sector.

Thermal energy storage (TES) technologies for buildings have been gaining considerable attention over the last few decades. Thermal energy storage mechanisms are known to decrease indoor temperature swings, improve indoor thermal comfort for occupants and shift electrical consumption from peak to off-peak hours by storing heat or cold for use at a later time when indoor thermal conditions fall outside of the comfort zone (Dincer & Rosen 2011; Mehling & Cabeza 2008). There are three physical processes of storing thermal energy i.e. sensible heat storage, latent heat storage (LHS) and chemical storage. Among these approaches, the latent heat thermal energy storage using phase change materials (PCMs) has attracted attention for its use in building applications due to its inherent ability to store and deliver lager amounts of energy at a narrow phase transition temperature (Pasupathy et al 2008; Zhang et al 2007).

Phase change materials are capable of storing and releasing large amounts of heat by melting and solidifying at a given temperature. Phase change materials are classified into three categories (i.e. Organic, Inorganic and Eutectic) based on their chemical makeup. However each of these PCMs can also be appended to construction materials forming a homogenous mixture which exhibits the heat storage properties of the PCM itself. The investigation of PCMs as thermal energy storage systems in buildings has a long history. However, the studies have been sporadic and scattered throughout the globe. This makes it hard to draw any conclusive guidelines for its viable use in buildings under different climatic conditions. Therefore there exists a widespread consensus among researchers and practitioners on the need for a more systematic and comprehensive study of the dynamic characteristics and energy performance of buildings using PCMs (Chen et al 2008; Zhu et al 2009; Roth et al 2007; Zhang et al 2006; Kuznik et al 2011). While PCM gypsum boards are becoming commercially available in the construction industry in the US, designers and engineers are still unsure as to the guidelines for selecting the proper PCM (i.e. Melting temperature, heat storage capacity) specific to particular climatic conditions.

The high capital cost and subsequently long payback period of new technologies is seen as one of the most significant barriers in implementing it in buildings (Cooke et al 2007). Three cash-flow analysis tools – payback period, return on investment and present worth analysis – are commonly used to evaluate investments that improve energy performance. While the latter two analyses are predicated on the notion of setting a time frame of useful life, the payback period analysis is the most basic financial gauge to obtain the time (usually in number of years) for an investment cumulative cash flow to reach zero. Assuming that energy prices rise to keep up with inflation the change in time value of money is ignored in this analysis. In addition, the availability of tax benefits and subsidies for energy efficient homes provided by the federal government adds significant complexity to the payback period analysis. The effect on the payback period by the inclusion of the time value of money, the savings accrued from the downsizing of HVAC equipment, reduction in construction costs, the lower interest rates provided by the energy efficient mortgage (EEM) will be analyzed in a further study. By relegating the 'systems' thinking approach for a later study, this paper therefore considers 'pseudo' payback periods (PPP) based solely on the initial capital investment for the PCM boards and the money saved due to the savings in energy.

In the existing literature, research on payback periods for the use of PCMs is predominantly assessed on the basis of its environmental impacts. In a rudimentary sense such payback period analysis seeks to answer questions such as, how long does it take for the use of PCMs in buildings to surpass its embodied energy to mitigate greenhouse gases. Chan (2011) has studied the environmental and economic impact of PCM impregnated walls in subtropical Hong Kong. Based on the embodied energy of the particular PCM in question, the study concludes an energy payback period of 23.4 years. On the other hand the economic payback period, disregarding the time value of money, is concluded to be 91 years. Gracia et al (2010) and Castell et al (2012) performed LCA analysis on five different test huts with and without PCM in Puigverd de Lleida, Spain. They concluded that the energy payback period can be reduced by lowering the embodied energy of PCM since it was too large to counteract the benefits during its operation. Stovall and Tomlinson (1995), through better management of the thermostat set point temperature schedules during the winter months and also by taking into account the differential tariff systems, found an economic payback of using PCM boards in a small house in Boston to be 5 years. Moheisen et al (2011) performed test on a typical office space in an environment chamber and have concluded that the economic payback period of PCM was 5 years as well. As such the economic payback period of using PCM in buildings depends on a number of factors (i.e. the cost of PCM and the cost of energy etc). For this paper the cost of PCM is set to an arbitrary yet reasonable number and the cost of energy is based on the cost per kilo-watt-hour of electricity according to the average state electricity rates.

