Validation Methodology to Allow Simulated Peak Reduction and Energy Performance Analysis of Residential Building Envelope with Phase Change Materials

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Validation Methodology to Allow Simulated Peak Reduction and Energy Performance Analysis of Residential Building Envelope with Phase Change Materials

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ABSTRACT

Phase change materials (PCMs) represent a potential technology to reduce peak loads and HVAC energy consumption in residential buildings. This paper summarizes NREL's efforts to obtain accurate energy simulations when PCMs are modeled in residential buildings: the overall methodology to verify and validate conduction finite difference (CondFD) and PCM algorithms in EnergyPlus is presented in this study. It also shows preliminary results of three residential building enclosure technologies containing PCM: PCM-enhanced insulation, PCM-impregnated drywall, and thin PCM layers. The results are compared based on predicted peak reduction and energy savings using the PCM and CondFD algorithms in EnergyPlus.

INTRODUCTION

Energy can be stored in buildings by sensible, latent, or chemical means. From these three types, latent storage using phase change materials (PCMs) has been the focus of multiple studies and considerations because it may be capable of greater thermal energy storage per volume than sensible storage. Several PCMs are commercially available that vary in type (salts, paraffins, fatty acids), encapsulation technology (micro and macro encapsulation), and melting temperatures (covering a range that is useful for building wallboard and enclosure applications, 64-104°F [18-40°C]).

Previous PCM studies have shown that there are important benefits related to thermal comfort, energy savings, and the potential for HVAC downsizing when thermal storage is added into buildings (Zhu et al. 2009). These benefits are achieved through the appropriate design and selection of PCMs, because PCMs can reduce temperature fluctuations and shift heating and cooling demand (Khudhair and Farid 2004). Early building energy simulations efforts in this area focused on wallboards impregnated with PCMs (Drake 1987; Peippo et al. 1991; Solomon 1979; Stovall and Tomlinson 1995; Tomlinson and Heberle 1990). Later building simulation studies focused on various PCM applications: PCM impregnated in fiber insulation (Kosny et al. 2010a; Shrestha et al. 2011), macro-encapsulated PCMs in walls (Kosny et al. 2010b), and floor heating systems that utilize shape-stabilized PCMs (Lin et al. 2004; Zhang et al. 2006). PCM energy modeling is a complex task that requires sophisticated building energy simulation programs that can accurately simulate PCMs for different applications in homes: attics, walls, and floors. There have also been efforts to benchmark PCM models with whole-building field data using a house with PCM distributed in the attic and wall insulation (Shrestha et al. 2011). However, the ability to reproduce the experimental results in EnergyPlus was limited because of issues with the software code in multi-zone buildings.

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However, the ability to reproduce the experimental results in EnergyPlus was limited because of issues with the software code in multi-zone buildings.

The objective of this study was to validate the EnergyPlus conduction finite difference (CondFD) algorithm for multi-zone buildings and to investigate the potential benefits when PCMs are installed in homes. This study also summarizes NREL validation efforts to conduct accurate energy simulations with PCMs, as this is part of an ongoing investigation with the overall goal of optimizing PCMs in buildings.

VERIFICATION AND VALIDATION METHODOLOGY

EnergyPlus can simulate PCMs only with the CondFD solution algorithm. CondFD discretizes walls, floors, and ceilings into several nodes and uses an implicit finite difference scheme to numerically solve the appropriate heat transfer equations (EnergyPlus 2011). To model PCMs, the CondFD method is coupled with an enthalpy-temperature function that users input to account for enthalpy changes during phase change. This function is used to develop an equivalent specific heat at each time step that inputs the CondFD equations (EnergyPlus 2011). Thus, accurate modeling of PCMs requires validation of the PCM and CondFD algorithms.

