Techno-Economic Analysis of Dynamic Building Envelopes Comprising Phase Change Materials and Switchable Insulations

Preprint

Ravi Anant Kishore, Chuck Booten, and
Marcus V. A. Bianchi

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National Renewable Energy Laboratory
15013 Denver West Parkway
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Techno-Economic Analysis of Dynamic Building Envelopes Comprising Phase Change Materials and Switchable Insulations

Ravi Anant Kishore, PhD
Associate ASHRAE

Chuck Booten, PhD
Associate ASHRAE

Marcus V. A. Bianchi, PhD
Member ASHRAE

ABSTRACT

Integrating phase change materials (PCMs) in building envelopes is a recognized technique to reduce the space heating/cooling loads and provide load shedding and shifting capacity. However, PCM benefits have been found to reduce dramatically with increase in the insulation requirements. Dynamic building envelopes that can alter their thermal resistance based on the indoor and outdoor conditions can effectively harness free ambient heating/cooling, thereby greatly enhancing the benefits of the PCM-integrated envelope in managing thermal loads. In this study, we examine various combinations of PCMs and switchable insulations and compare their combined impact on heat flow through the building envelope. Using numerical analysis, we investigate the PCM- and switchable insulation-integrated building walls, calculate the potential energy saving benefits compared to the conventional static walls, and finally perform techno-economic analysis to estimate the acceptable cost of the technology under various payback period scenarios.

INTRODUCTION

Heating and cooling loads account for nearly half of the total energy demand in buildings and contribute significantly to total CO_2 emissions in the United States (DOE 2015). Many prior studies demonstrated that adding phase change materials (PCMs) into building envelopes increases the thermal mass and improves the energy efficiency of the buildings by reducing the electricity demand for heating, ventilation, and air conditioning (HVAC) systems. PCMs, by virtue of phase change, provide significantly higher energy storage capacity than the typical sensible thermal storage medium. At the same time, building envelopes provide large surface areas for the heat exchange between the PCM and the indoor and outdoor environments, making the PCM-integrated envelope an attractive technology for thermal management in buildings. In general, PCM-integrated envelopes provide three-fold benefits: (1) reduce the thermal load in the buildings by storing and releasing the heat flowing across the building envelope; (2) shift the peak thermal load by a few hours, thereby avoiding the peak demand period; and (3) improve indoor thermal comfort for the occupants by minimizing the interior temperature fluctuations (Kishore et al. 2022, Wijesuriya et al. 2022).

PCM integration in building envelopes is a well-explored topic in the literature. Studies have indicated that this technique is more effective in lightweight constructions, such as insulated wooden-framed wall, than heavyweight constructions, such as concrete blocks (Kalnæs and Jelle 2015, Sun et al. 2013). Due to their latent heat, PCMs allow lightweight constructions to increase their thermal mass without much increase in their actual mass. Various studies have investigated PCM-integrated envelopes using both experimental as well as modeling techniques. Childs and Stovall (2012) examined the effect of uniformly distributed PCM-cellulose mixture in a wall cavity on the building's cooling loads in

Ravi A Kishore is a research engineer in the Building Energy Science Group at the National Renewable Energy Laboratory, Golden, CO.
Chuck Booten and Marcus Bianchi are senior research engineers in the Building Energy Science Group at the National Renewable Energy Laboratory, Golden, CO.

Phoenix and Baltimore and noted a decrease in cooling electricity by up to 8% and 34%, respectively. In a similar study, Kosny et al. (2012) investigated the influence of PCM-insulation mixture having 30% PCM by weight on heat flux through a south-facing vertical wall and reported a 20%–35% decrease in peak cooling load. Likewise, a study by Biswas and Abhari (2014) showed that, compared to the cellulose-only insulation, the encapsulated paraffins mixed with cellulose insulation reduced electricity consumption for space conditioning by 11%. Kishore et al. (2020a) studied the benefits of adding a concentrated PCM layer in the wall cavity and reported an annual heat gain reduction in the range of 3.5%–47.2% and an annual heat loss reduction in the range of −2.8% to 8.3% under various U.S. climates. Later, a detailed parametric study on the PCM-integrated walls was also performed, which suggested that a thin layer of PCM with appropriate transition temperature and thermophysical properties when combined with an optimal precooling/preheating strategy can completely invert transient heat flow profiles of the building wall, thereby providing more than 70% reduction in the wall-related heat load during peak hours (Kishore et al. 2020b, 2021a).