## 1.0 METHODOLOGY

The aim and scope of this research is to identify the optimum melting temperature and enthalpy of PCM for each given climate type and also quantify the 'pseudo' payback period (PPP) associated with the use each optimum PCM board. The energy analysis was performed using EnergyPlus, a whole building energy simulation software developed by the US Department of Energy. The objective is also to perform a sensitivity analysis as to understand the magnitude of difference in savings if a less than optimum melting temperature or enthalpy is chosen. To that end different theoretical gypsum boards-PCM mixture (PCM boards) were defined using the Enthalpy-Temperature function in EnergyPlus. The PCM property was thus appended to the Gypsum board which lined the interior surface for all walls and the roof. A total of 60 different PCMs were defined to test the optimum PCM for each specific climate. The PCM's melting temperature ranged from 16$^{o}$C to 30$^{o}$C in increments of 1 degree. Each PCM was defined to have a sharp melting range of 0.1 degree. Similarly, for each PCM board the enthalpy ranged from 20kJ/kg to 80 kJ/kg in increments of 20 kJ/kg.

The International Energy Conservation Code (IECC) and the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) have identified eight climate zones in the United States, each determined on the basis of annual degree heating and degree cooling days. Climate zones are further divided into moist, dry and coastal regions leading to 15 specific climates each represented by cities within the United States (PNNL 2011).

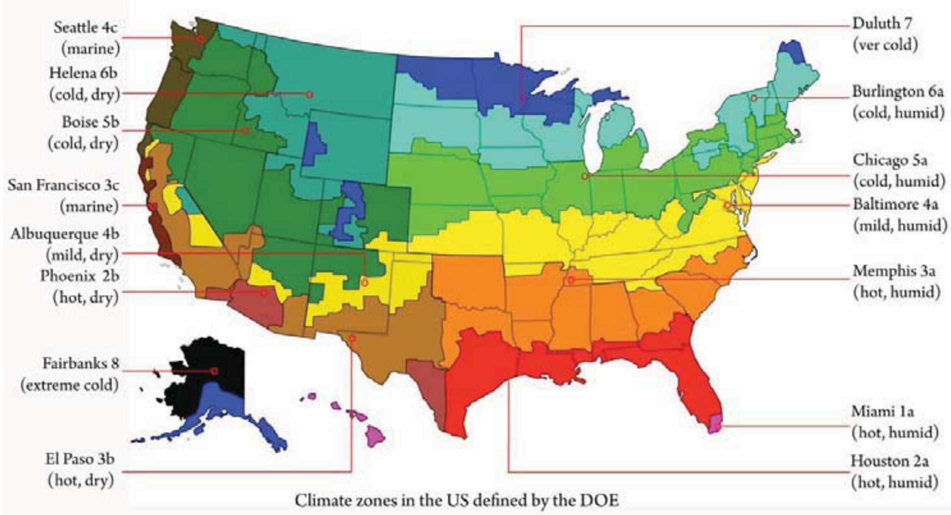


**Figure 1**: DOE developed climate zones and representative cities. Source: (PNNL 2011)

A baseline building was developed for each representative city following the guidelines recommended in the ASHRAE 90.1 - 2010 standard. The 15 different climate specific buildings were created to match the specific recommendations on the insulation R-value, window SHGC and U-value in the standard. The construction specifics recommended in the standard were adopted for the building surface as well as the fenestration components. Figure 2 depicts the surface construction and the dimensions of the building simulated for this study.