This validation work was completed at NREL following ASHRAE Standard 140 and NREL validation methodologies, which consist of analytical verification, comparative testing, and empirical validation (Judkoff and Neymark 2006). Overall, the process is divided in two levels (wall or building) and the two algorithms (CondFD and PCM), as shown in **Table 1**. The wall-level tests were detailed tests that focused on a single wall subjected to particular boundary conditions on both sides for a relatively short period of time. Thus, the wall level validation tested the ability of only the specific CondFD and PCM algorithms to accurately model building envelope applications. The wall-level tests for CondFD and PCM algorithms were presented in previous studies (Tabares-Velasco and Griffith 2012; Tabares-Velasco et al. 2012). This was an important step, but it did not guarantee that the algorithms would work with more realistic situations and different HVAC systems.

Table 1. Verification and Validation

Verification/ Validation Level	CondFD	PCM
Wall	Analytical: • Variable k • Composite wall • Const heat flux (2) • Periodic BC • Symmetry Comparative: • H7.3 transient variable k • H7.3 transient multilayer wall	Analytical: • Stefan Problem Comparative: • Heating 7.3 Empirical: • DuPont Hotbox
Building	Comparative: • ASHRAE 140 Case 600 • BEopt[1] retrofit house • BEopt new house	Evaluation: • ASHRAE 140 Case 600 • BEopt retrofit house • BEopt new house

In contrast, the whole-house tests of this study focus on an entire building, considering interactions between the weather, building envelope, HVAC, and internal loads for periods of time that vary from a few days to a year. Building-level validation tests single-zone or multi-zone houses and is mainly a comparison between conduction transfer functions (CTFs) and CondFD. Building-level verification compares hourly surface temperatures, average zone temperatures, hourly heating

[1]Building Energy Optimization (BEopt) is residential building energy optimization software. See http://beopt.nrel.gov/.

and cooling energy, and total heating and cooling energy between CondFD and CTFs. A building-level evaluation of the PCM algorithm is presented in another study (Tabares-Velasco et al. 2012). However, PCM results could not be compared to the CTF[2] results because PCMs cannot be modeled using the CTF algorithm. Thus, this work was called "evaluation" instead of "verification" (see **Table 1**). Nevertheless, the evaluation compared the run time and number of iterations required for CondFD to converge for various PCM applications as a measure to confirm models were converging without previous stability problems detected. All simulations had similar run times and required similar numbers of iterations, which was consistent with the wall-level verification for PCMs (Tabares-Velasco et al. 2012). Overall the PCM model is now validated after wall-level validation and building-level evaluation. Thus, this paper presents the comparative verification for CondFD using the whole-building test (lower-left quadrant of **Table 1**).

WHOLE-BUILDING COMPARATIVE VERIFICATION OF CONDFD

The comparative building level verification for CondFD without PCMs consisted of:

1. ASHRAE Standard 140 Case 600: a simple single-zone building with lightweight construction (ASHRAE 2004).
2. BEopt retrofit house: a one-story, 1,280-ft^2 (120-m^2), 1960s-era house with three bedrooms, two bathrooms, and an unconditioned attic modeled in six of the eight original U.S. cities considered in previous retrofit analysis efforts (Polly et al. 2011).
3. BEopt new house: a two-story, 2500-ft^2 (231-m^2) house with three bedrooms, two bathrooms, a garage, and an unconditioned attic. The new homes were developed in BEopt according to the 2010 Building America Simulation Protocols, which represent a house built according to the 2009 International Energy Conservation Code (IECC) and federal appliance standards in effect as of January 1, 2010 (Hendron and Engebrecht 2010). More details about the house can be found in the literature (Casey and Booten 2011).

BEopt houses were created in BEopt version 1.1; the simulation files (idf) were later modified outside of BEopt to allow comparison between CTF and CondFD. The foundation type of the homes varied according to location, as shown in **Figure 1**. The verification was done using 1-minute time step (shortest allowed in EnergyPlus; default time step for CTFs is 10 minutes) for CondFD as well as for CTFs and other time steps. We have found that CondFD users should use time steps 3 minutes or shorter. However, future research is necessary to address time step sensitivity more fully.