While the benefits of PCM-integrated building envelopes are well-established, their full potential can only be harnessed if the PCM undergoes full phase change using free ambient heating/cooling. The continuous push for increased insulation in the building envelope thermally isolates the PCM from the outdoor conditions, thereby reducing its thermal performance. Kosny et al. (2013) showed that the energy-saving capacity of a PCM-integrated wall reduces dramatically with increases in thermal insulation of the wall. Similarly, Miller et al. (2012) reported that PCMs in an insulated wall were fully active for less than 30 days in a year. The conventional thermal insulation with a fixed thermal resistance restrains the heat flow needed for phase transition of the PCM in the envelope, which eventually limits its energy saving potential. A few recent studies have proposed active or dynamic insulation materials and systems, which exhibit switchable thermal resistance that can be controlled based on the indoor and outdoor conditions. In this paper, we will explore and summarize various concepts of dynamic envelopes proposed in the literature, analyze their operating principle, impact, and limitations on building energy use, and perform techno-economic analysis to estimate the acceptable cost of the technology under various simple payback period scenarios.

LITERATURE REVIEW

The concept of dynamic insulations for buildings was introduced several decades ago. Researchers like Anderlind and Johansson (1983), Wallentén (1996), and Taylor and Imbabi (1998) proposed the idea of breathing walls that allow the movement of air and moisture through the external walls of a building. The airflow direction is typically opposite to that of the heat flow to minimize the energy loss through the buildings and improve indoor air quality. The breathing walls, however, required permeable envelope materials to allow air ventilation under a certain pressure difference between interior and exterior of the building. This makes building envelopes very susceptible to air infiltration, causing a fully functional dynamically breathing wall difficult to implement considering operational complexity and thermal comfort of the occupants (Gan 2000).

The efforts to develop dynamic envelopes have been limited until very recently when the concept was reintroduced through a simpler mechanical design. One of such designs (Dabbagh and Krarti 2020) is shown in Figure 1(a). The design consists of movable insulation layers inside the wall cavity that rotate, creating and closing air gaps when required. Depending on the rotational angle, the thermal resistance of the dynamic envelope changes from 2.30 m^2·K/W (13.1 °F·ft^2·h/BTU) when insulation layers are fully closed to 0.38 m^2·K/W (2.16 °F·ft^2·h/BTU) when insulation layers are fully open.

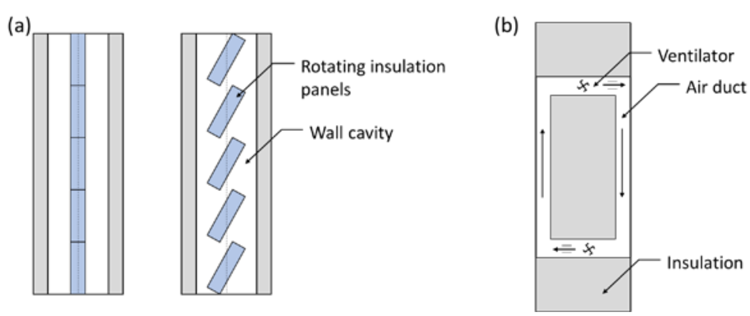

Figure 1. Examples of dynamic insulation designs proposed in the literature. Dynamic insulation system based on (a)

rotatable fines (Dabbagh and Krarti 2020), and (b) closed loop forced convection (Koenders, Loonen and Hensen 2018).

Another dynamic insulation design based on the closed loop forced convection (Koenders, Loonen and Hensen 2018) is shown in Figure 1(b) that comprises ventilators/fans and an air duct. When fans are off and the air in the duct is stagnant, the system acts as a regular insulation panel, providing a high thermal resistance. Alternatively, when the fans are on, airflow promotes heat exchange between inside and outside, thereby bypassing the central insulation layer. The thermal resistance of building envelope was 5.405 K·m^2/W (30.7 °F·ft^2·h/BTU) in "off" mode and 0.603 K·m^2/W (3.4 °F·ft^2·h/BTU) in "on" mode.

Recent studies have noted that the benefits of dynamic insulation can be enhanced by adding a thermal storage system (e.g., a layer of PCM) in the building envelope. Thermal storage allows the building envelope to store the surplus energy when it is readily available, such as free ambient cooling/heating, and utilize it when the energy supply is deficit or expensive. This provides controlled heat transfer between indoors and outdoors, thus substantially enhancing energy savings in the buildings. A recent study (Kishore et al. 2021b) reports that compared to the wall containing only dynamic insulation, PCM + dynamic insulation-integrated wall provides nearly 5 times higher reduction in wall-related heat losses. The benefits further increase with the latent heat capacity of the PCM (Figure 2).