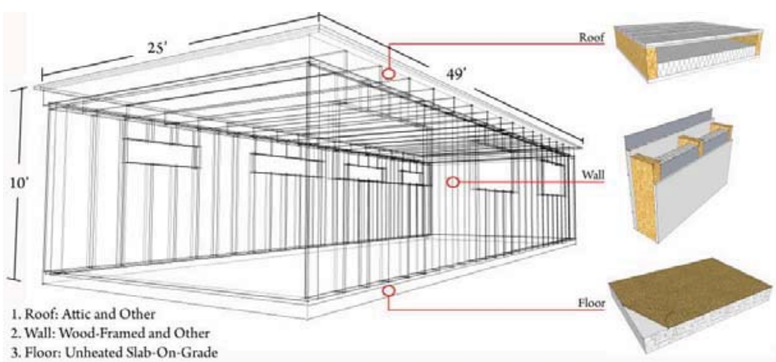


**Figure 2**: Baseline building construction as per ASHRAE 90.1 – 2010.

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In terms of the internal loads, the building was set to be occupied by five people throughout the 24 hours of the day and every day through the year. Each person was set to dissipate 120 watts of energy into the interior environment. The heating and cooling thermostat setpoint temperatures were set at 21$^{o}$ and 25$^{o}$ Celsius respectively throughout the year and the building was set to be conditioned by the Ideal Air Loads System. The energy performance of each specific building was simulated for the 15 different cities using the typical meteorological data (TMY3) weather data available from the EnergyPlus weather repository. The output variables, annual cooling and heating energy were requested as the dependent variables. Due to the high number of simulations required for each climate the software JEplus (Zhang 2009) was used to setup and perform parametric runs for each PCM board. The data was then compared to the control or baseline building without PCM properties appended to the gypsum board in order to quantify the magnitude of savings offered by the inclusion of PCM.

## 2.0. RESULTS AND DISCUSSION

### 2.1. Optimum melting temperature and enthalpy

The results for each climate was obtained and analyzed separately. It is clear from Figure 3 that the climate zone 8 (Fairbanks, AK) has the highest magnitude in annual load predominantly due to its high number of heating degree days (HDD) that requires a significant heating load throughout the winter. On the other end of the spectrum climate zone 3c (San Francisco, CA) has the lowest annual loads predominantly owing to its all year round mild temperature that requires neither too much heating nor cooling.

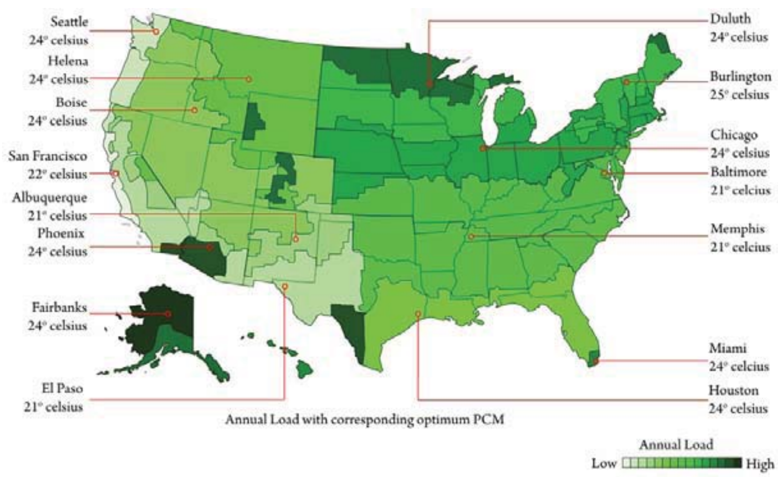


**Figure 3**: Analytical map for the annual load (magnitude) with the optimum PCM melting temperature for each climate.

The optimum melting temperature and enthalpy were determined for each climate by selecting the corresponding lowest annual load. The results show that the annual load for every climate was the lowest when the PCM board had the highest heat storage capacity. The PCM boards in this particular study were set to take four different heat storage capacity values (i.e. 20, 40, 60, 80 kJ/kg) and the optimum energy savings was obtained by the PCM board with 80 kJ/kg enthalpy for all the climates.