The retrofit and new house validation consisted of three-day summer and winter tests (instead of full annual tests) to reduce the run times. Initial findings from this procedure helped identify multiple problems in EnergyPlus that resulted in average energy use differences of up to 30%. The problems were related to the modeling of 1) walls between zones (e.g., walls between living space and garage/attic) and 2) adiabatic walls and massless walls. In both cases, CondFD was not correctly distinguished between external and internal boundary conditions when adiabatic walls were presented (among other minor bugs). We worked with the EnergyPlus development team to resolve the issues; the next release EnergyPlus in 2012 (version 7.1) will have a more reliable model. The "corrected" EnergyPlus model was used to conduct all simulations presented in this study. **Figure 1** shows the cooling energy calculated using the CTF and CondFD algorithms for the BEopt new houses. The green line represents the percent difference (on the right axis) between CTF and CondFD; all were less than 0.4%. Additional annual simulations for Chicago and Phoenix houses showed that the annual percent energy differences were even smaller than those calculated by the three-day tests. All tests showed very close agreement between CTF and CondFD.

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[2]The default CTF solution algorithm in EnergyPlus cannot simulate materials with variable properties such as PCMs (EnergyPlus 2011).

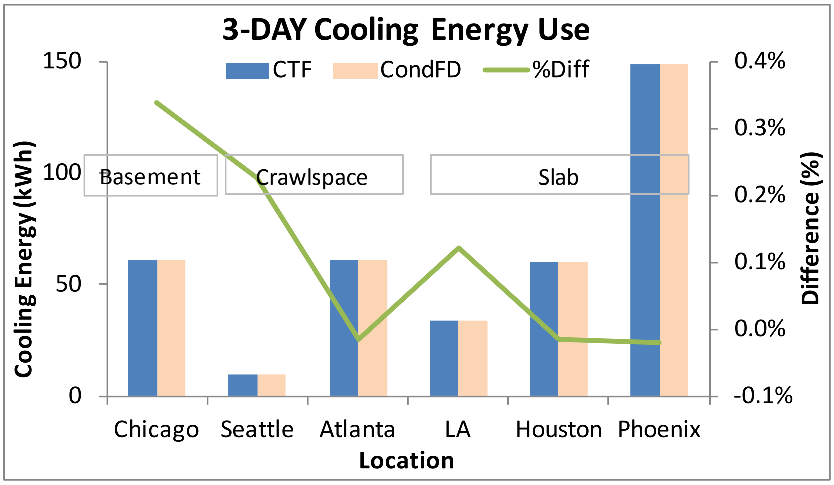

Figure 1. Three-Day Cooling Energy use calculated with EnergyPlus using the CTF and CondFD algorithms for BEopt new houses without PCMs. The green line represents differences between the algorithms, with values displayed on the right-Y axis.