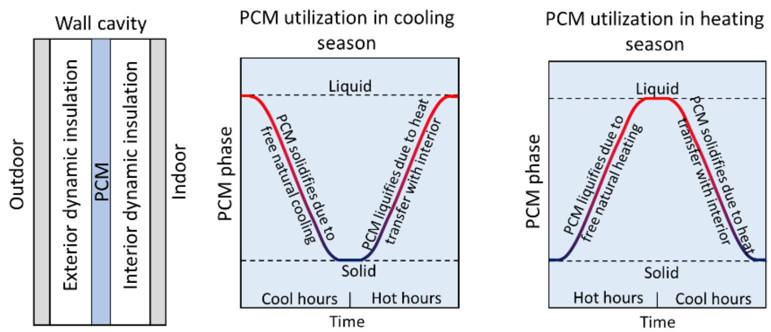

Figure 2. The operation of PCM-integrated dynamic building envelope (Kishore et al. 2021b) under cooling and heating seasons.

Figure 3 shows some of the PCM-integrated dynamic envelope designs proposed in the literature. Figure 3(a) depicts the dynamic building envelope integrated with a movable PCM layer (de Gracia 2019). With an option to vary the position of the PCM layer with respect to the insulating layer in the building envelope, PCM can be charged and discharged based on the indoor and outdoor condition. For instance, in the cooling season, the PCM layer can be located at the outer part of the wall cavity during the nighttime hours, allowing PCM to solidify and charge. Later during the daytime, the PCM layer can be moved toward the indoor side, thereby allowing PCM to liquify by absorbing the internal heat and thus reducing the cooling load of the building. Figure 3(b) illustrates another dynamic building wall (Iffa et al. 2022). The wall is equipped with a network of embedded pipes to dynamically switch the thermal resistance of the active insulation. In this design, cold water to and from a water chiller is connected to the wall with TES to store thermal energy. Allowing the chiller to operate during off-peak hours, when electricity is in low demand or excess renewable energy is available, allows TES to charge the thermal mass (or lowers its temperature). While the active insulation that surrounding the TES is off, low temperature in TES is retained, which is later used to reduce the cooling load during the peak hours.

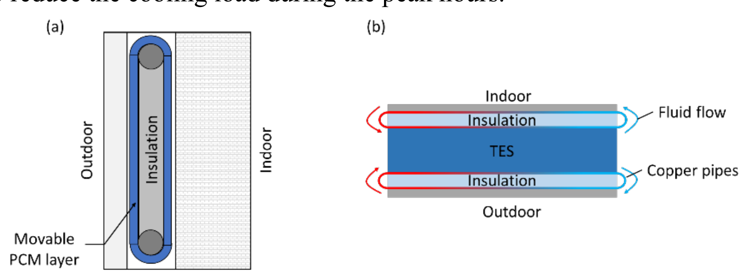

Figure 3. (a) Dynamic envelope integrated with a movable PCM layer (de Gracia 2019). (b) Dynamic building wall equipped with embedded pipes for fluid circulation (Iffa et al. 2022).

In addition to the designs discussed above, researchers have also proposed emerging thermotronic components such as thermal diodes, regulators, and switches as other promising alternatives to achieve dynamic insulation. Some of these options are currently being investigated by the U.S. Department of Energy's Building Technologies Office (Antretter 2019, Kommandur et al. 2021, Prasher 2019, Wehmeyer et al. 2017).

DYNAMIC BUILDING ENVELOPE

Mathematical Model

Figure 4(a) shows the geometry and dimensions used for the numerical modeling in this study. The model comprises all the key components of a wood-frame wall: exterior sheathing, insulation, and internal drywall, along with a layer of PCM at the center of the wall cavity. We considered only a section of the wall by using the lines of symmetry available at the middle of the studs and the cavity in a two-dimensional model to minimize the computational cost. The wall is made of 2×6 wood studs, which have a thickness of 1.5 in. (3.8 cm) and a depth of 5.5 in. (14 cm). The exterior sheathing and interior drywall have the same thickness of 0.5 in. (1.3 cm). The PCM layer is located at the center of the wall cavity and has a thickness of 0.5 in. (1.3 cm). Figure 4(b) shows the area fraction occupied by dynamic insulation. We considered four different cases, where dynamic insulation replaces 5%, 10%, 50%, and 100% of the surface area in wall cavity. Table 1 highlights the material properties of the key wall components.