In terms of the optimum melting temperature, it can be seen in Figure 3 that the melting temperatures vary by climate. Due to this variability in optimum melting temperature a causal relationship between the heating degree days (HDD) and cooling degree days (CDD) and the optimum PCM melting temperature cannot be conclusively drawn. The heating and cooling setpoint temperatures along with the HVAC schedule can be an important determining factor for the selection of the optimum melting temperature of the PCM. The HVAC system in this particular research was set to be available 24 hours a day and all year round. The heating and cooling setpoint temperatures were set to 21°C and 25°C respectively. The principle of free-cooling of PCM that can provide cold storage and also naturally 'charge' PCM through night ventilation was not applied for this study and set for a later study. The application of the PCM free-cooling principle can further help alleviate the stress on the HVAC systems by providing cold storage through night ventilation as well as help 'charge' the PCM for use the next day. Similarly different HVAC schedules can also provide for energy efficient management of indoor thermal conditions. The effect of these parameters on the optimum melting temperature will be presented and discussed in a later study.

### 2.2. Percent savings in energy

The magnitude in savings in energy was determined once the optimum melting temperature and enthalpy for each climate zone was obtained. It can be seen in Figure 4 that the maximum percent in savings was obtained for climate zone 4c (San Francisco, California). It should also be noted that the percent savings in energy (51.91%) for San Francisco is very high due to the fact that the annual load without PCM is very low compared to other climate zones to begin with. Since PCM was applied, the percent decrease in annual load came to be 51.91% compared to an already relatively low annual load compared to the other climates.

It is also clear that the highest percent savings occurs in the dry and marine climates. Within the subset of dry and marine climates, the PCM technology performs better in the warmer climates. The diurnal temperature fluctuates to a greater extent in the dry climates than in similar humid climates. It is not uncommon for the ambient air to cool significantly during the night in the dry climates and thereby cooling (discharging) the PCM boards for use the next day. Since the PCM is cooled by this drop in ambient temperature there is no need for the HVAC to expend extra energy in these dry climates to 'discharge' the PCM. It is possible that the effect of free-cooling and cold storage will improve the percent energy savings in the colder climates.

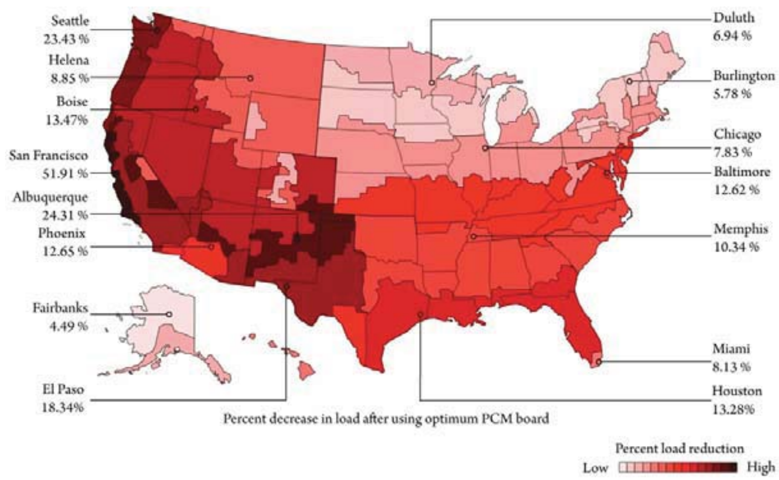


**Figure 4**: Analytical map of the energy savings in magnitude by using the optimum PCM in each climate zone

A sensitivity analysis on the optimum temperature was also performed in order to provide an understanding of the magnitude of loss in percent savings if optimum temperatures of 1 degree higher or 1 degree lower is to be chosen.