DETAILED DIAGNOSTICS AVAILABLE WITH WHOLE BUILDING ANALYSIS FOR PCM SYSTEMS WITH VALIDATED PCM MODEL

Once the CondFD and PCM algorithms were validated, a similar house to the BEopt new house was analyzed in more detail in EnergyPlus for the Phoenix location and weather data using 2010 Building America Simulation Protocols (Hendron and Engebrecht 2010). Thus, the house has natural ventilation as long as it can meet the cooling load and the indoor temperature stays above the heating set point. Cooling and heating set points were 76°F (24.4°C) and 71°F (21.7°C), respectively, with a COP of 3.9. The intent of this analysis is to show how the whole-building analysis of a PCM system can produce information that is useful for selecting the type, amount, and location of PCMs for improved energy performance. However, it is not the intention of this study to perform a parametric analysis of PCMs or show the potential energy savings from PCMs. The original building model generated in BEopt was modified to accommodate PCMs: walls and attic were assumed to be studless and trussless. This assumption was necessary, as BEopt cannot model PCMs at this time. BEopt calculates "equivalent" material layers for stud and cavity using the parallel path method; therefore, there is currently no easy way to correctly model PCM materials in parallel with other materials using BEopt. These assumptions resulted in R-values for the studless wall of RSI-2.7 (RIP-15.3) and RSI-6.7 (RIP-40) for the trussless attic. **Table 2** shows the properties of the PCM aggregate materials analyzed in this study: PCM distributed in insulation, PCM distributed in drywall, and concentrated PCM layer. These three cases represent products that are already on the market or that have been previously investigated (Kedl 1990; Kosny et al. 2010a; Kosny et al. 2010b). From these three materials, concentrated PCM has more thermal storage capacity (in Btu/ft^2 or kJ/m^2), as it is the only concentrated application analyzed in this study.

Figure 2 shows predicted monthly cooling electric energy reduction for the analyzed PCM applications. All monthly savings were divided by the annual energy use for the building without PCMs. The PCM applications analyzed are: PCM distributed in drywall on the ceiling (DW_Ceil) and walls (DW_Walls), PCM distributed in wall insulation (Walls), PCM concentrated at the middle of the wall cavity insulation (RCRWall) and a combination of RCRWall with PCM distributed in Drywall (RCRWall-DW). The last application was selected because the two PCM applications showed the best performance during cooling season. Thus, it is added here to show the potential savings when multiple PCM applications are used within a single building. For this particular case, the combination of RCRWall with RCRWall-DW achieved the highest annual percentage savings, which were around 4% or approximately 716 kBtu (210 kWh). However, more in-depth parametric analysis is needed before any conclusions can be made, as this study did not analyze several melting temperatures or storage capacities to optimize energy and/or peak load savings.

Table 2. Properties of PCM Strategies Analyzed

Properties	PCM Distributed Insulation	PCM Distributed Drywall	Concentrated PCM Layer
% Weight of PCM in Wall Layer	40%	30%	100%
Equivalent Latent Heat	9.5 Btu/lb (68 kJ/kg)	14 Btu/lb (33 kJ/kg)	56 Btu/lb (130 kJ/kg)
Melting Temperature Range	83-87°F (28.5-30.5°C)	72-76°F (22.5-24.5°C)	83-87°F (28.5-30.5°C)
Thermal Conductivity	0.2337 Btu in/(h ft R) (0.0337 W/m K)	1.595Btu in/(h ft R) (0.23 W/m K)	1.109 Btu in/(h ft R) (0.16 W/m K)
Density	4.4 lb/ft³ (70 kg/m³)	62.4 lb/ft³ (1000 kg/m³)	53.1 lb/ft³ (850 kg/m³)
Specific Heat	0.229Btu/lb R (960 J/kg K)	0.334 Btu/lb R (1400 J/kg K)	0.597 Btu/lb R (2500 J/kg K)
Thickness Wall	3.5in (0.089m)	0.5in (0.0127m)	0.2in (0.005m)
Walls Latent Storage	37.2 Btu/ft² (423 kJ/m²)	36.8 Btu/ft² (420 kJ/m²)	48.6 Btu/ft² (550 kJ/m²)
Amount of PCM	0.5 lb/ft² (2.5 kg/m²)	0.8 lb/ft² (3.8kg/m²)	0.9 lb/ft² (4.2kg/m²)