The transient heat flow in a PCM-integrated wall is given as (Kishore et al. 2022):

$$\rho_{eff} C_{eff} \frac{\partial T}{\partial t} + \nabla \cdot \left(-k_{eff} \nabla T\right) = 0 \quad (1)$$

where ρ_{eff} and $\mathrm{k_{eff}}$ are the mass density and thermal conductivity of the wall components, respectively. The effective thermal properties of the PCM are expressed as (COMSOL 2014):

$$\rho_{eff} = \theta_s \rho_s + \theta_l \rho_l \quad (2)$$

$$k_{eff} = \theta_s k_s + \theta_l k_l \quad (3)$$

where θ is the volume fraction of the solid ("s") and liquid ("l") phases of the PCM.

The effective heat capacity of the PCM is given as (COMSOL 2014):

$$C_{eff} = \frac{1}{\rho_{eff}} (\theta_s \rho_s C_s + \theta_l \rho_l C_l) + L_{s\to l} \frac{\partial \alpha_{s\to l}}{\partial T} \quad (4)$$

$$\alpha_{s\to l} = \frac{1}{2} \frac{\theta_l \rho_l - \theta_s \rho_s}{\theta_s \rho_s + \theta_l \rho_l} \quad (5)$$

where C_s and C_l are the specific heat of the pure solid and liquid states, $L_{s\to l}$ is the total latent heat capacity associated with the phase change, and $\alpha_{s\to l}$ is the fractional change in the PCM composition during the phase transition that varies from -0.5 to 0.5 when PCM transition from pure solid to pure liquid.

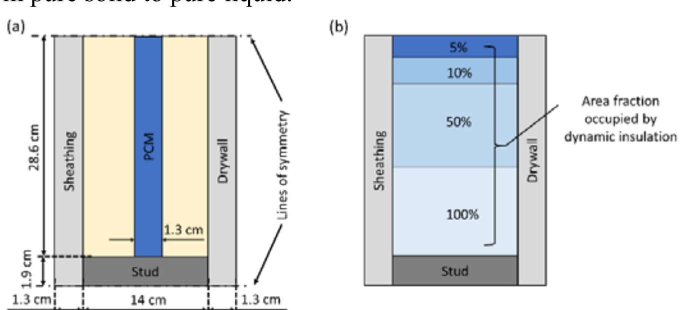

Figure 4. (a) Model geometry and key dimensions used for analysis. (b) Area fraction occupied by dynamic insulation.

Table 1. Material properties of the building wall comprising PCM and dynamic insulations (Kishore et al. (2021b)).

Component	Density	Thermal Conductivity	Specific Heat	Thermal resistance	Latent Heat
Static insulation	24 kg/m^3 1.5 lbs/ft^3	0.042 W/m·K 0.291 BTU·in/h·ft²·°F	1.214 kJ/kg·K 0.290 BTU/lb·°F	3.33 K·m^2/W 18.9°F·ft^2·h/BTU	---
Studs	577 kg/m^3 36 lbs/ft^3	0.144 W/m·K 1.0 BTU·in/h·ft²·°F	1.633 kJ/kg·K 0.390 BTU/lb·°F	0.97 K·m^2/W 5.52°F·ft^2·h/BTU	---
Exterior sheathing	640 kg/m^3 40 lbs/ft^3	0.130 W/m·K 0.902 BTU·in/h·ft²·°F	1.410 kJ/kg·K 0.337 BTU/lb·°F	0.098 K·m^2/W 0.55°F·ft^2·h/BTU	---
Interior drywall	550 kg/m^3 34 lbs/ft^3	0.153 W/m·K 1.06 BTU·in/h·ft²·°F	1.089 kJ/kg·K 0.260 BTU/lb·°F	0.083 K·m^2/W 0.47°F·ft^2·h/BTU	---
PCM (solid)	887 kg/m^3 55 lbs/ft^3	0.300 W/m·K 2.08 BTU·in/h·ft²·°F	2.750 kJ/kg·K 0.657 BTU/lb·°F	0.042 K·m^2/W 0.24°F·ft^2·h/BTU	100 kJ/kg 43 BTU/lb
PCM (liquid)	898 kg/m^3 56 lbs/ft^3	0.100 W/m·K 0.694 BTU·in/h·ft²·°F	1.848 kJ/kg·K 0.442 BTU/lb·°F	0.127 K·m^2/W 0.72°F·ft^2·h/BTU	100 kJ/kg 43 BTU/lb
Dynamic insulation	24 kg/m^3 1.5 lbs/ft^3	Low: 0.042 W/m·K 0.291 BTU·in/h·ft²·°F High: 0.42 W/m·K 2.91 BTU·in/h·ft²·°F	1.214 kJ/kg·K 0.290 BTU/lb·°F	Low: 3.33 K·m^2/W 18.9°F·ft^2·h/BTU High: 0.333 K·m^2/W 1.89°F·ft^2·h/BTU	---