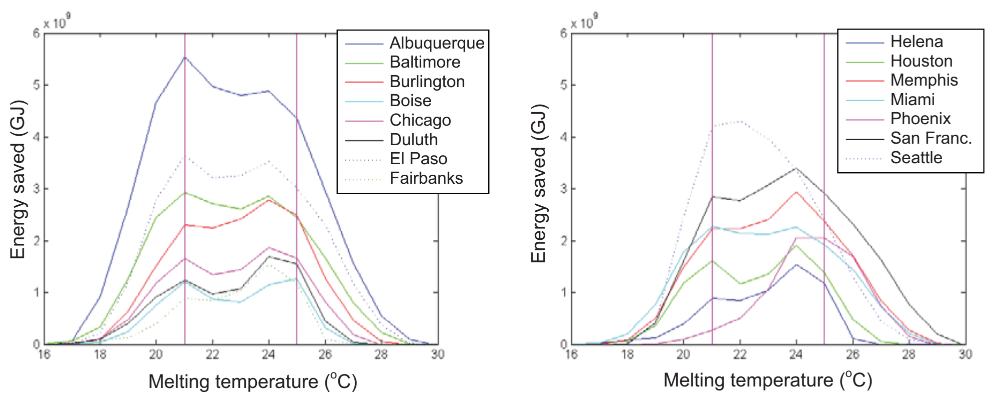


**Figure 5**: Energy saved as function of PCM's melting temperature for the 15 climates (setpoint temperatures: 21°C and 25°C)

In Figure 5, PCM boards melting at 21°C offers the most in energy savings for Albuquerque. If however the designer chooses to select a PCM melting temperature of 20°C then there is a loss of 20% in energy savings. A similar trend can be seen for the other climates as well. It is crucial to choose the optimum melting temperature to obtain the maximum benefits of using PCM boards.

Additionally it can also be seen that the optimum melting temperature hovers in and around the heating and cooling setpoint temperatures. There is no distinct pattern in the results to suggest a direct correlation between the setpoint temperatures and the optimum melting temperature. Clear guidelines for the selection of optimum melting temperature based solely on the setpoint temperatures are not feasible.

## 2.3. Payback period

A 'pseudo' payback period (PPP) is determined for the use of the PCM boards for each climate. The cost of commercially available PCM boards varies on the basis of melting temperature, heat storage capacity from each manufacturer. In order to evaluate the PPP of the optimum PCM boards for every climate type, a wider range of costs were incorporated into the calculation. The cost of PCM board was therefore set to vary from $1/kg to $3/kg. Similarly every state has a different electricity tariff. In order to encompass a wider range of tariffs the cost of electricity was also set to vary from $0.07/kWh to $0.18/kWh. In the PPP calculations the time value of money, the savings accrued due to the downsizing of HVAC equipment, reduction in construction costs, and the lower interest rates provided by the energy efficient mortgage (EEM) and other federal subsidies for the investment in energy efficient homes are ignored.

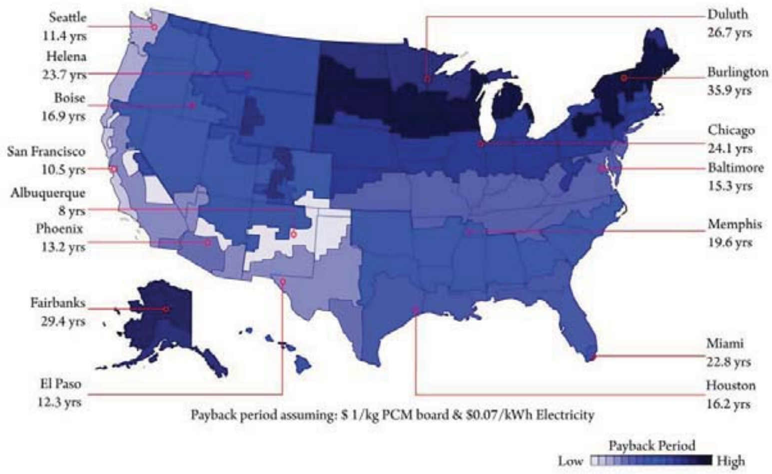


**Figure 6**: Analytical map of the pseudo payback period assuming a $1/kg cost of PCM board & $0.07/kWh cost of electricity

It is evident from Figure 6 that the lowest PPP is for the climate zone 3b represented by Albuquerque, which is a mild and dry climate. Even though the highest percentage savings in energy was seen for climate zone 4c represented by San Francisco, climate zone 3b fares better in terms of the economic payback period. Similarly while climate zone 2a represented by Houston, exhibited a slightly higher percentage savings in energy than climate zone 2b represented by Phoenix, zone 2b is better in terms of the number of years to payback the initial investment in PCM boards. Again it can be seen that PCM boards perform best in the warm, dry and marine climates as opposed to cold and humid climates.