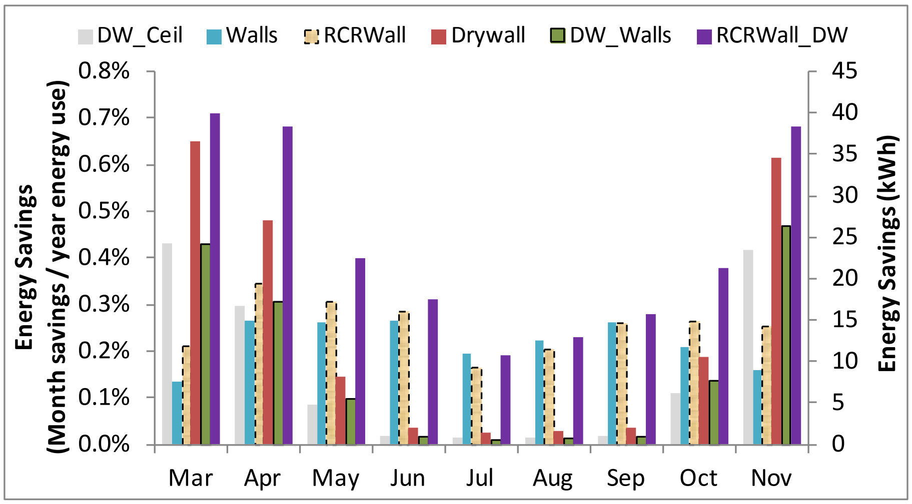

Figure 2. Predicted cooling energy savings for PCM strategies.

It is also interesting to see the seasonal performance variability of the PCM applications: all PCM-drywall applications performed the best during the swing seasons; the system with the concentrated application offered more continuous benefits. Moreover, the results show only small differences between installing the PCM drywall in the walls and the ceiling (DW_Walls and. DW_Ceil). **Figure 3** shows the peak cooling reduction benefits for the same house and PCM applications. Similar to energy savings, the PCM application with the highest reduction was the combination of RCRWall and RCRWall-DW. However, the highest peak reduction was achieved during April and May, months when electricity peak demand typically is not a concern, as July and August are typically the months when local utilities struggle to meet the cooling demand.

Figure 4 shows the predicted hourly cooling energy savings from four of the six PCM applications analyzed for four sunny days in April with diurnal temperature variations of 59-95°F (15-35°C). Energy savings from installing PCMs are shown in the left Y-axis. The cooling energy use of the house without PCM (CoolingEnerg) is shown in the right Y-axis as a reference. During these days, PCM savings peak at the same time when the cooling energy use peaks. This is due to the large temperature variation that went below and above the melting temperature range of the PCMs. Thus, allowing them to melt and solidify daily. Day-to-day variations are due to weather change: outdoor air temperatures were slightly warmer for the last two days. Overall PCM locations have an important role that need to be considered when designing PCMs.

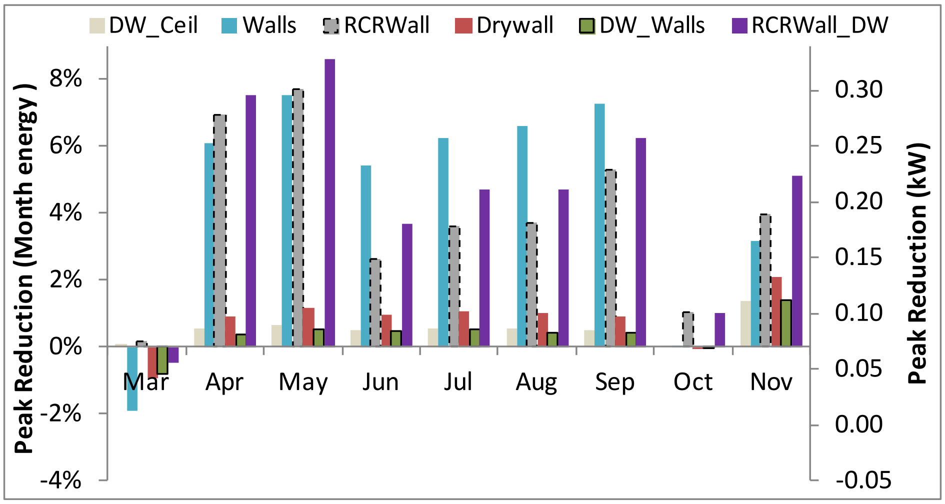

Figure 3. Predicted peak cooling reduction from PCM strategies.