Results and Discussion

For the discussions in this section, we considered Baltimore's climate as the exterior condition. It was assumed that the wall is facing south and has solar absorptivity of 0.6. The exterior and interior surfaces have heat transfer coefficients of 32 W/m^2·K (5.64 BTU/h·ft²·°F) and 2.5 W/m^2·K (0.44 BTU/h·ft²·°F), respectively. The interior temperature was maintained at 20±1 °C in heating season (Oct-Apr) and 22±1 °C in cooling season (May-Sept), with sinusoidal variation from minimum at 3 a.m. to maximum at 3 p.m. The thermal conductivity of the dynamic insulation was varied from 0.042 W/m·K (0.291 BTU·in/h·ft²·°F) under resistive condition to 0.42 W/m·K (2.91 BTU·in/h·ft²·°F) under conductive condition. The control function to switch the thermal conductivity value is based on interior and exterior temperature conditions and is described in our previous publication (Kishore et al. 2021b).

Figure 5 shows the effect of the area fraction occupied by the dynamic insulation on the wall-related heat loads. The annual heat gain/loss through the wall was calculated by integrating the transient heat gain and the transient heat loss through the wall over the entire year.

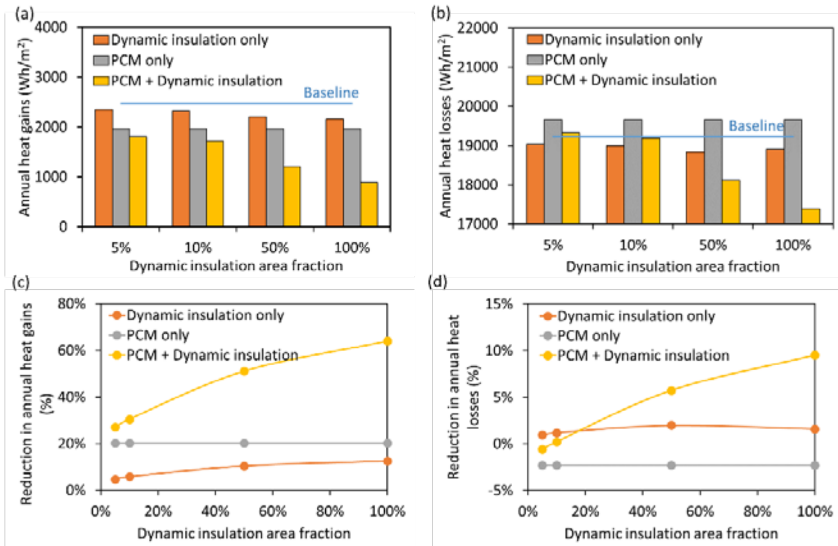

Figure 5. Reduction in wall-related heat loads using PCM and dynamic insulation. (a) Annual heat gains, (b) Reduction in annual heat losses, (c) Reduction in annual heat gains, (d) Reduction in annual heat losses.

Figures 5(a-b) compare the net heat gain and heat loss through the wall under various PCM and dynamic insulation conditions. It can be noted that while PCM and dynamic insulation alone provide limited benefits, combining the two technologies substantially improves the heat load reduction potential. More importantly, the heat load reduction capacity of the dynamic insulation increases with the area fraction. During the cooling season, the PCM alone provides nearly 20% reduction in heat gains, whereas the dynamic insulation alone provides between 5% and 13% heat gain reduction when its area fraction increases from 5% to 100%. During the heating season, the dynamic insulation alone provides very a small heat loss reduction (1%–2%), whereas the thermal performance of PCM alone is worse than that of the traditional wall. This happens because replacing the insulation with PCM greatly reduces the thermal resistance of the wall. Because the temperature difference between indoors and outdoors in Baltimore during the heating season is very large, any thermal storage benefits provided by the PCM is small when compared with the effects of reducing the thermal resistance. The PCM + dynamic insulation, on the other hand, provides 25%–64% reduction in heat gains (cooling season) and up to 10% reduction in heat losses (heating season).