The PPPs were plotted against the cost of PCM and electricity (Figure 7(a)). In addition, the required costs of PCM and electricity to achieve a PPP period of 10, 20 and 30 years were obtained for each climate (Figure 7(b) shows the case of Albuquerque).

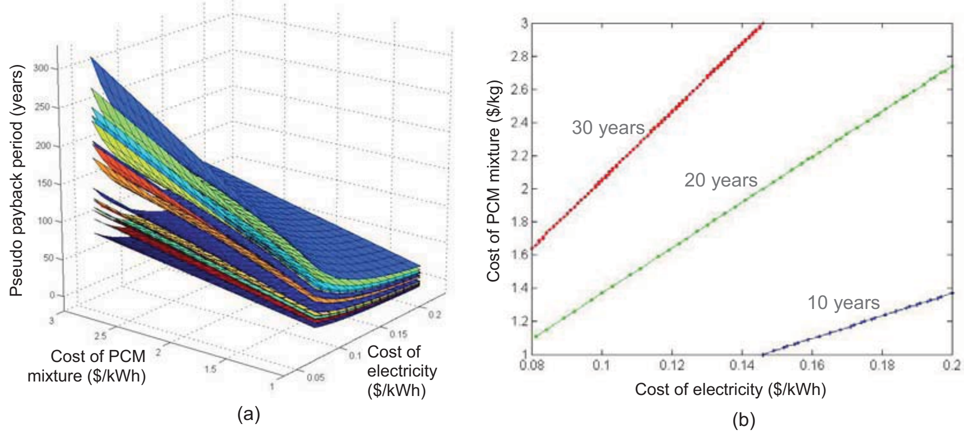


**Figure 7**: (a) Pseudo payback period as function of cost of PCM mixture and cost of electricity for all 15 climates and (b) Cost of PCM and electricity needed to achieve a PPP of 10, 20 and 30 years in Albuquerque.

The PPP of all the 15 climates can be visualized in Figure 7(a). The PPP is influenced by a greater degree by the cost of PCM due to the greater slope. The cold and humid climates exhibited a PPP far greater than the warm and dry climates. The plot in Figure 7(b) shows the optimum cost of PCM and electricity for Albuquerque. If a PPP of 10 years is desired for Albuquerque then any combination of cost of PCM and cost of electricity on the blue line will achieve that.

## CONCLUSION

In this study, building energy performance simulations were performed for a simple building fitted with PCM boards on all interior surfaces except the floor. The simulations were carried out for the 15 different climate types as defined by the U.S. Department of Energy. The application of PCM wallboards in those buildings shows significant benefits in terms of annual energy savings.

- The PCM boards perform best in hot, dry and marine climates. The diurnal fluctuation of ambient temperature in the hot and dry climates as well as the mild marine climates can be attributed to the better performance of PCMs.
- The PCM boards did not perform well in the cold and humid climates. This can probably be improved by allowing free-cooling during the night. In addition, different set point schedules for the HVAC, different occupancy schedules as well as different night ventilation schemes need to be further studied in order to optimize the performance of PCM boards in such climates.
- The 'pseudo' payback period of the use of PCM boards were comparatively very high. For the PCM boards to be economically viable, the cost needs to be close to $1/kg and have a higher heat storage capacity. The effect of the time value of money, the savings accrued due to the downsizing of HVAC equipment, reduction in construction costs, and the lower interest rates provided by the energy efficient mortgage (EEM) and other federal subsidies for the investment in energy efficient homes need to be applied as well in order to conclusively determine the economic viability of PCM wall boards in the US climates.
- The sensitivity study shows that the optimum temperature is an important factor in determining the energy saving potential of the PCM board. A slight divergence from the optimum temperatures for each climate can reduce the energy saving potential by 5-10 percent.

The present study is an attempt to assess theoretically the energy performance of PCM boards on all climates in the United States. Starting with a simple building model the later studies will gradually add more variables to the simulations and register the changes assessed.

## ACKNOWLEDGEMENTS

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