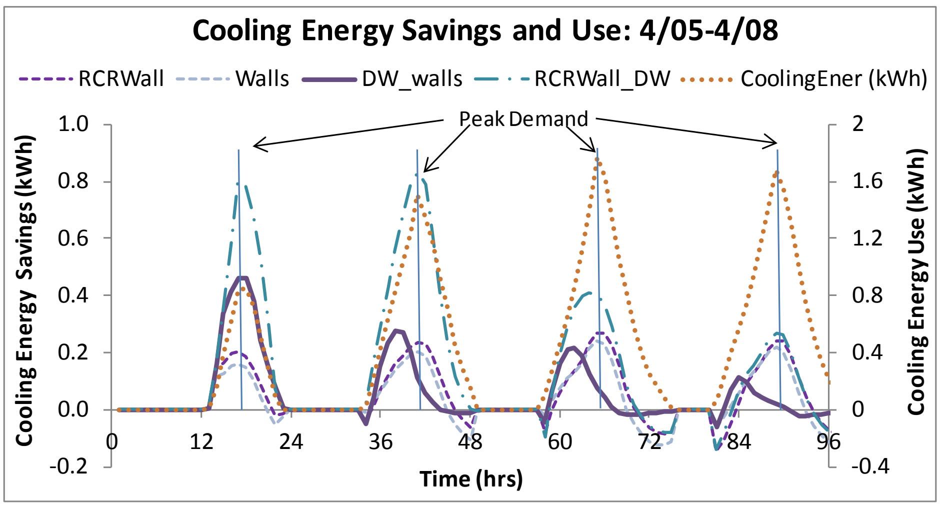

Figure 4. Predicted hourly energy savings from PCM wall applications in April in Phoenix. Right Y-axis shows hourly energy use for house without PCMs (CoolingEner).

Figure 5 shows the predicted hourly cooling energy savings for the same PCM applications shown in **Figure 4**, but for four days in July with diurnal temperature variations of 86-113°F (30-45°C). During these days, PCM energy savings peak earlier than the peak cooling demand and overall energy savings are smaller than in April. This is due to the mismatch between the thermal properties for the selected PCMs and the outdoor temperatures during the warm summer weather; the PCMs selected melt between 83-87°F (28-30°C), so the outdoor temperature is above the melting range for most of the four-day period. Thus, the chosen PCMs were not able to melt and solidify daily, which limited their ability to store additional heat. Higher savings could be obtained if a PCM with higher melting temperature and/or storage capacity is selected. Overall, these results show strong seasonal variations for energy savings and peak load reductions, which suggests that the characteristics of optimal PCM solutions depend strongly on the user's energy goals.

Figure 6 shows predicted monthly heating energy savings for the analyzed PCM applications. For the heating season, the PCM application with drywall in the interior of the house obtained the best performance, with 25% predicted annual savings. These savings might be improved if PCM properties are optimized in future studies. Similar to the cooling case, there were only small changes between PCM drywall installed in the ceiling and walls. For this particular climate and building for these selected PCMs, percent heating energy savings were higher than percent cooling energy savings. Despite the fact that annual onsite heating energy use represented about 1/2 of the total cooling onsite energy, the predicted absolute heating energy savings were almost 3 times higher than cooling energy savings for this particular house, climate, and PCM selection.