Figure 6 shows the effect of switching ratio (ratio of thermal conductivity in conductive and resistive states) of the dynamic envelope and latent heat of the PCM. The high R-value was kept constant while low R-value was varied to obtain the various switching ratio. The thermal performance of the dynamic envelope increases with switching ratio; however, the performance nearly saturates beyond switching ratio of 50. Likewise, the performance of PCM-integrated dynamic envelope increases with PCM latent heat; however, there is diminishing returns beyond latent heat of 300 kJ/kg.

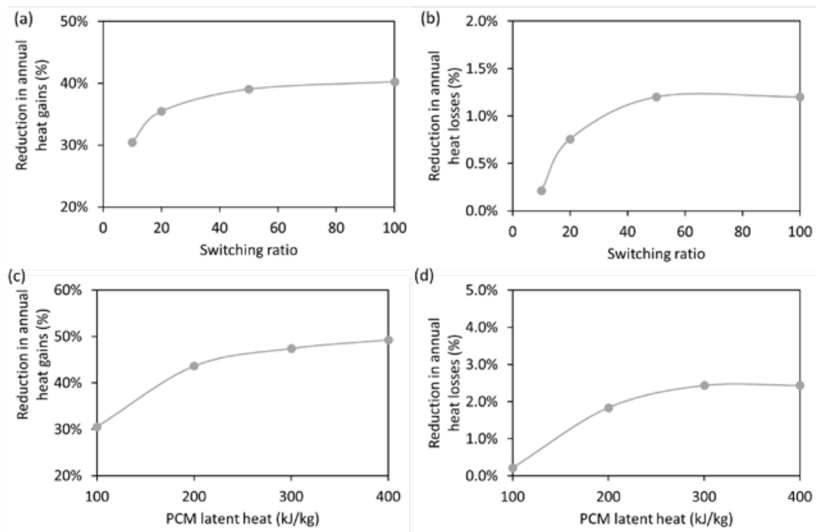

Figure 6. Effect of switching ratio and PCM latent heat on (a,c) reduction in annual heat gains (latent heat: 100 kJ/kg), (b,d) reduction in annual heat losses (switching ratio: 10).

Using simple payback period (SPP), the maximum incremental cost of the dynamic insulation (per unit area) can be calculated as (Fernandez et al. 2015):

$$IC = \frac{1}{f}\left(\frac{\Delta Q}{COP}\right) * r_{elec} * (SPP) \qquad (8)$$

where IC is incremental cost, f is area fraction, ΔQ is the reduction in thermal load, COP is the coefficient of performance of the heat pump (taken as 3.25), r_{elec} is the electricity rate ($0.132/kWh), and SPP is the simple payback period.

Figure 7(a) shows the maximum acceptable incremental cost of the PCM and dynamic insulation-integrated envelope technology. Depending on the area fraction occupied by the dynamic insulation, the incremental cost varies from less of 14 cents/m^2 (1.3 cents/ft^2) to 45 cents/m^2 (4.2 cents/ft^2) for SPP of 1 year and $2.8/m^2 (26 cents/ft^2) to $9.0/m^2 (83 cents/ft^2) for SPP of 20 years. The incremental cost of the PCM + dynamic insulation-integrated envelope can be increased by enhancing switching ratio of the dynamic insulation and latent heat of the PCM. For instance, at switching ratio of 50 and latent heat of 400 kJ/kg, the incremental cost increases to nearly $3.4/m^2 (32 cents/ft^2) for SPP of 5 years and about $13.7/m^2 (127 cents/ft^2) for SPP of 20 years. Note the diminishing returns beyond 200–300 kJ/kg (Figure 7(b)).

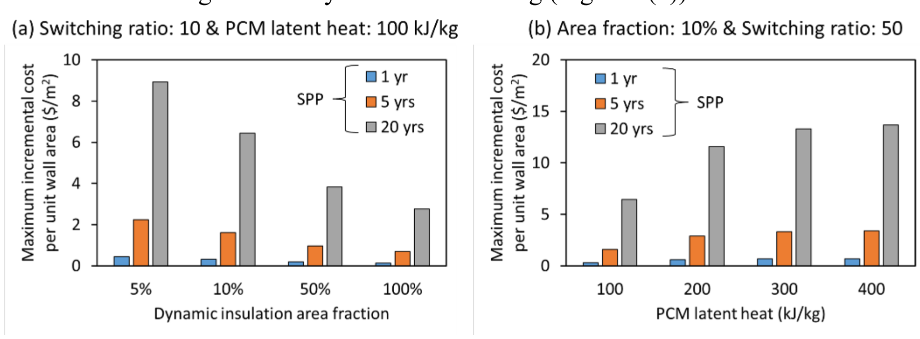

Figure 7. Maximum acceptable incremental cost of the PCM and switchable insulation-integrated dynamic envelope.

CONCLUSION

This paper describes various scenarios for implementing PCM and switchable insulations in a dynamic building wall. Using numerical analysis, we note that combining PCM and dynamic insulation can provide up to 64% reduction in wall-related heat gains, and up to 10% reduction in wall-related heat losses. The techno-economic analysis, however, reveals that depending on the simple payback period considered, the maximum acceptable incremental cost of the technology is 14–45 cents/m^2 (1.3-4.2 cents/ft^2) for SPP of 1 year to up to 2.8–9.0 $/m^2 (26-83 cents/ft^2) for SPP of 20 years, which makes it economically challenging to implement for short-term payback period. To increase the incremental cost of the technology above 10 $/m^2$ (93 cents/ft^2) for SPP of 20 years, the switching ratio of dynamic envelope, occupying 10% of the wall surface area, should be more than 50 and PCM latent heat should be above 200 kJ/kg. Please note that the current analysis is limited to a wall-scale model under a fixed climate, the cost scenario can change based on the whole building analysis, building-type, and climatic conditions.

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NOMENCLATURE

ρ = mass density
k = thermal conductivity
θ = volume fraction
L = latent heat
α = phase change indicator
C = Specific heat

Subscripts

s = solid
l = liquid
eff = effective

REFERENCES

Anderlind, Gunnar and Bernt Johansson. 1983. "Dynamic Insulation: A Theoretical Analysis of Thermal Insulation through Which a Gas or Fluid Flows." Vol.: Statens Raad foer Byggnadsforskning, Stockholm (Sweden).

Antretter, Florian. 2019. "Active Insulation Systems. 2019 BTO Peer Review. https://www.energy.gov/sites/prod/files/2019/05/f62/bto-peer%E2%80%932019-ornl-active-insulation-systems.pdf_. Accessed on July 04, 2020."

Biswas, Kaushik and Ramin Abhari. 2014. "Low-Cost Phase Change Material as an Energy Storage Medium in Building Envelopes: Experimental and Numerical Analyses." *Energy conversion and management* 88:1020-31.

Childs, Kenneth and Therese Stovall. 2012. "Potential Energy Savings Due to Phase Change Material in a Building Wall Assembly: An Examination of Two Climates." *Oak Ridge National Laboratory, Oak Ridge, TN, Technical Report No. ORNL/TM-2012/6* 10:1038077.

COMSOL. 2014. "Comsol Multiphysics User's Guide." *Version: COMSOL Multiphysics 5.6* 3.

Dabbagh, M. and M. Krarti. 2020. "Evaluation of the Performance for a Dynamic Insulation System Suitable for Switchable Building Envelope." *Energy and Buildings* 222:110025.

de Gracia, Alvaro. 2019. "Dynamic Building Envelope with Pcm for Cooling Purposes–Proof of Concept." *Applied Energy* 235:1245-53.

DOE, U. S. 2015. "An Assessment of Energy Technologies and Research Opportunities." *Quadrennial Technology Review*.

Fernandez, Nicholas, Weimin Wang, Kyle J. Alvine and Srinivas Katipamula. 2015. "Energy Savings Potential of Radiative Cooling Technologies." Vol.: Pacific Northwest National Lab.(PNNL), Richland, WA (United States).

Gan, Guohui. 2000. "Numerical Evaluation of Thermal Comfort in Rooms with Dynamic Insulation." *Building and Environment* 35(5):445-53.

Iffa, Emishaw, Diana Hun, Mikael Salonvaara, Som Shrestha and Melissa Lapsa. 2022. "Performance Evaluation of a Dynamic Wall Integrated with Active Insulation and Thermal Energy Storage Systems." *Journal of Energy Storage* 46:103815.

Kalnæs, Simen Edsjø and Bjørn Petter Jelle. 2015. "Phase Change Materials and Products for Building Applications: A State-of-the-Art Review and Future Research Opportunities." *Energy and Buildings* 94:150-76.