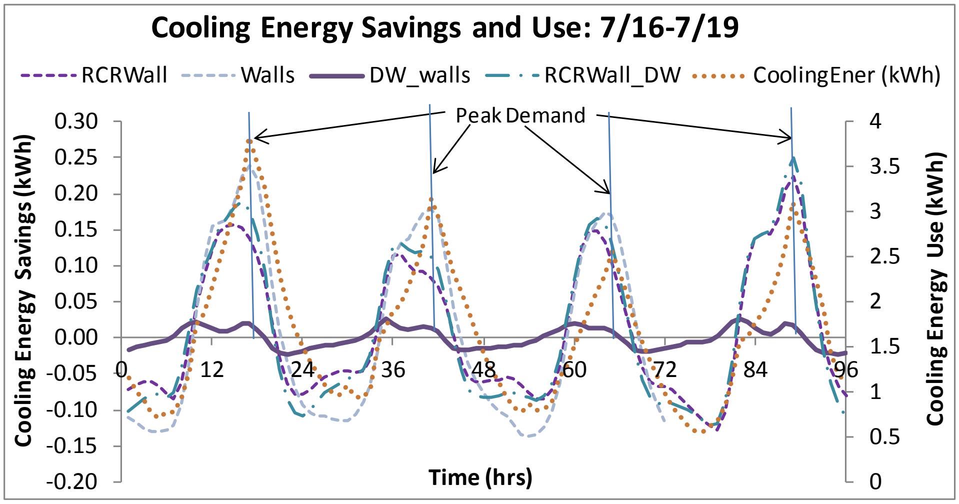

Figure 5. Predicted hourly energy savings from PCM wall applications in July in Phoenix. Right Y-axis shows hourly energy use for house without PCMs (CoolingEner).

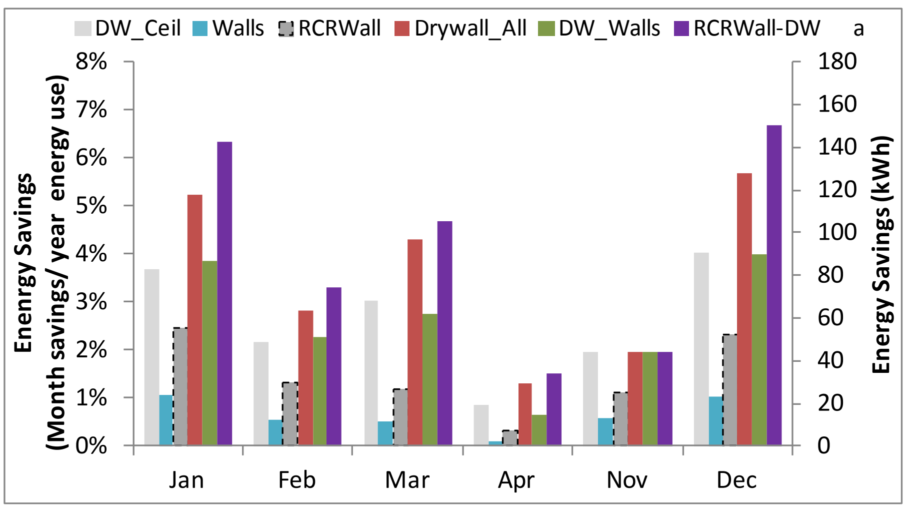

Figure 6. Predicted heating energy savings from PCM strategies.

CONCLUSION

This paper summarizes the approach to validate the CondFD and PCM algorithms in EnergyPlus. This study also shows how the whole-building analysis of a PCM system can produce information that is useful for selecting the type, amount, and location of PCMs for improved energy performance. This application of whole-building analysis is demonstrated for three residential building envelope technologies containing specific PCMs: PCM distributed in insulation, PCM distributed in drywall, and concentrated PCM layer between insulation in the walls. These technologies are compared based on peak reduction and energy savings using the CondFD algorithm in EnergyPlus. Preliminary results suggest that considerable annual energy savings could be achieved using PCMs in residential buildings, but that careful design is needed to optimize PCM solutions according to the specific user goals for peak demand and energy use reductions. Future research will include more detailed parametric analyses to optimize PCM wall strategies as well as analyzing cooling and heating control strategies.

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