Kishore, Ravi Anant, Marcus V. A. Bianchi, Chuck Booten, Judith Vidal and Roderick Jackson. 2020a. "Optimizing Pcm-Integrated Walls for Potential Energy Savings in US Buildings." *Energy and Buildings* 226:110355.

Kishore, Ravi Anant, Marcus V. A. Bianchi, Chuck Booten, Judith Vidal and Roderick Jackson. 2020b. "Modulating Thermal Load through Lightweight Residential Building Walls Using Thermal Energy Storage and Controlled Precooling Strategy." *Applied Thermal Engineering* 180:115870.

Kishore, Ravi Anant, Marcus V. A. Bianchi, Chuck Booten, Judith Vidal and Roderick Jackson. 2021a. "Parametric and Sensitivity Analysis of a Pcm-Integrated Wall for Optimal Thermal Load Modulation in Lightweight Buildings." *Applied Thermal Engineering* 187:116568.

Kishore, Ravi Anant, Marcus V. A. Bianchi, Chuck Booten, Judith Vidal and Roderick Jackson. 2021b. "Enhancing Building Energy Performance by Effectively Using Phase Change Material and Dynamic Insulation in Walls." *Applied Energy* 283:116306.

Kishore, Ravi Anant, Chuck Booten, Marcus V. A. Bianchi, Judith Vidal and Roderick Jackson. 2022. "Evaluating Cascaded and Tunable Phase Change Materials for Enhanced Thermal Energy Storage Utilization and Effectiveness in Building Envelopes." *Energy and Buildings* 260:111937.

Koenders, S. J. M., Rcgm Loonen and J. L. M. Hensen. 2018. "Investigating the Potential of a Closed-Loop Dynamic Insulation System for Opaque Building Elements." *Energy and Buildings* 173:409-27.

Kommandur, Sampath, Ravi Anant Kishore, Chuck Booten, Shuang Cui, Lance M. Wheeler and Judith Vidal. 2021. "Dual Phase Change Thermal Diodes with High Rectification for Thermal Management near Room Temperature." *Advanced Materials Technologies*:2101060.

Kosny, Jan, Elizabeth Kossecka, Andrzej Brzezinski, Akhan Tleoubaev and David Yarbrough. 2012. "Dynamic Thermal Performance Analysis of Fiber Insulations Containing Bio-Based Phase Change Materials (Pcms)." *Energy and Buildings* 52:122-31.

Kosny, Jan, Nitin Shukla and Ali Fallahi. 2013. "Cost Analysis of Simple Phase Change Material-Enhanced Building Envelopes in Southern Us Climates." Vol.: National Renewable Energy Lab.(NREL), Golden, CO (United States).

Miller, William, Som Shrestha, Kenneth Childs and Eric Stannard. 2012. "Field Study and Energy-Plus Benchmarks for Energy Saver Homes Having Different Envelope Designs." Pp. 12-17.

Prasher, Ravi. 2019. "2019 BTO Peer Review – LBNL & NREL – Solid State Tunable Thermal Energy Storage and Switches for Smart Building Envelopes. https://www. eenergy.gov/sites/prod/files/2019/05/f62/bto-peer%E2%80%932019-lbnl-nrel-solid-state-tunable-tes.pdf. Accessed on April 21, 2020.".

Sun, Yongjun, Shengwei Wang, Fu Xiao and Diance Gao. 2013. "Peak Load Shifting Control Using Different Cold Thermal Energy Storage Facilities in Commercial Buildings: A Review." *Energy conversion and management* 71:101-14.

Taylor, B. J. and M. S. Imbabi. 1998. "The Application of Dynamic Insulation in Buildings." *Renewable energy* 15(1-4):377-82.

Wallentén, Petter. 1996. "Dynamic Insulation. Analysis and Field Measurements." *Lund Univ. (Sweden). Dept. of Building Science*.

Wehmeyer, Geoff, Tomohide Yabuki, Christian Monachon, Junqiao Wu and Chris Dames. 2017. "Thermal Diodes, Regulators, and Switches: Physical Mechanisms and Potential Applications." *Applied Physics Reviews* 4(4):041304.

Wijesuriya, Sajith, Chuck Booten, Marcus Bianchi and Ravi Anant Kishore. 2022. "Building Energy Efficiency and Load Flexibility Optimization Using Phase Change Materials under Futuristic Grid Scenario." *Journal of Cleaner Production*:130561.